

SOLUTIONS MANUAL

PAVEMENT

ANALYSIS AND

DESIGN

SECOND EDITION

YANG H. HUANG

SOLUTIONS MANUAL

**PAVEMENT ANALYSIS
AND DESIGN**

SECOND EDITION

YANG H. HUANG



Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

Acquisitions Editor: *Laura Fischer*
Supplement Editor: *Andrea Messineo*
Executive Managing Editor: *Vince O'Brien*
Managing Editor: *David A. George*
Production Editor: *Barbara A. Till*
Manufacturing Buyer: *Ilene Kahn*



© 2004 by Pearson Education, Inc.
Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, NJ 07458

All rights reserved. No part of this book may be reproduced in any form or by any means, without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Pearson Prentice Hall[®] is a trademark of Pearson Education, Inc.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-184244-7

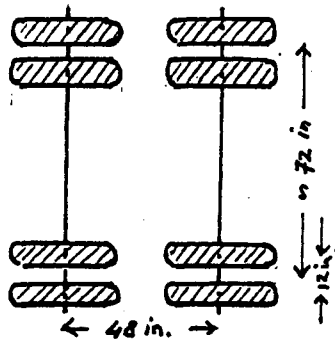
Pearson Education Ltd., *London*
Pearson Education Australia Pty. Ltd., *Sydney*
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd., *Hong Kong*
Pearson Education Canada, Inc., *Toronto*
Pearson Educación de México, S.A. de C.V.
Pearson Education—Japan, *Tokyo*
Pearson Education Malaysia, Pte. Ltd.
Pearson Education, Inc., *Upper Saddle River, New Jersey*

Contents

1	Introduction	1
2	Stresses and Strains in Flexible Pavements	2
3	KENLAYER Computer Program	11
4	Stresses and Deflections in Rigid Pavements	19
5	KENSLABS Computer Program	32
6	Traffic Loading and Volume	42
7	Material Characterization	49
8	Drainage Design	58
9	Pavement Performance	63
10	Reliability	70
11	Flexible Pavement Design	84
12	Rigid Pavement Design	91
13	Design of Overlays	102

Chapter 1 Introduction

1-1. The wheel configuration for a dual-tandem axle is as follows :



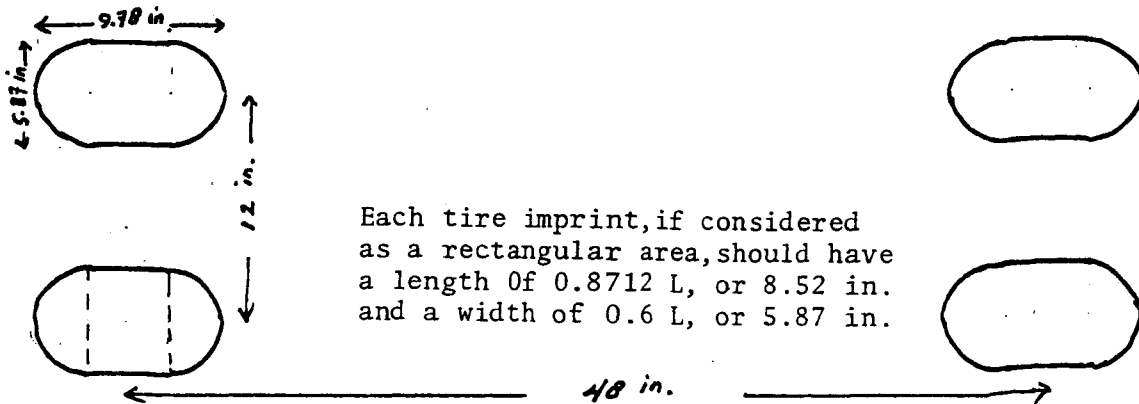
The 40 Kip load is applied over 8 tires. Thus, each tire bears 5000 Lbs (22.2 kN) load with 100 Psi (690 kPa) tire pressure. The contact area of each tire, $A_c = \text{Load of each tire} / \text{tire pressure} = 5000 / 100 = 50 \text{ in.}^2$ ($8.2 \times 10^4 \text{ mm}^2$). The dimension of the contact area is :

From Eq.1.7. (Lecture Text) :

$$L = \sqrt{A_c / 0.5227} = \sqrt{50 / 0.5227} = 9.78 \text{ in. (248 mm).}$$

$$\text{width} = 0.6 L = 5.87 \text{ in (149 mm.)}$$

The most realistic contact area consisting a rectangle and two semi-circles as shown in following figure :



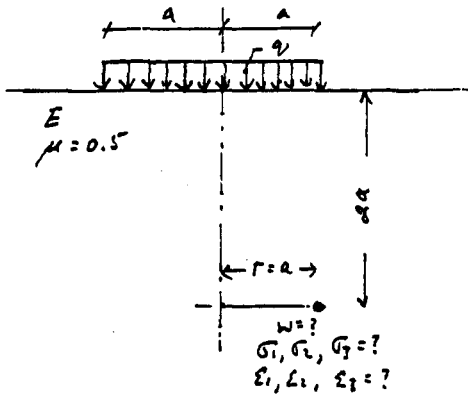
Each tire imprint, if considered as a rectangular area, should have a length of $0.8712 L$, or 8.52 in. and a width of $0.6 L$, or 5.87 in.

1-2. Freezing Index = $(32 - 24) \times 30 + (32 + 3) \times 31 + (32 - 14) \times 31 + (32 - 16) \times 28 + (32 - 22) \times 31 + (32 - 25) \times 30 = \underline{2851}$ degree days.

Yes, this value is likely to be different because the last few days in October and the first few days in May may have mean daily temperatures lower than 32°F , so the degree days for these two months may not be zero.

Chapter 2 Stresses and Strains in Flexible Pavements

2-1.



Solution:

$$r/a = 1 ; z/a = 2$$

From Fig. 2.2:

$$(\sigma_z/q) 100\% = 18$$

$$\sigma_z = 0.18 q$$

From Fig. 2.3:

$$(\tau_{rz}/q) 100\% = 4.05$$

$$\tau_{rz} = 0.0405 q$$

From Fig. 2.4:

$$(\sigma_r/q) 100\% = 1.1$$

$$\sigma_r = 0.011 q$$

From Fig. 2.4: $(\tau_{rz}/q) 100\% = 8.0$

$$\therefore \tau_{rz} = 0.08 q$$

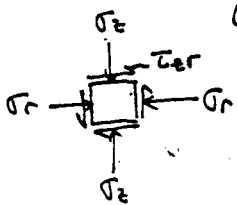
The principal stresses can be calculated by following formula:

$$\text{General form: } \sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\tau_{xy}^2 + \left(\frac{\sigma_x - \sigma_y}{2}\right)^2}$$

$$\sigma_1, \sigma_3 = \frac{\sigma_z + \sigma_r}{2} \pm \sqrt{\tau_{rz}^2 + \left(\frac{\sigma_z - \sigma_r}{2}\right)^2}$$

$$= \frac{0.18q + 0.0405q}{2} \pm \sqrt{0.08q^2 + \left(\frac{0.18q - 0.0405q}{2}\right)^2}$$

$$\sigma_1 = 0.22 q \quad \checkmark \quad \sigma_3 = 0.0041 q \quad \checkmark$$



(z-r plane).

There is no shear stress in z-t plane, therefore

$$\sigma_z = \sigma_2 = 0.011 q \text{ is principal stress. } \checkmark$$

Vertical displacement:

From Fig. 2.6, for $r/a = 1$ & $z/a = 2 \rightarrow F = 0.57$

$$\therefore W = \frac{q a}{E} \times F = \underline{\underline{0.57 \frac{q a}{E}}} \quad \checkmark$$

Strain:

$$\epsilon_1 = \frac{1}{E} [\sigma_1 - \mu (\sigma_2 + \sigma_3)]$$

$$= \frac{1}{E} [0.22 - 0.5(0.0041 + 0.011)]$$

$$\underline{\underline{\epsilon_1 = 0.212 q/E}} \quad \checkmark$$

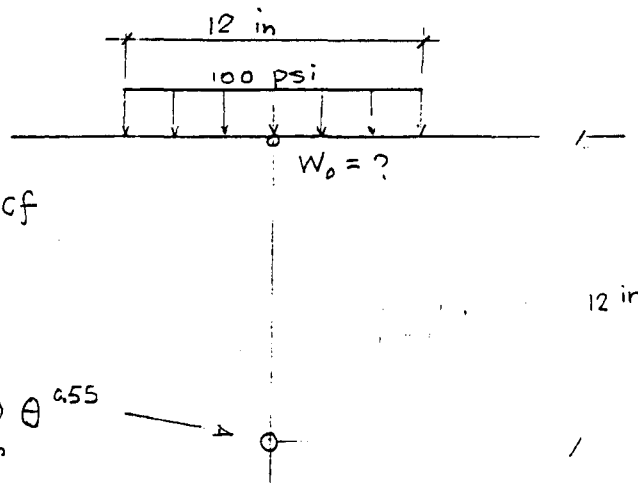
$$\begin{aligned}\epsilon_2 &= \frac{1}{E} [\sigma_2 - \mu(\sigma_1 + \sigma_3)] \\ &= \frac{q}{E} [0.011 - 0.5(0.22 + 0.004)] \\ \underline{\epsilon_2} &= \underline{-0.101 \text{ } q/E} \quad \checkmark\end{aligned}$$

$$\begin{aligned}\epsilon_3 &= \frac{1}{E} [\sigma_3 - \mu(\sigma_1 + \sigma_2)] \\ &= \frac{q}{E} [0.0041 - 0.5(0.22 + 0.011)] \\ \underline{\epsilon_3} &= \underline{-0.1114 \text{ } q/E} \quad \checkmark\end{aligned}$$

$$\begin{aligned}\therefore \sigma_1 &= 0.22 \text{ } q, \quad \sigma_2 = 0.011 \text{ } q, \quad \sigma_3 = 0.0041 \text{ } q \\ \epsilon_1 &= 0.212 \text{ } q/E; \quad \epsilon_2 = -0.101 \text{ } q/E; \quad \epsilon_3 = -0.1114 \text{ } q/E \\ W &= 0.57 \frac{q}{E} \quad \checkmark\end{aligned}$$

2-2.

Given:



$$\gamma = 100 \text{ pcf}$$

$$K_0 = 0.6$$

$$\nu = 0.35$$

$$a = 6 \text{ in}$$

$$E = 3000 \text{ } \psi$$

$$z = 12 \text{ in}$$

Boussinesq's stress distribution is valid

$$\sigma = \sigma_z + \sigma_r + \sigma_t + \gamma \cdot z \cdot (1 + 2K_0)$$

$$\begin{aligned}\sigma_z &= q \left[1 - \frac{z^3}{(a^2 + z^2)^{3/2}} \right] \\ &= 100 \left[1 - \frac{12^3}{(6^2 + 12^2)^{3/2}} \right] \\ &= 28.446 \text{ } \psi\end{aligned}$$

$$\begin{aligned}\sigma_r = \sigma_t &= \frac{q}{z} \left[1 + 2\nu - \frac{z(1+\nu)}{(a^2 + z^2)^{1/2}} + \frac{z^3}{(a^2 + z^2)^{3/2}} \right] \\ &= \frac{100}{z} \left[1 + 2 \cdot 0.35 - \frac{z(1+0.35)}{(6^2 + 12^2)^{1/2}} + \frac{z^3}{(6^2 + 12^2)^{3/2}} \right] \\ &= 0.0294 \text{ } \psi\end{aligned}$$

$$\theta = 28.446 + 2 \times 0.0294 + \frac{100}{12^3} \times 12 \times (1 + 2 \times 0.6)$$

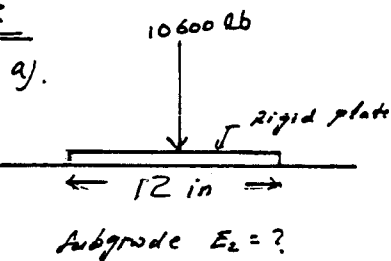
$$= 30.03 \text{ psi}$$

$$E = 3000 \theta^{0.55} = 19489.34 \text{ psi}$$

$$W_0 = \frac{(1+\nu) q a}{E} 2(1-\nu) = \frac{2(1-\nu^2) q a}{E}$$

$$= \frac{2(1-0.35^2) 100 \times E}{19489.34} = 0.054 \text{ in}$$

2-3:



Rigid plate deflects 0.2 in.

The average pressure on the plate:

$$q = \frac{P}{A} = \frac{10600}{\frac{1}{2} \pi 12^2} = 93.7 \text{ psi}$$

deflection of plate can be calculated by:

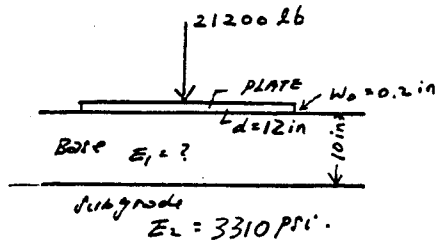
$$W_0 = \frac{\pi (1-\mu^2) q a}{2 E_2}$$

$$W_0 = 0.2 \text{ in}; a = 6 \text{ in}; \mu = 0.5$$

$$E_2 = \frac{\pi (1-\mu^2) q a}{2 W_0} = \frac{\pi (1-0.5^2) \times 93.7 \times 6}{2 \times 0.2}$$

$$E_2 = 3310 \text{ psi}$$

b).



$$q = \frac{P}{\pi d^2} = \frac{21200}{\frac{1}{2} \pi 12^2} = 187.5 \text{ psi}$$

$$h_1 = 10 \text{ in}; W_0 = 0.2 \text{ in}$$

$$a = 6 \text{ in}$$

Two-layer system \rightarrow Burmister:

$$h_1/a = \frac{10}{6} = 1.67$$

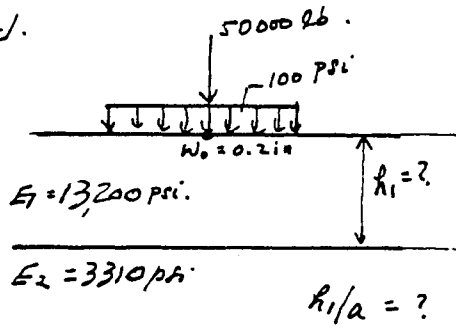
for Rigid plate: $W_0 = \frac{1.178 q \cdot a}{E_2} F_2$

$$F_2 = \frac{W_0 E_2}{1.178 q \cdot a} = \frac{0.2 \times 3310}{1.178 \times 187.5 \times 6} = 0.5$$

for $h_1/a = 1.67$; $F_2 = 0.5$, from Fig. 2.17, E_1/E_2 can be determined

$$E_1/E_2 = 4 \rightarrow E_1 = 13,200 \text{ psi}$$

cj.



$$A_c = \frac{P}{\sigma} = \frac{50000}{100} = 500 \text{ in}^2$$

$$a = 12.6 \text{ in}$$

Surface deflection

$$W_0 = \frac{1.5 q a}{E_2} F_2$$

$$F_2 = \frac{W_0 E_2}{1.5 q a} = \frac{0.2 \times 3310}{1.5 \times 100 \times 12.6}$$

$$F_2 = 0.35$$

From Fig. 2.17, for $F_2 = 0.35$ and $E_1/E_2 = 4$

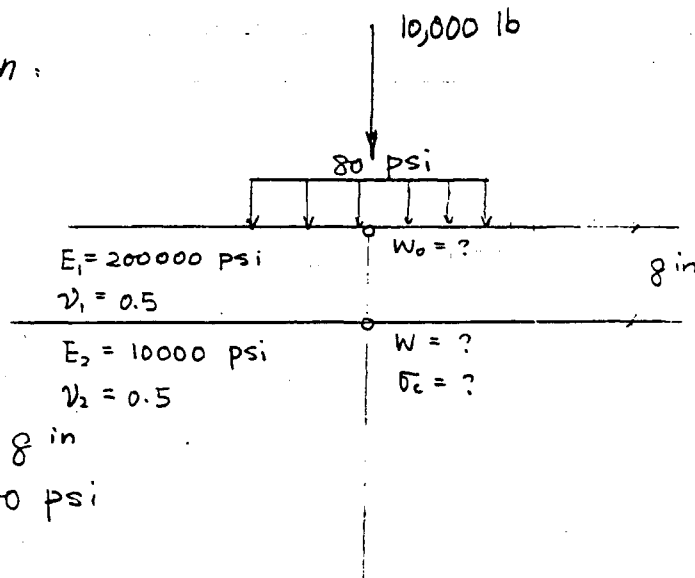
$$\frac{h_1}{a} = 5.5$$

$$h_1 = 5.5 a = 5.5 \times 12.6 = \underline{70 \text{ in.}}$$

$\therefore E_2 = 3310 \text{ psi}; E_1 = 13200 \text{ psi}; h_1 = 70 \text{ in.}$ ✓

2-4.

Given:



$$\frac{10000}{\pi a^2} = 80$$

$$a = \sqrt{\frac{10000}{\pi \times 80}} = 6.31 \text{ in}$$

$$W_0 = \frac{1.5 q a}{E_2} F_2$$

$$= \frac{1.5 \times 80 \times 6.31}{10000} \times 0.33$$

$$= \underline{0.025 \text{ in}} \quad \checkmark$$

$$(E_1/E_2 = 20, h_1/a = 1.268)$$

$$F_2 = 0.33 \quad (\text{Fig 2.17})$$

$$W = \frac{F a}{E} \cdot F$$

$$= \frac{80 + 6.31}{10000} \times 0.483$$

$$= \underline{0.0244} \text{ in. } \checkmark$$

($E_1/E_2 = 20$, $h/a = 1.268$, $\gamma/a = 0$)

Interpolate (Fig 2.19) $\left\{ \begin{array}{l} E_1/E_2 = 10 \quad F = 0.595 \\ E_1/E_2 = 25 \quad F = 0.425 \\ E_1/E_2 = 20 \quad F = 0.483 \end{array} \right.$

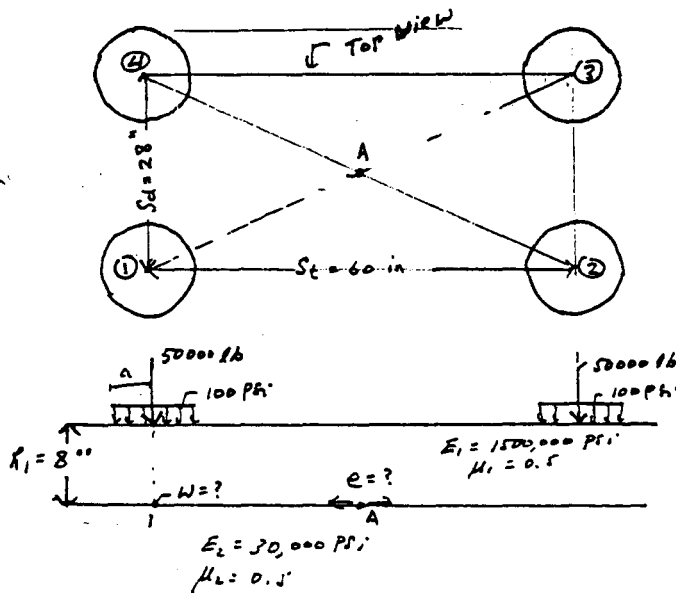
$$\sigma_c/q = 0.153$$

Interpolate (Fig 2.15) $\left\{ \begin{array}{l} E_1/E_2 = 10 \quad \sigma_c/q = 0.21 \\ E_1/E_2 = 25 \quad \sigma_c/q = 0.125 \\ E_1/E_2 = 20 \quad \sigma_c/q = 0.153 \\ a/h = 0.789 \end{array} \right.$

$$\sigma_c = 0.153 q = \underline{12.24} \text{ PSI } \checkmark$$

Note. The linear interpolation is used to get the coefficient value between 2 chart given values. The nonlinear interpolation has been also tried and no big difference was shown say linear interpolation $\sigma_c/q = 0.153$ use 2 points. Nonlinear interpolation: $\sigma_c/q = 0.15$ use 3 points

d-v:



$$\text{Contact area } A = \frac{P}{q} = \frac{50000}{100}$$

$$A = 500 \text{ in}^2$$

$$a = 12.6 \text{ in.}$$

$$s_d = 28 \text{ in}$$

$$s_t = 60 \text{ in.}$$

$$E_1/E_2 = 50$$

Now design charts are based on $s_d = 24 \text{ in}$. Thus, for $s_d = 28 \text{ in}$ a , h , s_t' must be modified:

$$s_t' = s_t \frac{24}{28} = 60 \times \frac{24}{28} = 51.4 \text{ in.}$$

$$a' = \frac{24}{28} a = 10.8 \text{ in.} \quad ; \quad h' = \frac{24}{28} h = 6.86 \text{ in.}$$

determination conversion factor C , using Figs. 2.26 and 2.27

• For $S_t = 48$ in ; $E_1/E_2 = 50$; $h' = 6.86$

$$C_2 = 1.135 \quad C_1 = 1.08$$

$$C = C_1 + 0.2 (A' - 3) \times (C_2 - C_1) = 1.166$$

• For $S_t = 72$ in ; $E_1/E_2 = 50$; $h' = 6.86$

$$C_2 = 1.3 ; C_1 = 1.12$$

$$C = 1.12 + 0.2 (10.8 - 3) (1.3 - 1.12) = 1.4$$

$$S_t = 72 \text{ in} \rightarrow C = 1.4$$

$$S_t' = 57.4 \text{ in} \rightarrow C = ? \rightarrow \text{Linear interpolation}$$

$$S_t = 48 \text{ in} \rightarrow C = 1.166$$

$$C \text{ for } S_t' = 57.4 \text{ in} = 1.4 - \left(\frac{1.4 - 1.166}{72 - 48} \right) (72 - 57.4) \\ = \underline{\underline{1.2}}$$

Strain Factor (F_e):

From Fig. 2.21

$$E_1/E_2 = 50, \quad F_e = 2.5 \quad \text{for } \frac{h'}{a} \text{ or } \frac{h}{a} = 0.64 \text{ and}$$

$$\text{Modified } F_e = F_e' = C \times F_e = 1.2 \times 2.5 = 3.0.$$

$$\text{Critical Article strain: } e = \frac{q}{E_1} F_e'$$

$$= \frac{100}{1500000} \times 3$$

$$\underline{\underline{e = 2.0 \times 10^{-4}}} \quad (\text{below point A}).$$

b). Vertical deflection on surface of subgrade under the center of one wheel (say, point 1).

using Fig. 2.17

deflection factor F can be determined.

	LOADING ① (x)	LOADING ②	LOADING ③	LOADING ④
E_1/E_2	50	50	50	50
h_1/a	0.635	0.635	0.635	0.635
a (in)	12.6	12.6	12.6	12.6
r (in)	0 (x)	60	66.2	28
r/a	0	4.76	5.21	2.22
F	0.62	0.20	0.15	0.37

(x). See: Wheel Configuration.

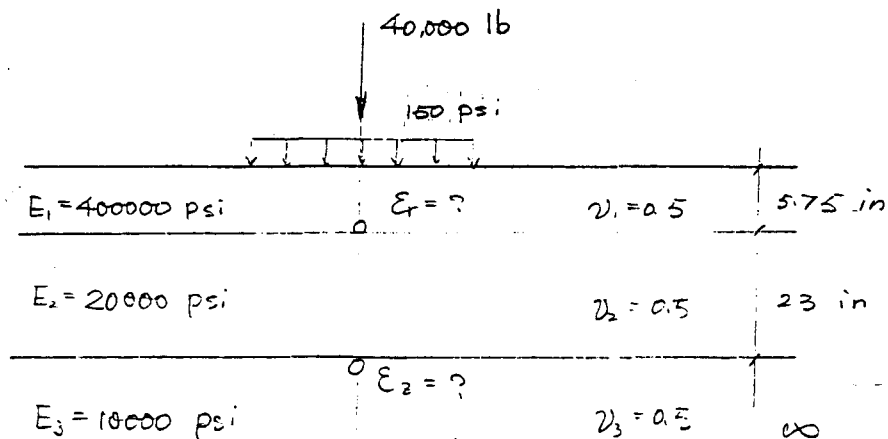
$$F_{\text{total}} = 1.34$$

$$W = \frac{q \cdot a}{E_L} F = \frac{100 \times 12.6}{30000} \times 1.34 = \underline{0.0563 \text{ in.}}$$

Answer: $e = 2.0 \times 10^{-4}$; $W = 0.0563 \text{ in.}$

2-6

Given



$$a = \sqrt{\frac{40000}{\pi \cdot 150}} = 5.21 \text{ in}$$

$$E_r = \frac{-q}{E} \left(\frac{Rr1 - 2Z1}{2} \right)$$

$$= \frac{-150}{400000} \dots + 2$$

$$= \underline{-0.00075} \text{ (tension)}$$

$$K_1 = \frac{E_1}{E_2} = 20$$

$$K_2 = \frac{E_2}{E_3} = 2$$

$$A = \frac{a}{h_2} = \frac{5.21}{23} = 0.4$$

$$H = \frac{h_1}{h_2} = \frac{5.75}{23} = 0.25$$

$$\frac{Rr1 - 2Z1}{2} = 2 \text{ (Fig 2.31c)}$$

If use Table 2.3

$$221 - RR1 = 3.86779$$

$$\epsilon_r = \frac{q}{E_1} \frac{(RR1 - 221)}{2}$$

$$= \frac{-150}{400000} \frac{3.86779}{2}$$

$$= -0.000725 \quad (\text{tension})$$

No big difference between:
Using Table from using
Figures.

when $\nu = 0.5$.

$$\sigma_{22} - \sigma_{r2} = \frac{q}{2} (222 - RR2)$$

$$= 150 \times 0.14159 = 21.23$$

Table 2.3
(222 - RR2) = 0.14159

$$\sigma_{22} - \sigma_{r2}' = (\sigma_{22} - \sigma_{r2}) / k_2$$

$$= 21.23 / 2 = 10.61 \text{ psi}$$

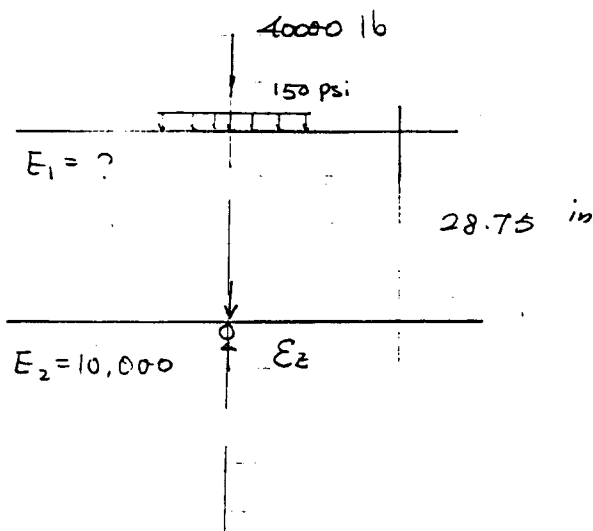
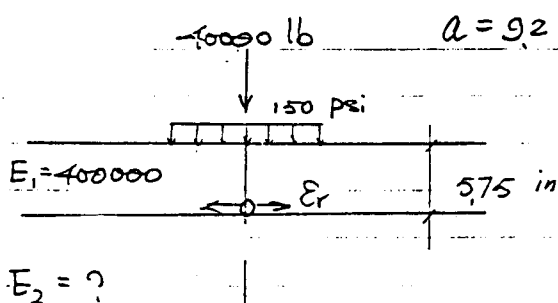
$$\epsilon_2 = \frac{\sigma_{22} - \sigma_{r2}'}{E_2} = \frac{10.61}{10000} = 0.001062 \quad \checkmark$$

2-7.

Given, $\epsilon_r = -0.000725$

$\epsilon_2 = 0.001062$

from 2-6



$$\epsilon_r = \frac{q}{E_1} F_e$$

$$F_e = \frac{\epsilon_r \cdot E_1}{q} = \frac{0.000725 \times 400000}{150} = 1.933 \quad \checkmark$$

$$h_1/a = 0.624 \quad \checkmark$$

$$E_1/E_2 = 20 \quad \text{from Fig. 2.17}$$

$$E_2 = E_1/20 = 400000/20 = 20,000 \text{ psi} \quad \checkmark$$

$$\epsilon_z = 0.00106, \text{ from Eq. 2.21, } \epsilon_y = 0.5 \epsilon_z = 0.00053$$

By trial and error, it was found $E_1 = 35,000$ psi

$$\text{because when } E_1 = 35,000 \text{ psi } F_e = \frac{0.00053 \times 35,000}{150} = 0.124$$

$$\text{and with } \frac{h_1}{a} = \frac{28.75}{9.21} = 3.12, \text{ from Fig. 2.21}$$

$$\frac{E_1}{E_2} = 3.5 \quad \text{or} \quad E_1 = 3.5 \times 10,000 = \underline{35,000 \text{ psi}}$$

2-8. For the Maxwell model $D(t) = \frac{1}{E_0} \left(1 + \frac{t}{T_0}\right)$

$$W_0 = \frac{2(1-\nu^2) \zeta q}{E} = \frac{2 \times 0.91 \times 80 \times 6}{10,000} \left(1 + \frac{t}{10}\right)$$

$$= 0.0874 \left(1 + 0.1t\right)$$

(a) For triangular loading

$$L(t) = \frac{2t}{d} + 1 \quad \text{for } -\frac{d}{2} < t \leq 0$$

$$\frac{dL}{dt} = \frac{2}{d}$$

Since the first term of W_0 is constant independent of t , so Boltzmann's superposition principle need only be applied to the second term

$$W_0 = 0.0874 + 0.0874 \times \frac{2}{10} \int_{-5}^0 0.1 t dt$$

$$= 0.0874 + 0.00175 \left. \frac{t^2}{2} \right|_{-5}^0 = \underline{0.109 \text{ in.}}$$

(b) For haversine loading, from Eqs 2.57 and 2.58

$$W_0 = 0.0874 + 0.0874 \left(-\frac{\pi}{10}\right) \times 0.1 \int_{-5}^0 \sin\left(\frac{2\pi t}{10}\right) t dt$$

$$= 0.0874 - 0.00275 \left[\frac{1}{(0.2\pi)^2} \sin(0.2\pi t) - \frac{t}{0.2\pi} \cos(0.2\pi t) \right]_{-5}^0$$

$$= 0.0874 + 0.00275 \left(\frac{5}{0.2\pi}\right) = \underline{0.109 \text{ in.}}$$

Chapter 3 KENLAYER Computer Program

```
1 (1) NPROB
Problem 3.1
2 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
2 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
12 (6) TH
0.35 0.35 (7) PR
0 (8) ZC
1 (9) NBOND
3000 3000 (11) E
0 (13) LOAD
6 100 (14) CR CP
1 (16) NR
0 (17) RC
2 2 (25) NOLAY ITENOL
1 0 2 0 (26) LAYNO NCLAY
12 12 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
1 (29) RELAX
145 0 (30) GAM
0.55 0.6 (31) K2 KO
0.55 0.6 (31) K2 KO
0 3000 (33) PHI K1
0 3000 (33) PHI K1
```

Answer: 0.05339 in.

```
1 (1) NPROB
PROBLEM 3.2
1 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
2 2 80 5 0 (5) NL NZ ICL NSTD NUNIT
8 (6) TH
0.5 0.5 (7) PR
0 8 (8) ZC
1 (9) NBOND
200000 10000 (11) E
0 (13) LOAD
6.308 80 (14) CR CP
1 (16) NR
0 (17) R
```

*Answer: 0.02512 in.
0.02347 in.
11.394 psi*

```
1 (1) NPROB
PROBLEM 3.3
1 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
2 1 80 9 0 (5) NL NZ ICL NSTD NUNIT
8 (6) TH
0.5 0.5 (7) PR
8 (8) ZC
1 (9) NBOND
1500000 30000 (11) E
2 (13) LOAD
12.616 100 (14) CR CP
1 (19) NPT
60 28 0 0 (20) XW YW XPT
```

*Answer: -2.065E-04
0.05709 in.*

1 (1) NPROB
PROBLEM 3.4
1 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
3 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
5.75 23 (6) TH
0.5 0.5 0.5 (7) PR
5.75 28.7501 (8) ZC
1 (9) NBOND
400000 20000 10000 (11) E
0 (13) LOAD
9.213 150 (14) CR CP
1 (16) NR
0 (17) RC

ANSWER:

-7.259E-04

1.065E-03

2 (1) NPROB
PROBLEM 3.5(a)
2 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
4 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
8 2 2 (6) TH
0.45 0.3 0.3 0.4 (7) PR
8 12.0001 (8) ZC
1 (9) NBOND
500000 30000 15000 5000 (11) E
0 (13) LOAD
4.5 75 (14) CR CP
1 (16) NR
0 (17) RC
3 15 (25) NOLAY ITENOL
2 0 3 0 4 1 (26) LAYNO NCLAY
9 11 13 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
145 135 135 130 (30) GAM
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
6.2 1110 178 0.8 (31) K2 K3 K4 K0
0 10000 (33) PHI K1
0 10000 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1

ANSWER:

-1.019E-04

2.845E-04

PROBLEM 3.5(b)
2 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
3 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
8 4 (6) TH
0.45 0.3 0.4 (7) PR
8 12.0001 (8) ZC
1 (9) NBOND
500000 20000 5000 (11) E
0 (13) LOAD
4.5 75 (14) CR CP
1 (16) NR
0 (17) RC
2 15 (25) NOLAY ITENOL
2 0 3 1 (26) LAYNO NCLAY
9 13 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
145 135 130 (30) GAM
0.5 0.6 (31) K2 K0
6.2 1110 178 0.8 (31) K2 K3 K4 K0
10000 10000 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1

ANSWER:

-1.040E-04

2.853E-04

1 (1) NPROB
 PROBLEM 3.6
 2 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 3 0 80 9 0 (5) NL NZ ICL NSTD NUNIT
 4 8 (6) TH
 0.4 0.3 0.45 (7) PR
 1 (9) NBOND
 400000 10000 10000 (11) E
 1 (13) LOAD
 4.5 75 (14) CR CP
 3 (19) NPT
 0 13.5 0 0 0 4.5 0 6.75 (20) XW YW XPT
 1 15 (25) NOLAY ITENOL
 2 0 (26) LAYNO NCLAY
 6 (27) ZCNOL
 0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
 0.5 (29) RELAX
 145 135 0 (30) GAM
 0.5 0.6 (31) K2 K0
 8000 8000 (33) PHI K1
 1 1 (46) NLBT NLTC
 1 (47) LNBT
 3 (48) LNTC
 36500 (49) TNLR
 0.0796 3.291 0.854 (50) FT1 FT2 FT3
 1.365E-09 4.477 (51) FT4 FT5

answer: 5.49 years

1 (1) NPROB
 PROBLEM 3.7
 2 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 6 0 80 9 0 (5) NL NZ ICL NSTD NUNIT
 4 2 2 2 2 (6) TH
 0.4 0.3 0.3 0.3 0.3 0.45 (7) PR
 1 (9) NBOND
 400000 50000 40000 30000 20000 10000 (11) E
 1 (13) LOAD
 4.5 75 (14) CR CP
 3 (19) NPT
 0 13.5 0 0 0 4.5 0 6.75 (20) XW YW XPT
 4 15 (25) NOLAY ITENOL
 2 0 3 0 4 0 5 0 (26) LAYNO NCLAY
 5 7 9 11 (27) ZCNOL
 0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
 0.5 (29) RELAX
 145 135 135 135 135 130 (30) GAM
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0 8000 (33) PHI K1
 0 8000 (33) PHI K1
 0 8000 (33) PHI K1
 0 8000 (33) PHI K1
 1 1 (46) NLBT NLTC
 1 (47) LNBT
 6 (48) LNTC
 36500 (49) TNLR
 .0796 3.291 .854 (50) FT1 FT2 FT3
 1.365E-09 4.477 (51) FT4 FT5

answer: 5.08 years

1 (1) NPROB
 PROBLEM 3.8
 2 0 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 3 1 80 9 0 (5) NL NZ ICL NSTD NUNIT
 4 8 (6) TH
 0.4 0.3 0.45 (7) PR
 6 (8) ZC
 1 (9) NBOND
 400000 8000 10000 (11) E
 1 (13) LOAD
 4.5 75 (14) CR CP
 1 (19) NPT
 0 13.5 0 6.75 (20) XW YW XPT
 1 15 (25) NOLAY ITENOL
 2 0 (26) LAYNO NCLAY
 6 (27) ZCNOL
 0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
 0.5 (29) RELAX
 145 135 0 (30) GAM
 0.5 0.6 (31) K2 K0
 8000 8000 (33) PHI K1

ANSWER: $2.956E+04$ PSI
 14,003 PSI
 1.113 PSI
 -3,083 PSI

1 (1) NPROB
 PROBLEM 3.9
 3 0 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 2 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
 8 (6) TH
 0.5 0.5 (7) PR
 0 (8) ZC
 1 (9) NBOND
 0 10000 (11) E
 0 (13) LOAD
 6 75 (14) CR CP
 1 (16) NR
 0 (17) RC
 0 (36) DUR
 1 1 (37) NVL LNV
 6 (38) NTYME
 0 0.01 0.1 1 10 100 (39) TYME
 0.113 70 (41) BETA TEMPREF
 0.000002 2.37E-06 3.81E-06 4.38E-06 4.57E-06 0.0000046 (42) CREEP
 70 (44) TEMP

ANSWER: 0.01561 in., 0.01657 in.,
 0.01957 in., 0.02056 in.,
 0.02087 in., 0.02092 in.

1 (1) NPROB
 PROBLEM 3.10
 3 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 2 0 80 9 0 (5) NL NZ ICL NSTD NUNIT
 8 (6) TH
 0.5 0.5 (7) PR
 1 (9) NBOND
 0 10000 (11) E
 0 (13) LOAD
 6 75 (14) CR CP
 1 (16) NR
 0 (17) RC
 0.1 (36) DUR
 1 1 (37) NVL LNV
 11 (38) NTYME
 0.001 0.003 0.01 0.03 0.1 0.3 1 3 10 30 100 (39) TYME

ANSWER: 21.09 years

0.113 70 (41) BETA TEMPREF
 2.04E-06 2.12E-06 2.37E-06 2.92E-06 3.81E-06 4.19E-06 4.38E-06
 4.49E-06 4.57E-06 0.0000046 0.0000046 (42) CREEP
 70 (44) TEMP
 1 1 (46) NLBT NLTC
 1 (47) LNBT
 2 (48) LNTC
 100000 (49) TNLR
 0.0796 3.291 0.854 (50) FT1 FT2 FT3
 1.365E-09 4.477 (51) FT4 FT5

1 (1) NPROB
 PROBLEM 3.11
 1 ① 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 3 0 80 9 0 (5) NL NZ ICL NSTD NUNIT
 6 8 (6) TH
 0.4 0.35 0.45 (7) PR
 1 (9) NBOND
 740000 23000 11000 (11) E
 2 (13) LOAD
 4.52 70 (14) CR CP
 3 (19) NPT
 48 13.5 0 0 0 3.375 0 6.75 (20) XW YW XPT
 1 1 (46) NLBT NLTC
 1 (47) LNBT
 3 (48) LNTC
 200000 (49) TNLR
 0.0796 3.291 0.854 (50) FT1 FT2 FT3
 1.365E-09 4.477 (51) FT4 FT5

*NDAMA should be 2 to get the following:
 Damage ratio due to max. tensile
 strain = 0.04357 and that due
 to differential strain = 0.008804*

answer: 19.09 years

3 (1) NPROB
 Problem 3-12(a)
 2 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 7 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
 2 2 2 2 2 2 (6) TH
 0.35 0.35 0.35 0.35 0.35 0.45 (7) PR
 1 (9) NBOND
 120000 100000 80000 68000 40000 20000 5000 (11) E
 0 (13) LOAD
 6 100 (14) CR CP
 1 (16) NR
 0 (17) RC
 7 15 (25) NOLAY ITENOL
 1 0 2 0 3 0 4 0 5 0 6 0 7 1 (26) LAYNO NCLAY
 1 3 5 7 9 11 13 (27) ZCNOL
 0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
 0.5 (29) RELAX
 135 135 135 135 135 135 115 (30) GAM
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 0.5 0.6 (31) K2 K0
 6.2 1110 178 0.8 (31) K2 K3 K4 K0
 0 10000 (33) PHI K1
 0 10000 (33) PHI K1
 0 10000 (33) PHI K1
 0 10000 (33) PHI K1
 0 10000 (33) PHI K1

0 10000 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1
0 1 (46) NLBT NLTC
7 (48) LNTC
1000 (49) TNLR
1.365E-09 4.477 (51) FT4 FT5
Problem 3-12 (b)
2 2 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
2 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
12 (6) TH
0.35 0.45 (7) PR
1 (9) NBOND
10000 3020 (11) E
0 (13) LOAD
6 100 (14) CR CP
1 (16) NR
0 (17) RC
2 15 (25) NOLAY ITENOL
1 0 2 1 (26) LAYNO NCLAY
4 13 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
135 115 (30) GAM
0.5 0.6 (31) K2 K0
6.2 1110 178 0.8 (31) K2 K3 K4 K0
10000 10000 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1
0 1 (46) NLBT NLTC
2 (48) LNTC
1000 (49) TNLR
1.365E-09 4.477 (51) FT4 FT5
Problem 3-12 (c)
2 2 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
2 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
12 (6) TH
0.35 0.45 (7) PR
1 (9) NBOND
10000 3020 (11) E
0 (13) LOAD
6 100 (14) CR CP
1 (16) NR
0 (17) RC
2 15 (25) NOLAY ITENOL
1 0 2 1 (26) LAYNO NCLAY
6 13 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
135 115 (30) GAM
0.5 0.6 (31) K2 K0
6.2 1110 178 0.8 (31) K2 K3 K4 K0
40 10000 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1
0 1 (46) NLBT NLTC
2 (48) LNTC
1000 (49) TNLR
1.365E-09 4.477 (51) FT4 FT5

answer: 1.89 years

answer: 24.22 years

answer: 7.75 years

2 (1) NPROB
 PROBLEM 3-13(a)
 3 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 2 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
 10 (6) TH
 0.5 0.5 (7) PR
 1 (9) NBOND
 0 0 (11) E
 0 (13) LOAD
 10 100 (14) CR CP
 1 (16) NR
 0 (17) RC
 0.1 (36) DUR
 2 1 2 (37) NVL LNV
 7 (38) NTYME
 0.01 0.03 0.1 0.3 1 3 10 (39) TYME
 0 0 (41) BETA TEMPREF
 1.02E-06 1.06E-06 1.21E-06 1.59E-06 2.68E-06 4.84E-06 9.27E-06 (42) CREEP
 0 0 (41) BETA TEMPREF
 0.000105 0.000289 0.000732 0.00125 0.00195 0.00359 0.00732 (42) CREEP
 0 0 (44) TEMP
 1 1 (46) NLBT NLTC
 1 (47) LNBT
 2 (48) LNTC
 60000 (49) TNLR
 0.0796 3.291 0.854 (50) FT1 FT2 FT3
 1.365E-09 4.477 (51) FT4 FT5

Answer: 11.62 years

PROBLEM 3-13(b)
 3 1 1 1 (3) MATL NDAMA NPY NLG
 0.001 (4) DEL
 2 2 80 9 0 (5) NL NZ ICL NSTD NUNIT
 10 (6) TH
 0.5 0.5 (7) PR
 1 (9) NBOND
 0 0 (11) E
 0 (13) LOAD
 10 100 (14) CR CP
 1 (16) NR
 0 (17) RC
 0.2 (36) DUR
 2 1 2 (37) NVL LNV
 7 (38) NTYME
 0.01 0.03 0.1 0.3 1 3 10 (39) TYME
 0 0 (41) BETA TEMPREF
 1.02E-06 1.06E-06 1.21E-06 1.59E-06 2.68E-06 4.84E-06 9.27E-06 (42) CREEP
 0 0 (41) BETA TEMPREF
 0.000105 0.000289 0.000732 0.00125 0.00195 0.00359 0.00732 (42) CREEP
 0 0 (44) TEMP
 1 0 (46) NLBT NLTC
 2 (47) LNBT
 60000 (49) TNLR
 0.0796 3.291 0.854 (50) FT1 FT2 FT3

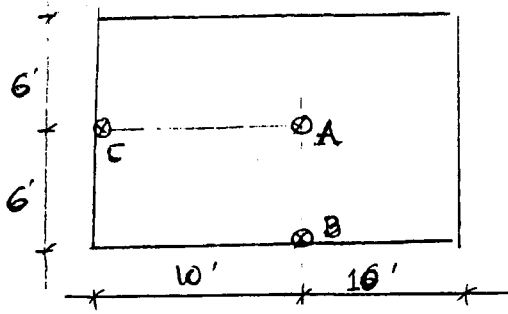
Answer: 7.54 years

1 (1) NPROB
PROBLEM 3-14
4 1 2 2 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
6 0 80 9 0 (5) NL NZ ICL NSTD NUNIT
6 2 2 2 2 (6) TH
0.4 0.35 0.35 0.35 0.35 0.45 (7) PR
1 (9) NBOND
0 7500 7500 7500 7500 3020 (11) E
0 10000 10000 10000 10000 12340 (11) E
0 (13) LOAD
5.35 100 (14) CR CP
1 (16) NR
0 (17) RC
1 (13) LOAD
4.52 70 (14) CR CP
3 (19) NPT
0 13.5 0 0 0 3.375 0 6.75 (20) XW YW XPT
5 15 (25) NOLAY ITENOL
2 0 3 0 4 0 5 0 6 1 (26) LAYNO NCLAY
7 9 11 13 15 (27) ZCNOL
0 0 6.75 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 0.5 (29) RELAX
145 135 135 135 135 125 (30) GAM
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
6.2 1110 178 0.8 (31) K2 K3 K4 K0
0 7500 (33) PHI K1
0 7500 (33) PHI K1
0 7500 (33) PHI K1
0 7500 (33) PHI K1
1827 7682 3020 (33) EMIN EMAX K1
0 10000 (33) PHI K1
0 10000 (33) PHI K1
0 10000 (33) PHI K1
0 10000 (33) PHI K1
7605 17002 12340 (33) EMIN EMAX K1
0.1 (36) DUR
1 1 (37) NVL LNV
11 (38) NTYME
0.001 0.003 0.01 0.03 0.1 0.3 1 3 10 30 100 (39) TYME
0.113 70 (41) BETA TEMPREF
3.7E-07 5.2E-07 8.6E-07 1.45E-06 0.0000025 0.000004 0.0000062 0.0000086
0.000012 0.000016 0.000019 (42) CREEP
60 (44) TEMP
80 (44) TEMP
1 1 (46) NLBT NLTC
1 (47) LNBT
3 (48) LNTC
9125 18250 (49) TNLR
9125 18250 (49) TNLR
0.0796 3.291 0.854 (50) FT1 FT2 FT3
1.365E-09 4.477 (51) FT4 FT5

Answer: 25.15 years

Chapter 4
Stresses and Deflections in Rigid Pavements

4-1
(a)



$h = 8''$
 $k = 50 \text{ pci}$
 $\Delta t = -24^\circ \text{ F}$
 $E = 4 \times 10^6 \text{ pci}$
 $\nu = 0.15$
 $\alpha_t = 5 \times 10^{-6} / ^\circ \text{ F}$

at interior:

$$\sigma_x = \frac{E \alpha_t \Delta t}{2(1-\nu^2)} + \frac{\nu E \alpha_t \Delta t}{2(1-\nu^2)}$$

// x-dir // y-dir

$$= \frac{E \alpha_t \Delta t}{2(1-\nu^2)} (1+\nu) = \frac{E \alpha_t \Delta t}{2(1-\nu)}$$

$$= \frac{4 \times 10^6 \times 5 \times 10^{-6} \times (-24)}{2(1-0.15)} = \underline{\underline{282,353 \text{ psi}}}$$

at edge:

$$\sigma_x = \frac{E \alpha_t \Delta t}{2}$$

// x-dir

$$= \frac{4 \times 10^6 \times 5 \times 10^{-6} \times (-24)}{2} = \underline{\underline{240 \text{ psi}}}$$

(b)

$$e = \sqrt[4]{\frac{E h^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{4 \times 10^6 \times 512}{12(1-0.15^2) \times 50}} = 43.228''$$

$L_x/e = \frac{20 \times 12}{43.228} = 5.552 \rightarrow C_x = 0.825$

from Chart (4.4)

$L_y/e = \frac{12 \times 12}{43.228} = 3.33 \rightarrow C_y = 0.23$

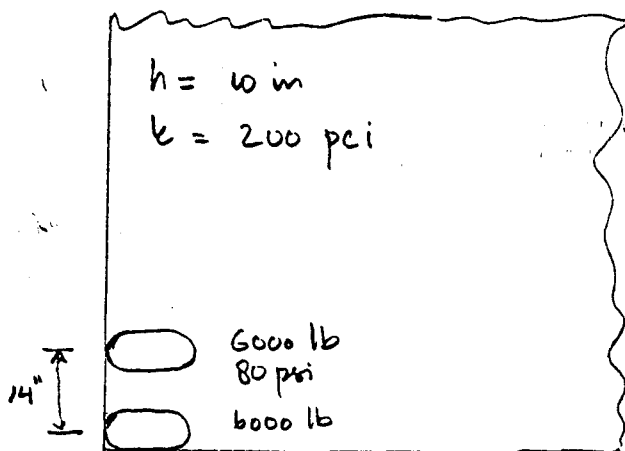
$$\sigma_{xA} = \frac{E \cdot \alpha \cdot \Delta t}{2(1-\nu^2)} (C_x + N \cdot C_y) = \frac{4 \times 10^6 \times 5 \times 10^{-6} \times 24}{2(1-0.15^2)} (0.825 + 0.23 \times 0.15)$$

$$= \underline{\underline{211.03 \text{ psi}}} \checkmark$$

$$\sigma_{xB} = \frac{E \cdot \alpha \cdot \Delta t \cdot C_x}{2} = \frac{4 \times 10^6 \times 5 \times 10^{-6} \times 24 \times 0.825}{2} = \underline{\underline{198 \text{ psi}}} \checkmark$$

$$\sigma_{yC} = \frac{E \cdot \alpha \cdot \Delta t \cdot C_y}{2} = \frac{4 \times 10^6 \times 5 \times 10^{-6} \times 24 \times 0.23}{2} = \underline{\underline{55.2 \text{ psi}}} \checkmark$$

4-2.



$$\nu = 0.15$$

$$q = 80 \text{ psi}$$

$$P_1 = 6,000 \text{ lb}$$

$$P = 12,000 \text{ lb}$$

$$S = 14 \text{ in.} \quad E = 4 \times 10^6 \text{ psi (concrete)}$$

Maximum stress in concrete by Westergaard's equation with equivalent contact area.

$$l = \sqrt{\frac{4 E h^3}{12(1-\nu^2) k}}$$

$$= \sqrt{\frac{4 \times 10^6 (10)^3}{12 [1 - (0.15)^2] 200}} = 36.135''$$

$$a = \sqrt{\frac{0.8521 P_d}{q_f \pi} + \frac{S_d}{\pi} \sqrt{\frac{P_d}{0.5227 q_f}}}$$

$$= \sqrt{\frac{0.8521 (6000)}{80 \pi} + \frac{14}{\pi} \sqrt{\frac{6000}{0.5227 (80)}}$$

$$= 8.986''$$

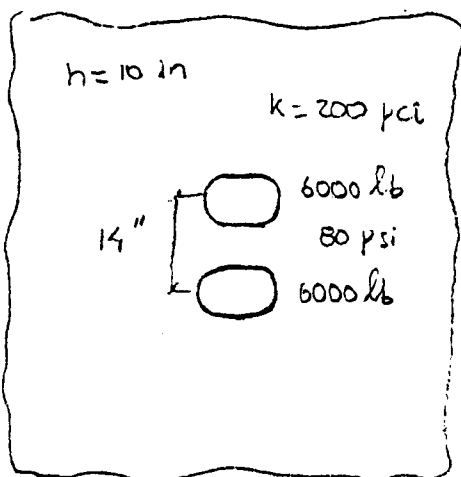
Maximum stress in concrete (σ_c)

$$\sigma_c = \frac{3P}{h^2} \left[1 - \left(\frac{a\sqrt{2}}{L} \right)^{0.6} \right]$$

$$= \frac{3 \times 12,000}{w^2} \left[1 - \left(\frac{8.986 \sqrt{2}}{36.135} \right)^{0.6} \right]$$

$$\sigma_c = 172.8 \text{ psi}$$

4.3 a) Westergaard's Eqn.



$$S_d = 14''$$

$$q_f = 80 \text{ psi}$$

$$P_d = 6000 \text{ lb}$$

$$a = \sqrt{\frac{0.8521 P_d}{q_f \pi} + \frac{S_d}{\pi} \sqrt{\frac{P_d}{0.5227 q_f}}}$$

$$= \sqrt{\frac{0.8521 (6000)}{80 \pi} + \frac{14}{\pi} \sqrt{\frac{6000}{0.5227 (80)}}$$

$$= 8.59 \text{ in}$$

$$\sigma_i = \frac{0.316 P}{h^2} \left[4 \log \left(\frac{l}{b} \right) + 1.069 \right]$$

$$l = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{(4 \times 10^4)(10)^3}{12(1-0.15^2)200}} = 36.14 \text{ in}$$

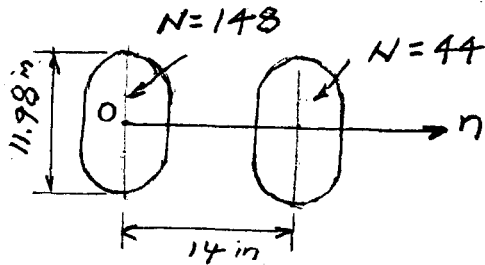
$$(1.724 l = 17.24 \text{ in}) > (8.59 \text{ in} = a)$$

$$b = \sqrt{1.6a^2 + h^2} - 0.675 h = 8.02 \text{ in}$$

$$\sigma_i = \frac{0.316 (12000)}{100} \left[4 \log \left(\frac{36.14}{8.02} \right) + 1.069 \right] = \underline{139.71 \text{ psi}}$$

(b) Influence Chart

$$\text{From Eq. 4.30} \quad L = \sqrt{\frac{6000}{0.5227 \times 80}} = 11.98 \text{ in}$$



Use $l = 36.14 \text{ in}$ on the top of Figure 4.14 as a scale, draw the configuration of the dual tires on a tracing paper. Center point o at the center of the

chart and count the number of blocks. $N = 192$

$$\text{From Eq. 4.32 a} \quad M = \frac{80 \times (36.14)^2 \times 192}{10,000} = 2006 \text{ lb-in./in.}$$

$$\text{From 4.32 b} \quad G = \frac{6 \times 2006}{(10)^2} = \underline{120.36 \text{ PSI}}$$

4-4.

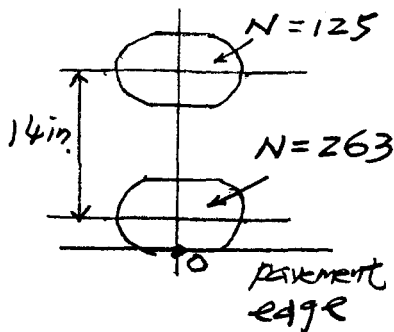
From problem 4-3 $a = 8.59$ in. $l = 36.14$ in.

(a) Westergaard's Equation (Eq. 4.26)

$$\sigma_e = \frac{0.803 \times 12,000}{(10)^2} \left[4 \log\left(\frac{36.14}{8.59}\right) + 0.666\left(\frac{8.59}{36.14}\right) - 0.034 \right]$$

$$= \underline{252.49 \text{ PSI}}$$

(b) Influence Chart (Fig. 4.15)



place point 0 at pavement edge
and count the number of blocks

$$N = 263 + 125 = 388$$

$$M = \frac{9 l^2 N}{10,000} = \frac{80 \times (36.14)^2 \times 388}{10,000} = 4054 \text{ in-lb/in.}$$

$$\sigma_e = \frac{6M}{h^2} = \frac{6 \times 4054}{(10)^2} = \underline{243.3 \text{ PSI}}$$

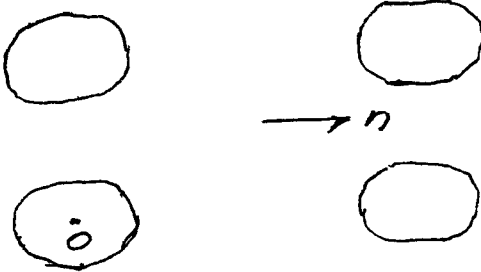
4-5. Using a scale, measure the length of the tire corresponding 22.6 in, say 2.05 units. Measure the length l at the top, say 5.27 units

$$l : 22.5 = 5.27 : 2.05$$

$$l = \frac{5.27}{2.05} \times 22.6 = \underline{58.1 \text{ in.}}$$

The number of blocks covered by the four tires

$$N = 280 \quad M = \frac{100 \times (58.1)^2 \times 280}{10,000} = 9452 \text{ in-lb/in.}$$



$$\sigma_{ii} = \frac{6 \times 9452}{(11)^2} = \underline{469 \text{ psi}}$$

To determine the moment in the longitudinal direction, the orientation of the tires must be rotated 90° , as shown in the left figure. Note that

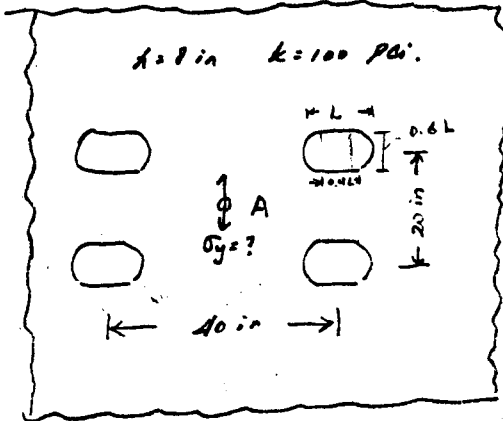
the right two tires straddles between positive and negative blocks and have very little effect on the block count $N = 250$

$$M = \frac{100 \times (58.1)^2 \times 250}{10,000} = 8439 \text{ in.-lb/in.} \quad \sigma_{ii} = \frac{6 \times 8939}{(11)^2} = \underline{418 \text{ psi}}$$

4-6:

$$\text{Total Height} = 40,000 \text{ lb} \quad \text{OR} = 10000 \text{ lb/wheel}$$

$$q = 100 \text{ psi}$$



$$L = \sqrt{10000 / (0.52379)} = 13.975 \text{ in}$$

$$B = 0.6L = 8.265 \text{ in.}$$

$$E_c = 4 \times 10^6 \text{ psi}; \quad \mu_c = 0.15$$

$$k = 8 \text{ in} \quad k = 100 \text{ psi.}$$

Radius of Relative Stiffness (R):

$$R = \sqrt[4]{\frac{4 \times 10^6 \times 8^3}{12(1 - 0.15^2)100}} = 36.35 \text{ in.}$$

Place point A on the center of influence chart. Due to asymmetry only 1 tire imprint area is needed.

x direction: number of blocks for 1 tire = 36.1 (X direction).

$$N = 4 \times 36.1 = 144.4$$

$$M_x = \frac{q R^2 N}{10000} = \frac{100 \times 36.35^2 \times 144.1}{10000} = 1904$$

$$\sigma_x = \frac{6M}{x^2} = 178.5 \text{ psi.}$$

y direction:

Number of blocks for 1 tire = 58.3

$$N = 4 \times 58.3 = 233.2$$

$$M_y = \frac{q R^2 N}{10000} = 2975.6$$

$$\sigma_y = \frac{6 \times 2975.6}{8^2} = \underline{279 \text{ psi.}}$$



4-7. Given:

$$h = 8 \text{ in}$$

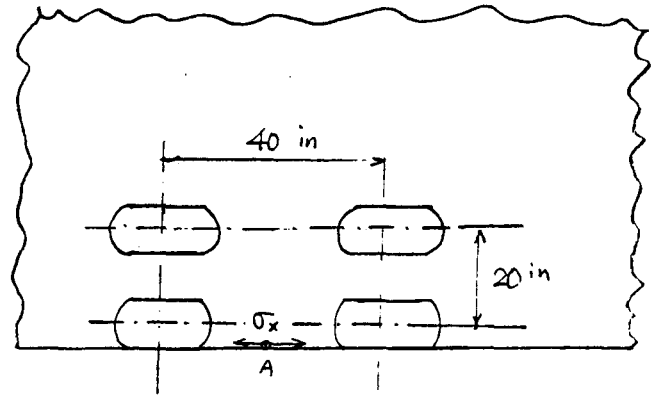
$$K = 100 \text{ pci}$$

$$P_d = 10,000 \text{ lb}$$

$$q = 100 \text{ psi}$$

Asked:

σ_x at point A

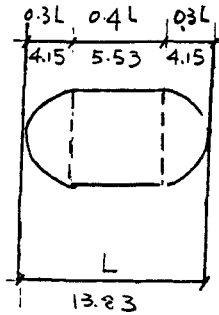


1). Converting duals into a semicircular area

$$L = \sqrt{P_d / (0.5227 q)}$$

$$= \sqrt{10000 / (0.5227 \times 100)}$$

$$= 13.83 \text{ in}$$



2). Radius of relative stiffness l

$$l = \sqrt[4]{\frac{E h^3}{12 (1 - \nu^2) K}}$$

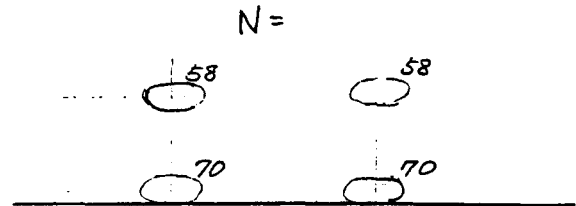
For concrete

$$E = 4 \times 10^6 \text{ psi}$$

$$\nu = 0.15$$

$$= \sqrt[4]{\frac{4 \times 10^6 \times 8^3}{12 (1 - 0.15^2) \times 100}} = 36.35 \text{ in.}$$

$$M = \frac{q l^2 N}{10,000}$$



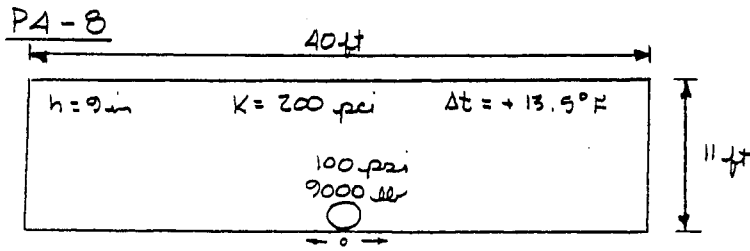
$$l = 36.35 \text{ in}$$

$$N = 58 + 58 + 70 + 70 = 256$$

$$q = 100 \text{ psi}$$

$$M = \frac{100 \times 36.35^2 \times 256}{10,000} = 3382.6 \text{ lb-in/in}$$

$$\sigma = \frac{6M}{h^2} = \frac{6 \times 3382.6}{8^2} = 317 \text{ psi}$$



σ_e due to combined curling and loading?

(a) Curling stress Temp. diff. = 1.5° F per in. of slab

$$J = \left[\frac{Eh^3}{12(1-\nu^2)K} \right]^{0.25} = \left[\frac{(4 \times 10^6)(9)^3}{12(1-0.15^2)(200)} \right]^{0.25} = 33.39 \text{ in} \quad \checkmark$$

$$L_x/J = (40 \times 12) / 33.39 = 14.38$$

$$L_y/J = (11 \times 12) / 33.39 = 3.95$$

From fig. 4.4,

$$C_x = 1.04 \quad (\text{max})$$

$$C_y = 0.4$$

$$\sigma = \frac{CE\alpha\Delta t}{2} = \frac{(1.04)(4 \times 10^6)(5 \times 10^{-6})(13.5)}{2} = 140.4 \text{ psi} \quad \checkmark$$

$$(b) \quad a = \sqrt{\frac{9000}{100 \pi}} = 5.35 \text{ in}$$

$$\sigma_e = \frac{0.803P}{h^2} \left[4 \log \left(\frac{J}{a} \right) + 0.666 \left(\frac{a}{J} \right) - 0.034 \right]$$

$$\sigma_e = \frac{0.803(9000)}{(9)^2} \left[4 \log \left(\frac{33.39}{5.35} \right) + 0.666 \left(\frac{5.35}{33.39} \right) - 0.034 \right]$$

$$\sigma_e = 290.3 \text{ psi} \quad \checkmark$$

(c) Combined stress

$$290.3 - 140.4 = 149.9 \text{ psi} \quad \checkmark$$

$$4-9. \quad A_s = \frac{\gamma_c b L f_a}{2f_s}$$

$$\text{longitudinal } A_s = \frac{0.0868(9)(40 \times 12)(1.5)}{2 \times 43,000} = 0.00654 \text{ in}^2/\text{in}$$

$$= 0.0785 \text{ in}^2/\text{ft}$$

$$\text{Transverse } A_s = \frac{0.0868(9)(11 \times 12)(1.5)}{43,000}$$

$$= 0.003597 \text{ in}^2/\text{in.} = \underline{0.0432 \text{ in}^2/\text{ft}}$$

use 6 x 12 - W4.5 x W4.5 wire mesh.

Because the allowable stress for tiebar is 27,000 psi

$$\text{Area required} = \frac{43,000}{27,000} \times 0.0432 = 0.0688 \text{ in}^2/\text{ft}$$

$$\text{use } \frac{1}{2} \text{ in. bar Area } 0.2 \text{ in. Spacing} = \frac{0.2}{0.0688} = 2.9 \text{ ft}$$

use $\frac{1}{2}$ in. deformed bars at 3 ft spacing.

$$\text{Length of bar } t = \frac{1}{2} \left(\frac{f_s d}{\mu} \right) + 3$$

$$t = \frac{1}{2} \left(\frac{27,000 \times 0.5}{350} \right) + 3 = 19.3 + 3 = 22.3 \text{ in. use } \underline{2 \text{ ft}}$$

4.10 Develop a design chart for required area of temp. steel in terms of the thickness and length of slab, assuming allowable $\sigma_t = 40,000$ psi

$$(4.37) \quad A_s = \frac{h L F_a}{2 f_s} = \frac{(0.0868)(6)(100 \times 12)(1.5)}{2(40,000)} = 0.011718 \text{ in} \times \frac{12 \text{ in}}{\text{ft of steel}} = 0.1406 \text{ in}^2/\text{ft of steel}$$

$$\frac{(0.0868)(8)(1200)(1.5)}{2(40,000)}$$

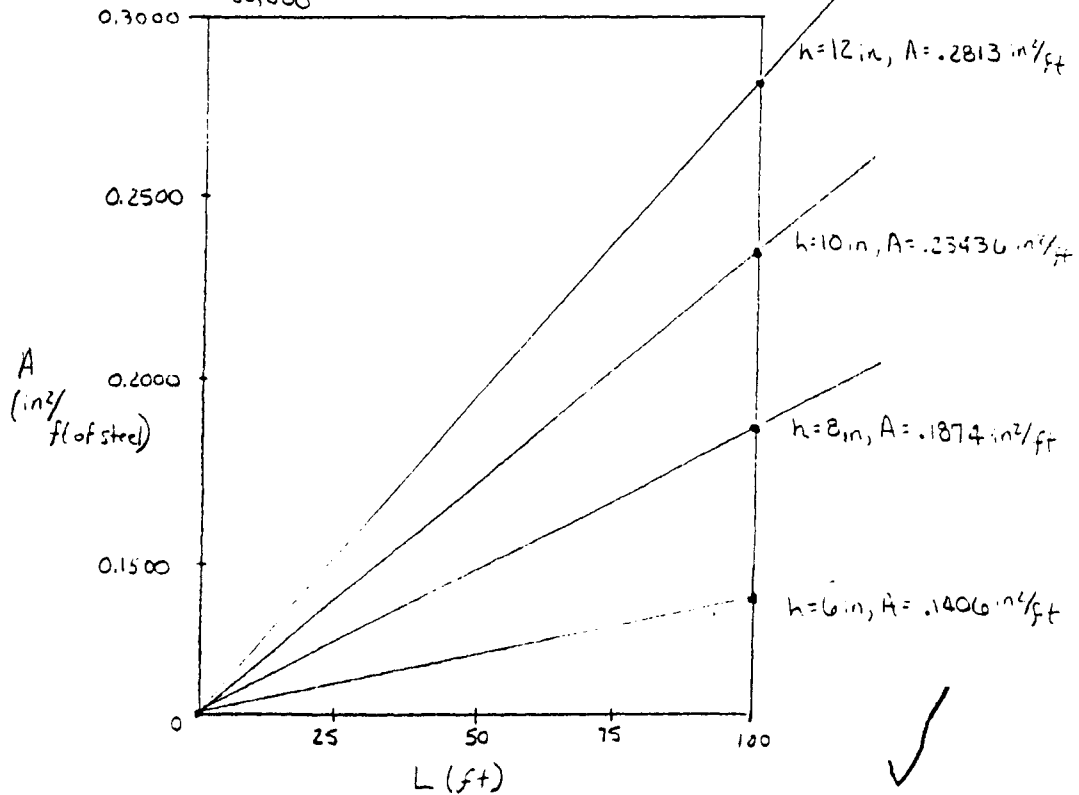
$$0.1874 \text{ in}^2/\text{ft}$$

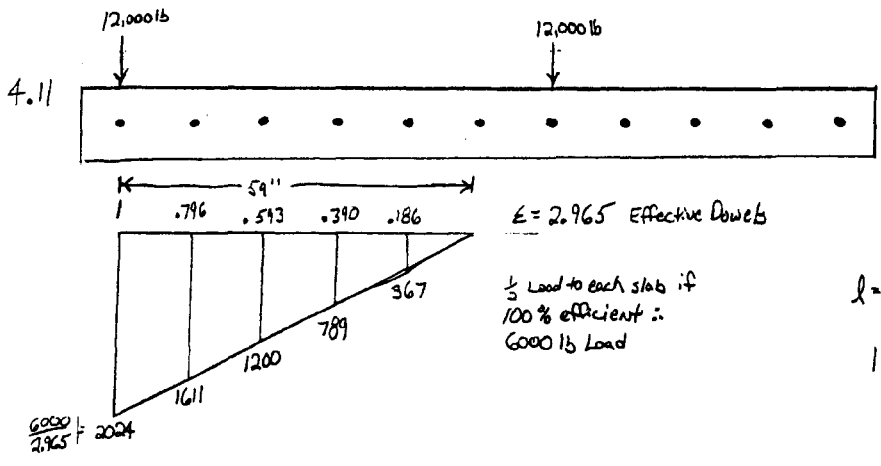
$$\frac{(0.0868)(10,000)(1.5)}{80,000} =$$

$$0.23436 \text{ in}^2/\text{ft}$$

$$\frac{(0.0868)(12)(1200)(1.5)}{80,000} =$$

$$0.28123 \text{ in}^2/\text{ft}$$





Width = 12' = 144"
 Thickness = 10"
 K = 300 pci
 Joint = 0.25 in
 Dowels = 1 in @ 12 in on centers

$\epsilon = 2.965$ Effective Dowels
 $\frac{1}{2}$ Load to each slab if 100% efficient \therefore 6000 lb Load

$$l = \left[\frac{Eh^3}{12(1-\nu^2)K} \right]^{.25} = \left[\frac{(4 \times 10^6) 10^3}{12(1-.25^2) 300} \right]^{.25} = 32.65''$$

$$1.8l = 1.8(32.65) = 58.77'' \approx 59''$$

$$I_d = \frac{1}{64} \pi d^4$$

$$\therefore \frac{1}{64} \pi (1)^4 = 0.0491 \text{ in}^4 \quad \text{Eq. 4.43}$$

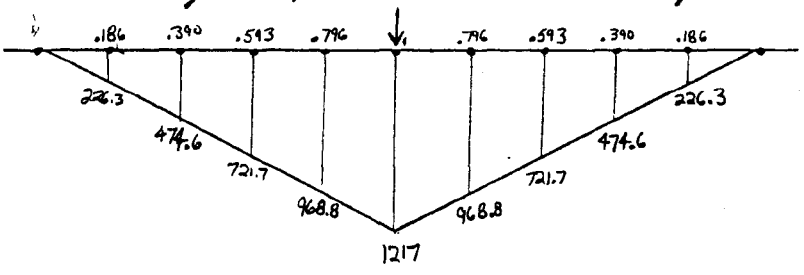
$$\beta = \sqrt[4]{\frac{Kd}{4E_d I_d}} = \sqrt[4]{\frac{(1.5 \times 10^6)(1)}{4(29 \times 10^6)(0.0491)}} = 0.71637 \quad \text{Eq. 4.44}$$

$$\sigma_b = \frac{K P_c (2 + \beta z)}{4 \beta^3 E_d I_d} \quad z = \text{Joint width}$$

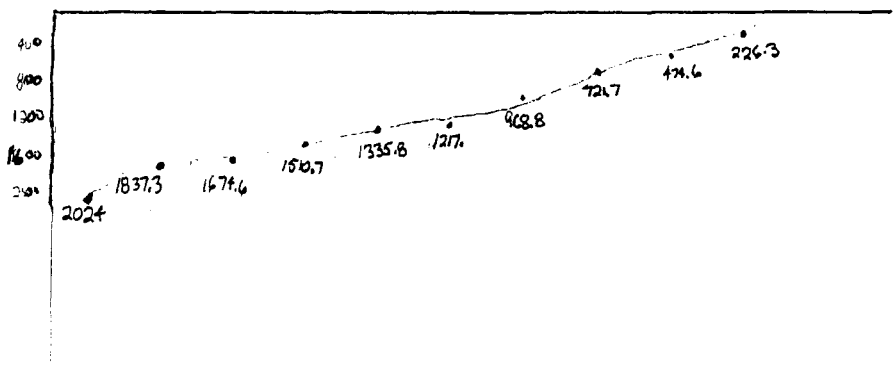
$$= \frac{(1.5 \times 10^6) 2024 (2 + 0.71637(0.25))}{4(0.71637)^3 (29 \times 10^6) \cdot 0.0491} \quad \text{Eq. 4.45}$$

$$= 3159.5 \text{ psi} \quad \text{Max Bearing stress between concrete and Dowel}$$

The maximum stress is at the dowel near to the right so you don't have to consider the interior load.



$$\frac{6000}{4.93} = 1217$$



4-12:

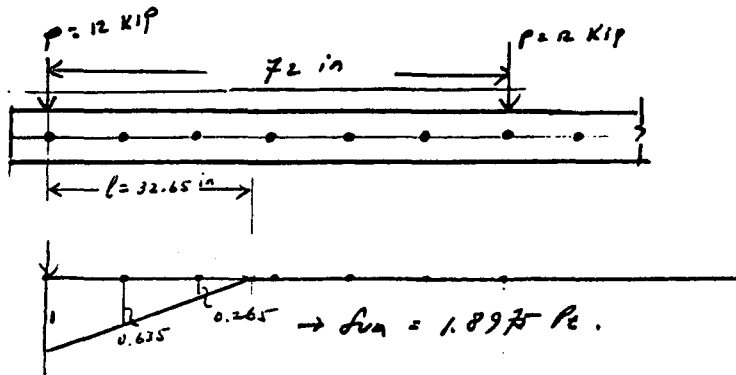
Slab width = 12 ft = 144 in.

$h = 10$ in

$k = 300$ pci, AxU load = 24000 lb.

$$z = \sqrt[4]{\frac{EA^3}{12(1-\mu^2)k}} = \sqrt[4]{\frac{4 \times 10^6 \times 10^3}{12(1-0.15^2)300}} = 32.65 \text{ in.}$$

Max. \ominus moment \ominus occurs at a distance of $l = 10z = 32.65$ in



Since loading spacing = 72 in $>$ $l = 32.65$ in, only load near the pavement edge to be considered. The right wheel has no effect on the maximum force (P_c) on the dowel near the pavement edge.

If joint 100% efficiency $\rightarrow P_c = \frac{12000 \times 0.5}{1.897} = 3162 \text{ lb.}$

$$I_d = \frac{1}{64} \pi d^4 = 0.0491 \text{ in}^4 \quad (d = 1 \text{ in}).$$

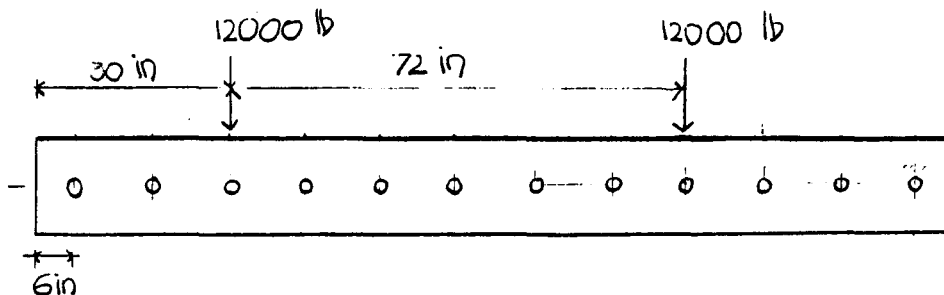
$$\beta = \sqrt[4]{\frac{k d l}{4 E_d I_d}} = \sqrt[4]{\frac{1.5 \times 10^6 \cdot 1}{4 \times 29 \times 10^6 \times 0.0491}} = 0.7164$$

$$\sigma_b = \frac{k P_c}{4 \beta^3 E_d I_d} (2 + \beta z)$$

for $z = 0.25$

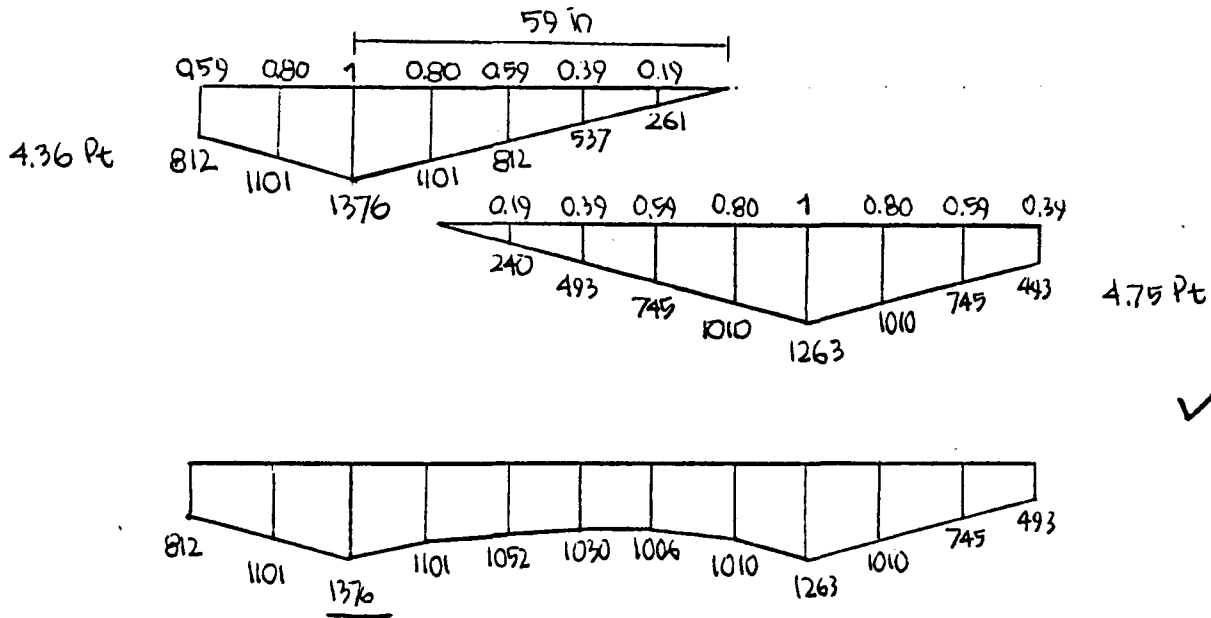
$$\begin{aligned} \sigma_b &= \frac{1.5 \times 10^6 \times 3162}{4 \times 0.7164^3 \times 29 \times 10^6 \times 0.0491} (2 + 0.7164 \times 0.25) \\ &= 4935 \text{ psi} \quad \checkmark \end{aligned}$$

#4.13.



$$l = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)k}} = \sqrt[4]{\frac{4 \times 10^6 \times 10^3}{12(1-0.15^2)300}} = 32.65 \text{ in}$$

$$\rightarrow 1.8 l \approx 59 \text{ in}$$



$$I_d = \frac{1}{64} \pi (d)^4 = \frac{1}{64} \pi (1)^4 = 0.049$$

$$\beta = \sqrt[4]{\frac{Kd}{4E_d I_d}} = \sqrt[4]{\frac{(1.5 \times 10^6) 1}{4(29 \times 10^6) 0.049}} = 0.717 \text{ in}^{-1}$$

$$\sigma_b = \frac{K Pt}{4 \beta^3 E_d I_d} (2 + \beta z) = \frac{(1.5 \times 10^6) 1376}{4(0.717)^3 (29 \times 10^6) (0.049)} (2 + 0.717 \times 0.25)$$

$$\sigma_b = \underline{2147 \text{ psi}}$$

4-14. Given:

$$\beta = 12 \text{ ft} = 144 \text{ in}$$

$$h = 10 \text{ in}$$

$$k = 300 \text{ pci}$$

$$E_c = 4 \times 10^6 \text{ psi}$$

$$\nu_c = 0.15$$

$$E_s = 29 \times 10^6 \text{ psi}$$

$$\nu_s = 0.3$$

100% transfer.

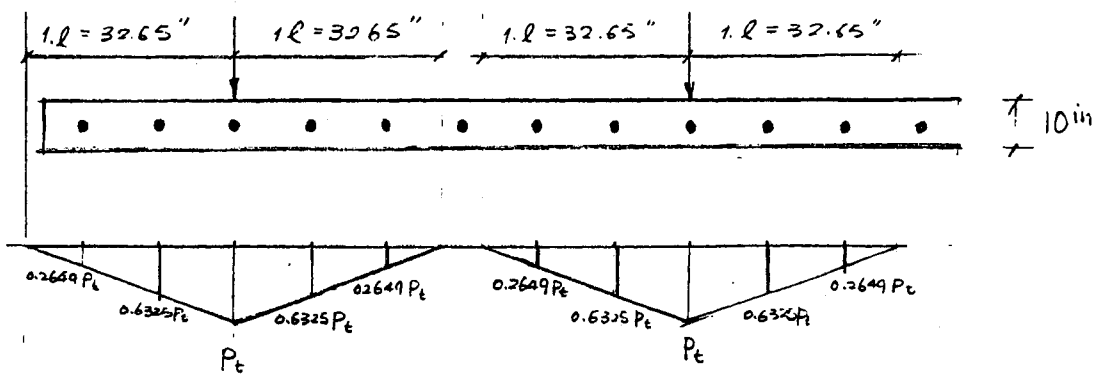
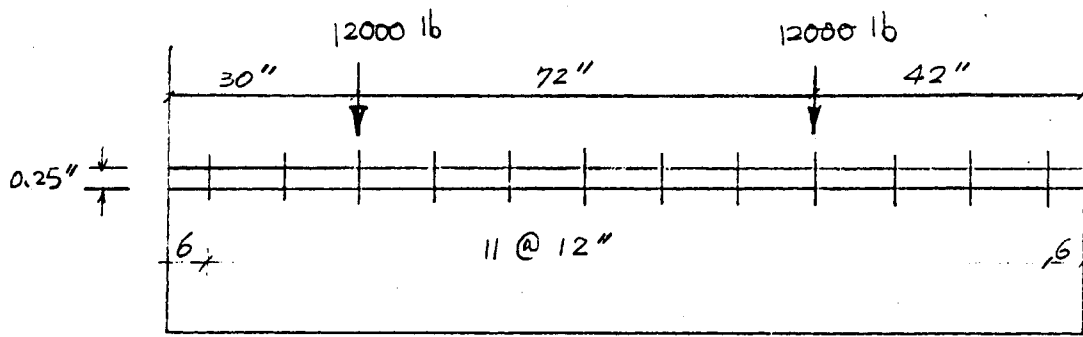
$$z = 0.12 \text{ in}$$

$$l = 1.0$$

$$d = 1 \text{ in}$$

$$K_d = 1.5 \times 10^6 \text{ psi/in}$$

$$E_d = 29 \times 10^6 \text{ psi}$$



SUM:

$$2.7948 P_t = 12000 \text{ lb} / 2$$

$$P_t = 2146 \text{ lb}$$

$$2.7948 P_t = 12000 \text{ lb} / 2$$

$$P_t = 2146 \text{ lb}$$

$$l = 4 \sqrt{\frac{Eh^3}{12(1-\nu^2)K}} = 4 \sqrt{\frac{4 \times 10^6 \times 10^3}{12 \times (1-0.15^2) \times 300}} = 32.65 \text{ in}$$

$$I_d = \frac{1}{64} \pi d^4 = \frac{1}{64} \times \pi \times 1^4 = 0.0491 \text{ in}^4$$

$$\beta = 4 \sqrt{\frac{K_d d}{4E_d I_d}} = 4 \sqrt{\frac{1.5 \times 10^6 \times 1}{4 \times 29 \times 10^6 \times 0.0491}} = 0.7164 \text{ in}^{-1}$$

$$\sigma_b = \frac{K_d P_t}{4\beta^3 E_d I_d} (2 + \beta z) = \frac{1.5 \times 10^6 \times 2146 \times (2 + 0.7164 \times 0.)}{4 \times 0.7164^3 \times 29 \times 10^6 \times 0.0491}$$

$$= \underline{3206.4} \text{ psi}$$

Chapter 5
KENSLABS Computer Program

5-1.

(a) Given $\sigma = 400$ psi and $h = 7$ in, find bending moment per in. width of slab

$$\sigma = 6M/h^2, \text{ so } M = \sigma h^2/6 = (400 \times 49)/6 = \underline{3267} \text{ lb-in./in. of slab.}$$

(b) Given: $E_1 = 7 \times 10^5$ psi, $E_2 = 4 \times 10^6$ psi and two bonded layer with $h_1 = 3$ in. and $h_2 = 5$ in. Find bending stress at top and bottom. With $E_1/E_2 = 0.175$, from Eq. 5.8,

$$d = \frac{0.175 \times 3(0.5 \times 3 + 7) + 0.5(7)^2}{0.175 \times 3 + 7} = 3.849 \text{ in. From Eq. 5.9,}$$

$$I_c = 0.175 \left[\frac{1}{12} (3)^3 + 3(0.5 \times 3 + 7 - 3.849)^2 \right] + \frac{1}{12} (7)^3 + 7(3.849 - 0.5 \times 7)^2$$

$$= 11.750 + 28.583 + 0.853 = 41.186 \text{ in}^3$$

Bending stress at bottom of PCC

$$f_2 = \frac{3267 \times 3.849}{41.186} = \underline{305.3} \text{ psi}$$

Bending stress at top of HMA

$$f_1 = \frac{3267 \times (10 - 3.849)}{41.186} \times 0.175 = \underline{85.4} \text{ psi}$$

5-2. Same as 5-1, but the two layers are unbonded.

From Eqs. 5.12, the modulus of rigidity of each layer

$$R_1 = \frac{7 \times 10^5 \times (3)^3}{12[1 - (0.4)^2]} = 1.875 \times 10^6 \text{ lb-in.}^2$$

$$R_2 = \frac{4 \times 10^6 \times (7)^3}{12[1 - (0.15)^2]} = 1.1696 \times 10^8 \text{ lb-in.}^2$$

$R_1 + R_2 = 1.1884 \times 10^8$ The moment carried by each layer is proportional to R,

$$M_1 = (1.875 \times 10^6 / 1.1884 \times 10^8) \times 3267 = 51.545 \text{ in.-lb/in.}$$

$$M_2 = 3267 - 51.545 = 3215.455 \text{ in.-lb/in.}$$

$$f_1 = (51.545 \times 6)/(3)^2 = \underline{34.4} \text{ psi}$$

$$f_2 = (3215.455 \times 6)/(7)^2 = \underline{393.7} \text{ psi}$$

```

1 (1) NPROB
Problem 5-3
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
9 6 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 1 0 1 0 0 9 6 0 0 2 1 2 (6) N LAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
-24 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 12 28 44 60 76 92 108 120 0 12 28 44 60 72 (9) X's and then Y's
8 0.15 4000000 (10) T PR YM Answer: at Node 54 -214.269 psi
0 (12) NUDDL
0 (13) NCNF 49 -207.423 psi
0 0 (14) NNMK NNMV
6 12 18 24 30 36 42 48 54 (19) NODSX 6 -57.865 psi
49 50 51 52 53 54 (20) NODSY
1 (22) FSAF
0 50 (24) NAS SUBMOD

```

```

1 (1) NPROB
Problem 5.4
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
7 6 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 2 2 (6) N LAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 12 24 36 54 78 120 0 17.6 36 54 78 120 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
2 (12) NUDDL
0 (13) NCNF answer: at node 20 174.576 psi
0 0 (14) NNMK NNMV
1 0 10.44 0 7.19 79.932 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 10.44 14.005 21.195 79.932 (15) LS XL1 XL2 YL1 YL2 QQ
1 (22) FSAF
0 200 (24) NAS SUBMOD

```

```

1 (1) NPROB
Problem 5.5
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
7 7 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 7 7 0 0 1 2 2 (6) N LAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 7 14 26 48 83 118 0 7 14 26 48 83 118 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
1 (12) NUDDL
0 (13) NCNF answer: at Node 2 -128.407
0 0 (14) NNMK NNMV
1 0 5.22 3.405 10.595 79.932 (15) LS XL1 XL2 YL1 YL2 QQ
1 8 15 22 29 36 43 (19) NODSX
1 2 3 4 5 6 7 (20) NODSY
1 (22) FSAF
0 200 (24) NAS SUBMOD

```

```

1 (1) NPROB
Problem 5.6
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
7 7 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 7 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 8 18 30 54 84 120 0 8 17.6 30 54 84 120 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
2 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 0 5.22 0 7.19 79.932 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 5.22 14.005 21.195 79.932 (15) LS XL1 XL2 YL1 YL2 QQ
1 2 3 4 5 6 7 (20) NODSY
1 (22) FSAF
0 200 (24) NAS SUBMOD

```

answer: at Node 1 -251.392 Psi

```

1 (1) NPROB
Problem 5.7
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
7 7 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 7 7 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 10 20 40 60 90 120 0 10 20 40 60 90 120 (9) X's and then Y's
8 0.15 4000000 (10) T PR YM
1 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 13.975 26.025 5.85 14.15 99.985 (15) LS XL1 XL2 YL1 YL2 QQ
1 8 15 22 29 36 43 (19) NODSX
1 2 3 4 5 6 7 (20) NODSY
1 (22) FSAF
0 100 (24) NAS SUBMOD

```

answer: at Node 1 -299.320 Psi

```

1 (1) NPROB
Problem 5.8
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
7 7 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 0 0 1 0 0 0 7 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 10 20 40 60 90 120 0 12 24.15 36 60 90 120 (9) X's and then Y's
8 0.15 4000000 (10) T PR YM
2 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 13.975 26.025 0 8.3 99.985 (15) LS XL1 XL2 YL1 YL2 QQ
1 13.975 26.025 20 28.3 99.985 (15) LS XL1 XL2 YL1 YL2 QQ
1 2 3 4 5 6 7 (20) NODSY
1 (22) FSAF
0 100 (24) NAS SUBMOD

```

answer: at Node 1 -314.844 Psi

```

1 (1) NPROB
Problem 5.9
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
8 6 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 0 0 0 1 0 1 0 0 0 6 0 0 1 1 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
13.5 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 12 30 54 90 138 186 240 0 12 24 48 84 132 (9) X's and then Y's
9 0.15 4000000 (10) T PR YM
1 (12) NUDL
0 (13) NCNF
0 0 (14) NNMx NNMy
1 0 4.744 0 9.487 99.997 (15) LS XL1 XL2 YL1 YL2 QQ
1 2 3 4 5 6 (20) NODSY
1 (22) FSAF
0 200 (24) NAS SUBMOD

```

answer: at Note 1 -158.257 psi

```

1 (1) NPROB
Problem 5.10
0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 9 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 9 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 46 0 0 0 0 0 0 0 1 0 0 0 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 12 24 42 66 78 90 117 144 (9) X's and then Y's
0 12 30 60 90 120 0 12 24 42 66 78 90 117 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
2 (12) NUDL
0 (13) NCNF
0 0 (14) NNMx NNMy
1 108 120 0 12 83.333 (15) LS XL1 XL2 YL1 YL2 QQ
1 108 120 72 84 83.333 (15) LS XL1 XL2 YL1 YL2 QQ
1 (22) FSAF
0 300 (24) NAS SUBMOD
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

```

answer: at note 46 -4529.8 psi

```

1 (1) NPROB
Problem 5.11
0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 14 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 14 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 46 0 0 0 0 0 0 0 1 0 0 0 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 6 18 30 42 54 66 78 90 102 114
126 138 144 (9) X's and then Y's
0 12 30 60 90 120 0 6 18 30 42 54 66 78 90 102 114
126 138 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
2 (12) NUDL
0 (13) NCNF
0 0 (14) NNMx NNMy
1 108 120 0 12 83.333 (15) LS XL1 XL2 YL1 YL2 QQ

```

*answer: at Note 72 -9042.9 psi
78 -170.826 psi
71 0.02277 in.*

1 108 120 72 84 83.333 (15) LS XL1 XL2 YL1 YL2 QQ
1 (22) FSAF
0 300 (24) NAS SUBMOD
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 14 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0 1 1 1 1 1 1 1 1 1 1 1 0 (36) BARNO

1 (1) NPROB

Problem 5.12

0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 9 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 9 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 46 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 12 24 42 66 78 90 117 144 (9) X's and then Y's
0 12 30 60 90 120 0 12 24 42 66 78 90 117 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM

2 (12) NUDL

0 (13) NCNF

0 0 (14) NNMK NNMV

1 108 120 0 12 83.333 (15) LS XL1 XL2 YL1 YL2 QQ

1 108 120 72 84 83.333 (15) LS XL1 XL2 YL1 YL2 QQ

1 (22) FSAF

0 300 (24) NAS SUBMOD

29000000 0.3 (34) YMSB PRSB

0 0 1500000 1 12 0.25 0.01 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

Answer: at Node 46 -3829.1 psi

1 (1) NPROB

Problem 5.13

0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 6 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 6 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 34 0 0 0 0 0 0 0 1 0 0 12 0 0 0 2 2 1 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 10 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 15 30 42 54 72 (9) X's and then Y's
0 12 30 60 90 120 0 15 30 42 54 72 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM

0 (12) NUDL

1 (13) NCNF

0 0 (14) NNMK NNMV

34 12000 (16) NN EF

1 7 13 19 25 31 37 43 49 55 61 67 (19) NODSX

1 (22) FSAF

0 300 (24) NAS SUBMOD

29000000 0.3 (34) YMSB PRSB

0 0 1500000 1 12 0.25 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

answer: at Node 34 -2267.0 psi

1 (1) NPROB

Problem 5.14

0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 8 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 8 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 45 0 0 0 0 0 0 0 1 0 0 12 0 0 0 2 2 1 (6) NLayer NNCK NOTCON NGAP


```

NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 10 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 6 18 30 42 54 66 72 (9) X's and then Y's
0 12 30 60 90 120 0 6 18 30 42 54 66 72 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
0 (12) NUDL
1 (13) NCNF
0 0 (14) NNMK NNMV
45 12000 (16) NN FF
1 9 17 25 33 41 49 57 65 73 81 89 (19) NODSX
1 (22) FSAF
0 300 (24) NAS SUBMOD
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 8 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0 1 1 1 1 1 1 0 (36) BARNO

```

answer: at Node 45 -2284.2 psi

```

1 (1) NPROB
Problem 5.15
0 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 6 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 6 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 34 0 0 1 0 0 0 0 1 0 0 12 0 0 0 2 2 1 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 15 30 42 54 72 (9) X's and then Y's
0 12 30 60 90 120 0 15 30 42 54 72 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
0 (12) NUDL
1 (13) NCNF
0 0 (14) NNMK NNMV
34 12000 (16) NN FF
34 (18) NP
1 7 13 19 25 31 37 43 49 55 61 67 (19) NODSX
1 (22) FSAF
0 300 (24) NAS SUBMOD
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0.01 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

```

Answer: at Node 34 -1655.9 psi

```

1 (1) NPROB
Problem 5.16
0 0 1 1 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
9 6 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 22 0 0 0 0 0 0 0 1 0 0 9 6 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 14 28 41 54 72 96 132 168 0 10 20 29.5 38.75 48 (9) X's and then Y's
8 0.15 4000000 (10) T PR YM
1 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 37.5 44.5 23.5 35.5 150 (15) LS XL1 XL2 YL1 YL2 QQ
1 7 13 19 25 31 37 43 49 (19) NODSX
1 2 3 4 5 6 (20) NODSY
1 (22) FSAF
0 150 (24) NAS SUBMOD

```

Answer: at Node 22 -283.756 psi

```

1 (1) NPROB
Problem 5.17
1 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
6 14 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 14 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 46 0 0 42 0 0 0 1 0 0 0 0 0 1 2 2 (6) N LAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 30 60 90 108 120 0 6 18 30 42 54 66 78 90 102 114
126 138 144 (9) X's and then Y's
0 12 30 60 90 120 0 6 18 30 42 54 66 78 90 102 114
126 138 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
2 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 108 120 0 12 83.333 (15) LS XL1 XL2 YL1 YL2 QQ
1 108 120 72 84 83.333 (15) LS XL1 XL2 YL1 YL2 QQ
43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59
60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76
77 78 79 80 81 82 83 84 (18) NP
1 (22) FSAF
16000 0.4 (28) YMS PRS
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 14 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
0 1 1 1 1 1 1 1 1 1 1 1 0 (36) BARNO

```

*Answer: at Node 72 -3087.4 PSI
78 -185269 PSI
71 0.02249 in.*

```

2 (1) NPROB
PROBLEM 5.18 (1st step)
1 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
7 8 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 8 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 49 0 0 11 0 0 0 1 10 0 0 0 0 0 2 1 2 (6) N LAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 0 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0 0 0 0 (8) F1(1) F1(2) F2(1) F2(2)
0 60 110 128 146 164 180 0 16 41 66 82 98 121 144 (9) X's and then Y's
0 16 40 80 120 180 0 16 41 66 82 98 121 144 (9) X's and then Y's
7 0.15 4000000 (10) T PR YM
0 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
17 25 29 33 41 49 50 51 52 53 54 (18) NP
1 (22) FSAF
5000 0.45 (28) YMS PRS
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ
PROBLEM 5.18 (2nd step)
1 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
7 8 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
6 8 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 49 0 0 11 1 0 0 10 0 0 0 0 0 1 1 2 (6) N LAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 0 0 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0 0 0 0 (8) F1(1) F1(2) F2(1) F2(2)
0 60 110 128 146 164 180 0 16 41 66 82 98 121 144 (9) X's and then Y's
0 16 40 80 120 180 0 16 41 66 82 98 121 144 (9) X's and then Y's
7 0.15 4000000 (10) T PR YM
8 (12) NUDL
0 (13) NCNF

```

```

0 0 (14) NNMK NNMV
1 123.983 132.017 0 5.532 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 123.983 132.017 13.234 18.766 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 123.983 132.017 72.484 78.016 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 123.983 132.017 85.984 91.516 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 171.967 180 0 5.532 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 171.967 180 13.234 18.766 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 171.967 180 72.484 78.016 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
1 171.967 180 85.984 91.516 90.007 (15) LS XL1 XL2 YL1 YL2 QQ
17 25 29 33 41 49 50 51 52 53 54 (18) NP
1 (22) FSAF
5000 0.45 (28) YMS PRS
29000000 0.3 (34) YMSB PRSB
0 0 1500000 1 12 0.25 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

```

Answer: at Note 25 - 226.331 Psi
49 0.05384 in.

```

1 (1) NPROB
PROBLEM 5.19
1 2 2 3 (3) NFOUND NDAMA NPY NLG
1 0 (4) NSLAB NJOINT
9 9 0 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 1 0 0 3 0 0 0 0 1 0 0 0 9 0 0 1 2 2 (6) NLayer NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 0 0 600 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
14.75 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)
0 12 24 36 48 72 96 132 168 0 10 20 39 58 77 97 120 144 (9) X's and then Y's
8 0.15 4000000 (10) T PR YM
4 4 8 (12) NUDDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 0 4.042 0 5.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 14.433 20 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 77 82.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 91.433 97 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 19.958 28.042 0 5.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 19.958 28.042 14.433 20 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 19.958 28.042 77 82.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 19.958 28.042 91.433 97 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 0 5.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 14.433 20 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 77 82.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 0 4.042 91.433 97 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 43.958 52.042 0 5.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 43.958 52.042 14.433 20 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 43.958 52.042 77 82.567 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 43.958 52.042 91.433 97 100 (15) LS XL1 XL2 YL1 YL2 QQ
1 19 37 (18) NP
1 2 3 4 5 6 7 8 9 (20) NODSY
1 0.8 (22) FSAF
5000 0.4 (28) YMS PRS
3650 3650 3650 (37) TNLR
3650 3650 3650 (37) TNLR

```

Answer: Design life for Example 4 is 17.44 years.

If $F1 = 14.75$, the design life is 17.41 years.
 The Secondary Cracking Index = $0.00000307 + 0.00001733 + 0.00000253 + 0.00002067 = 0.0000436$, which is 0.076% of a total of 0.057433.

```

2 (1) NPROB
PROBLEM 5.20 (first step)
2 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
8 9 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
8 9 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 68 0 32 0 0 0 1 1 10 0 0 1 0 1 0 2 1 2 (6) N LAYER NNCK NOTCON
NGAP NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
-20 150 135 0 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0 0 0 0 (8) F1(1) F1(2) F2(1) F2(2)
0 40 80 120 140 160 170 180 0 26 52 62 72 82 92 118 144 (9) X's and then Y's
0 10 20 40 60 100 140 180 0 26 52 62 72 82 92 118 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
0 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 (19) NODSX
9 0.05 18 0.05 27 0.05 36 0.05 45 0.05 54 0.05 63 0.05 72
0.05 81 0.05 90 0.05 99 0.05 108 0.05 117 0.05 126 0.05 135
0.05 144 0.05 64 0.05 65 0.05 66 0.05 67 0.05 68 0.05 69
0.05 70 0.05 71 0.05 73 0.05 74 0.05 75 0.05 76 0.05 77
0.05 78 0.05 79 0.05 80 0.05 (21) NG CURL
1 (22) FSAF
2 30 (30) NL MAXIC
8 (31) TH
20000 5000 (32) E
0.3 0.4 (33) PRBF
29000000 0.3 (34) YMSB PRSB
0 0 1000000 1 12 0.125 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

```

PROBLEM 5.20 (second step)

```

2 0 1 1 (3) NFOUND NDAMA NPY NLG
2 1 (4) NSLAB NJOINT
8 9 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
8 9 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4
1 68 0 0 0 1 0 0 0 1 0 0 1 1 2 (6) N LAYER NNCK NOTCON NGAP
NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL
0 150 135 0 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX
0 0 0 0 (8) F1(1) F1(2) F2(1) F2(2)
0 40 80 120 140 160 170 180 0 26 52 62 72 82 92 118 144 (9) X's and then Y's
0 10 20 40 60 100 140 180 0 26 52 62 72 82 92 118 144 (9) X's and then Y's
10 0.15 4000000 (10) T PR YM
1 (12) NUDL
0 (13) NCNF
0 0 (14) NNMK NNMV
1 170 180 67 77 200 (15) LS XL1 XL2 YL1 YL2 QQ
1 (19) NODSX
1 (22) FSAF
2 30 (30) NL MAXIC
8 (31) TH
20000 5000 (32) E
0.3 0.4 (33) PRBF
29000000 0.3 (34) YMSB PRSB
0 0 1000000 1 12 0.125 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

```

Answer: at Node 68 -459.416 psi
at Node 68 -2487.9 psi

1 (1) NPROB

Problem 5.21

1 0 1 1 (3) NFOUND NDAMA NPY NLG

2 1 (4) NSLAB NJOINT

6 6 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4

6 6 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4

1 34 0 0 1 0 0 0 0 1 0 0 12 0 0 0 2 2 1 (6) N LAYER NNCK NOTCON NGAP

NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL

0 150 0 500 0 0.000005 0.001 1 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX

17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)

0 30 60 90 108 120 0 15 30 42 54 72 (9) X's and then Y's

0 12 30 60 90 120 0 15 30 42 54 72 (9) X's and then Y's

10 0.15 4000000 (10) T PR YM

0 (12) NUDL

1 (13) NCFN

0 0 (14) NNMK NNMV

34 12000 (16) NN FF

34 (18) NP

1 7 13 19 25 31 37 43 49 55 61 67 (19) NODSX

1 (22) FSAF

15000 0.4 (28) YMS PRS

29000000 0.3 (34) YMSB PRSB

0 0 1500000 1 12 0.25 0 0 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

Answer: at Note 34 -2050.2 psi

1 (1) NPROB

Problem 5.22

1 0 1 1 (3) NFOUND NDAMA NPY NLG

2 1 (4) NSLAB NJOINT

6 8 0 1 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4

6 8 1 0 0 0 (5) NX NY JONO1 JONO2 JONO3 JONO4

1 45 0 0 1 0 0 0 0 1 0 0 12 0 0 0 2 2 1 (6) N LAYER NNCK NOTCON NGAP

NPRINT INPUT NBOND NTEMP NWT NCYCLE NAT1 NAT2 NSX NSY MDPO NUNIT UL TC CL

0 150 0 500 0 0.000005 0.001 10 (7) TEMP GAMA(1) GAMA(2) PMR(1) PMR(2) CT DEL FMAX

17.61 0 17.61 0 (8) F1(1) F1(2) F2(1) F2(2)

0 30 60 90 108 120 0 6 18 30 42 54 66 72 (9) X's and then Y's

0 12 30 60 90 120 0 6 18 30 42 54 66 72 (9) X's and then Y's

10 0.15 4000000 (10) T PR YM

0 (12) NUDL

1 (13) NCFN

0 0 (14) NNMK NNMV

45 12000 (16) NN FF

45 (18) NP

1 9 17 25 33 41 49 57 65 73 81 89 (19) NODSX

1 (22) FSAF

15000 0.4 (28) YMS PRS

29000000 0.3 (34) YMSB PRSB

0 0 1500000 1 12 0.25 0 8 (35) SPCON1 SPCON2 SCKV BD BS WJ GDC NNAJ

0 1 1 1 1 1 1 0 (36) BARNO

Answer: at Note 45 -2063.2 psi

Chapter 6 Traffic Loading and Volume

6-1 $S_d = 34$ in
 $P_d = 45,000 / 2 = 22,500$ lb. $f_c = 100$ psi
 $z = 25$ in

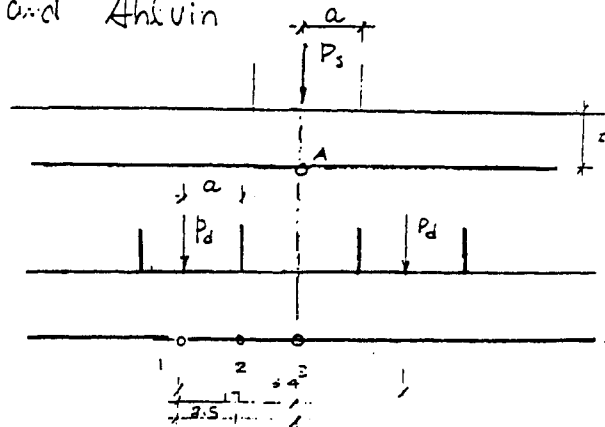
$$a = \sqrt{\frac{P_d}{\pi \cdot f_c}} = \sqrt{\frac{45,000/2}{\pi \cdot 100}} = 8.46284$$

$$d = S_d - 2a = 34 - 2 \cdot 8.46284 = 17.0743 \text{ in}$$

1). Boyd and Foster Method.

$$\begin{aligned} \log(\text{ESWL}) &= \log P_a + \frac{0.301 \log \left(\frac{2 \cdot z}{d} \right)}{\log \left(\frac{4 S_d}{d} \right)} \\ &= \log 22500 + \frac{0.301 \log \left(\frac{2 \cdot 25}{17.0743} \right)}{\log \left(\frac{4 \cdot 34}{17.0743} \right)} \\ &= 4.35218 + 0.301 \cdot 0.4666271 / 0.901196 \\ &= 4.5080337 \\ \text{ESWL} &= \underline{32213.2 \text{ lb}} \quad \checkmark \end{aligned}$$

2). Foster and Ahlvin



Point No.	Left wheel		right wheel		Sum F_d
	r/a	F	r/a	F	
1	0	0.48	4	0.22	0.60
2	1	0.42	3	0.27	0.69
3	2	0.35	2	0.35	0.70 \checkmark

$$z/a = 2.954$$

$$ESWL = \frac{0.70}{0.48} \cdot 22500 = \underline{32812.5} \text{ lb.} \quad \checkmark$$

c. Huang's Method.

$$S_d = 34. \quad a = 8.46284$$

$$a' = \frac{48}{S_d} \cdot a = \frac{48}{34} \cdot 8.46284 = 11.948$$

$$h_1 = 25$$

$$h_1' = \frac{48}{S_d} \cdot h_1 = \frac{48}{34} \cdot 25 = 35.294 \quad \checkmark$$

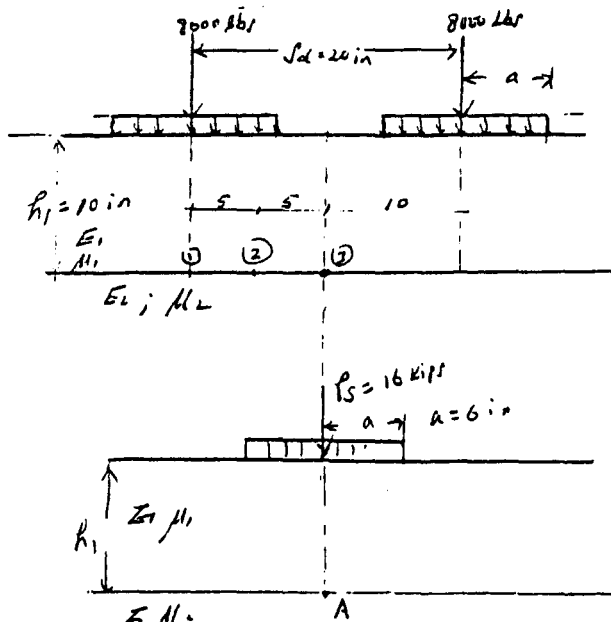
$$E_1/E_2 = 1$$

$$\left. \begin{aligned} L_1 &= 1.395 \\ L_2 &= 1.345 \end{aligned} \right\} \text{ from Fig. 6.4}$$

$$\begin{aligned} L &= L_1 - (L_1 - L_2) \frac{a' - 6}{10} \\ &= 1.395 - (1.395 - 1.345) \frac{11.948 - 6}{10} \\ &= 1.3666 \end{aligned}$$

$$ESWL = \frac{2 P_d}{L} = \frac{2 \cdot 22500}{1.3666} = \underline{32928.4} \text{ lb.} \quad \checkmark$$

6-2



$$P_2 = 8000 \text{ lb.}$$

$$a = 6 \text{ in}$$

$$E_1 = 250,000 \text{ psi}$$

$$E_2 = 10,000 \text{ psi}$$

$$\mu_1 = \mu_2 = 0.5$$

②. Based on Equal interface deflection.

single load:

$$h_1/a = \frac{10}{6} = 1.667$$

$$r/a = 0$$

using interface vertical deflection (Huang) Fig. 2.19.

$$\text{for } E_1/E_2 = 25 \rightarrow F = 0.35$$

Dual loads: (for $E_1/E_2 = 25$ & $h_1/a = 1.667$):
 using Indentor def. (After Huang):

POINT	Left Wheel		Right Wheel		SUM OF F
	r/a	F	r/a	F	
1	0	0.30	3.733	0.23	0.58
2	0.833	0.32	2.5	0.285	0.605
3	1.667	0.3	1.667	0.3	0.60

$$F_L = 0.612 ; F_R = 0.30$$

$$\frac{F_L}{F_R} = \frac{0.605}{0.30} = 1.73$$

$$\therefore ESWL = 1.73 \quad P_L = 1.73 \times 8000 = \underline{13840 \text{ lbs.}} \quad \checkmark$$

b) Based on tensile strain at the bottom of asphalt layer.

$$L_d = 20 \text{ in} \quad j = 8 \text{ in.}$$

using Fig. 2.23. Conversion factor for dual wheel (after Huang 1930).

$$a' = \frac{2d}{20} \cdot 6 = 7.2 \text{ in}$$

$$X' = \frac{2d}{20} \times 10 = 12 \text{ in} \quad \left. \begin{array}{l} \rightarrow C_1 = 1.27 \quad \checkmark \quad C_2 = 1.58 \quad \checkmark \\ \end{array} \right\}$$

$$\begin{aligned} E_1/E_2 = 25 \quad \left. \begin{array}{l} \rightarrow C = C_1 + 0.2 (a'-3) \times (C_2 - C_1) \\ = 1.3624 \quad \checkmark \end{array} \right\} \end{aligned}$$

$$ESWL = C \times P_L = 1.3624 \times 8000 = \underline{10,899 \text{ lbs.}} \quad \checkmark$$

6-3. Given: 20 years = 20 * 365 days

1) TAI:

L_x Axle Load (Kip)	F_i EALF	n_i Number per day	$EALF$
12	0.189	200	0.198
14	0.360	117.4	0.366
16	0.623	84.5	0.624
18	1.000	61.4	1.000
20	1.51	47.2	1.524
22	2.18	21.4	2.232
24	3.03	12.9	3.160
26	4.09	6.1	4.353
28	5.39	2.9	5.855
30	6.97	1.2	7.716
32	8.88	0.7	9.988
34	11.18	0.3	12.729

2) $EALF = \left(\frac{L_x}{18}\right)^4$

$$1) \quad EAL = \sum_{i=1}^{12} F_i n_i \times 365 \times 20 = \underline{2.99 \times 10^6} \quad \checkmark$$

$$2) \quad EAL = \sum_{i=1}^{17} F_i n_i \times 365 \times 20 = \underline{3.07 \times 10^6}$$

$$6-5 \quad GY = \int_0^Y (1+r)^n \, dn = \frac{(1+r)^n}{\ln(1+r)} \Big|_0^Y$$

$$\ln(1+r) = r - \frac{1}{2}r^2 + \dots$$

When r is much smaller than 1, the second and all the higher order terms can be neglected or

$$\ln(1+r) = r, \quad \text{so}$$

$$GY = \frac{(1+r)^Y}{r} - \frac{1}{r} = \frac{(1+r)^Y - 1}{r}$$

The assumption is $r \ll 1$

6-6.

$$\text{From Eq. 6.30 } ESAL = (ADT)_0 (T) (T_f) (G) (D) (L) (365) (Y)$$

$$(ADT)_0 (T) = 1,000, \quad \text{From Table 6.10, } T_f = 0.52$$

$$\text{From Eq. 6.33 } (G)(Y) = \frac{(1+0.05)^{20} - 1}{0.05} = 33.06$$

$$\text{From Table 6.15 } (DL) = 0.45$$

$$ESAL = 1,000 \times 0.52 \times 0.45 \times 365 \times 33.06$$

$$= \underline{\underline{2,823,654}}$$

6-7

		SINGLE AXLE	
LOAD	EALF (TABLE 6.4)	NUMBER	ESAL
1.5	.0001	0	0
5	.005	3188	15.94
7.5	.02695	2843	76.61885
10	.0877	9942	871.9134
14	.36	3111	1119.96
17	.796	1899	1511.604
18.5	1.12	1078	1207.36
19.5	1.375	423	581.625
21	1.83	598	1094.34
23	2.58	144	371.52
25	3.53	6	21.18
28	5.39	6	32.34

		TANDEM AXLE	
LOAD	EALF (TABLE 6.4)	NUMBER	ESAL
3	0	7	0
9	0	2631	0
15	.036	2541	91.476
21	.148	2362	349.576
27	.426	3103	1321.878
30.75	.72925	703	512.66275
31.75	.831	141	117.171
33	.971	503	488.413
35	1.23	388	477.24
37	1.53	280	428.4
39	1.89	247	466.83
41	2.29	183	419.07
43	2.76	160	441.6
45	3.27	51	166.77
48	4.17	64	266.88
52	5.63	7	39.41

COMBINED ESAL FOR 24 DAY PERIOD
 ESAL DURING FIRST YEAR (365.25 DAYS)

12491.778
190109



6-8.

Load kips	EALF Table 6.7	Number Table P6.7	ESAL col C x col D
Single Axle			
5	0.006	3188	19.128
7.5	0.0265	2843	75.3395
10	0.082	9942	815.244
14	0.341	3111	1060.851
17	0.802	1899	1522.998
18.5	1.1425	1078	1231.615
19.5	1.4275	423	603.8325
21	1.955	598	1169.09
23	2.85	144	410.4
25	4.015	6	24.09
28	6.29	6	37.74
			6970.328
Tandem Axle			
3	0.0003	7	0.0021
9	0.009	2631	23.679
15	0.065	2541	165.165
21	0.257	2362	607.034
27	0.736	3103	2283.808
30.75	1.271	703	893.513
31.75	1.446	141	203.886
33	1.705	503	857.615
35	2.175	388	843.9
37	2.73	280	764.4
39	3.385	247	836.095
41	4.145	183	758.535
43	5.015	160	802.4
45	6.005	51	306.255
48	7.73	64	494.72
52	10.6	7	74.2
		Sum	9915.2071
		Total Sum	16885.5351

$$\begin{aligned}
 \text{ESAL (for 1st year)} &= \frac{16885.535}{24} \times 365.25 \\
 &= \underline{\underline{256,977}}
 \end{aligned}$$

6-9

$$\begin{aligned} & \text{Total Vehicles Counted} \\ & \text{for 24 days} \\ & = 12197 \end{aligned}$$

$$\begin{aligned} & \text{Equivalent Total Vehicle} \\ & \text{Counted for One Year} \\ & = 12197 * \frac{365}{24} \\ & = 185496.0417 \end{aligned}$$

$$\begin{aligned} & \text{Total EAL for One year} \\ & = 191992.4 \end{aligned}$$

Truck factor

$$\frac{191992.4}{185496.0417} = \underline{1.035} \quad \checkmark$$

6-10.

$$\text{Total vehicle counted for 24 days} = 12,197$$

$$\begin{aligned} \text{Total vehicle counted for one year} & = 12,197 * \frac{365}{24} \\ & = 185,500 \end{aligned}$$

$$\text{Total ESAL from problem 6-8} = 257,000$$

$$\text{Truck factor} = \frac{257,000}{185,500} = \underline{1.38}$$

Chapter 7 Material Characterization

7-1 The result of repeated load tests on granular material:

Confining Press. (Psi)	DEVIATOR STRESS σ_d (Psi)	Recoverable Strain ϵ_r (10^{-4})	MR (10^3) C (Psi)	STRAIN Zones θ (Psi)
2	6	5.8	10.345	12
5	15	7.4	22.270	30
10	30	9.5	31.579	60
20	60	11.4	52.632	120
2	6	6.0	10.000	12

Note:
 $MR = \frac{\sigma_d}{\epsilon_r}$
 $\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$

The values of MR vs. θ are plotted on log-log plot as shown in Fig. below.

Based on Regression analysis:

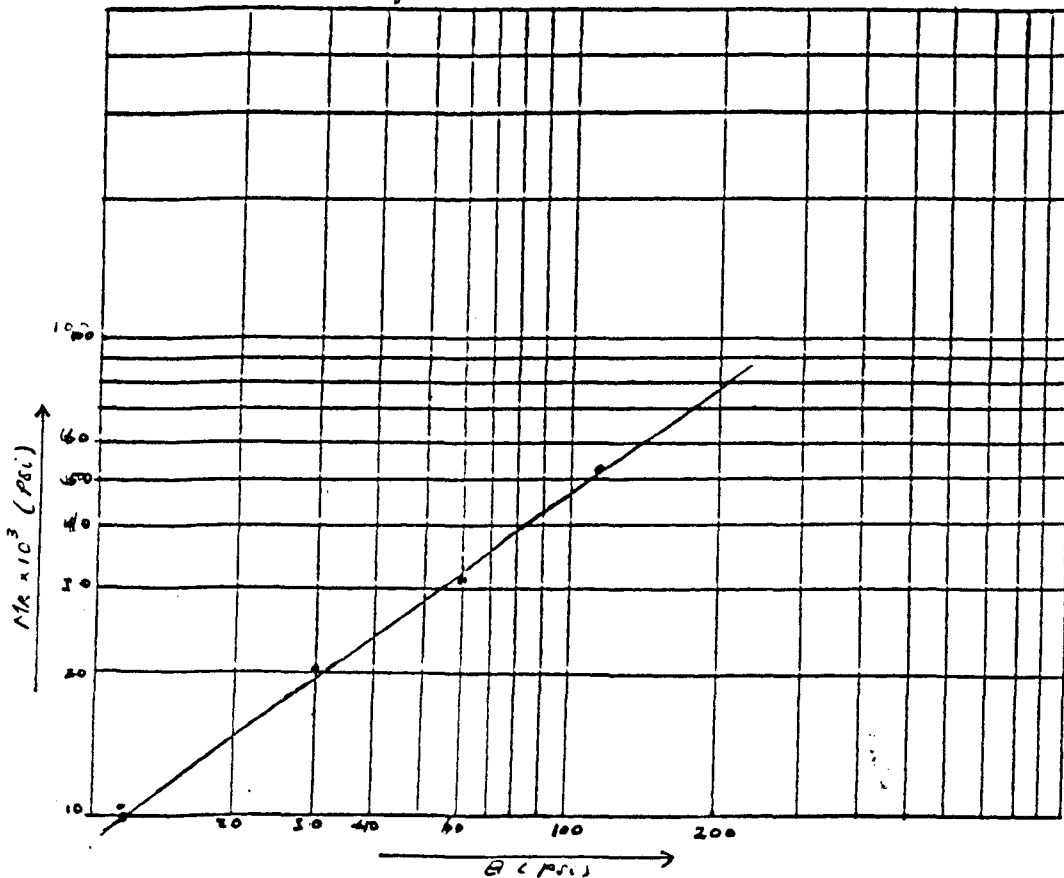
$$\log MR = 3.24308 + 0.7109 \log \theta$$

For $\theta = 1$ Psi: $\log MR = 3.24308$

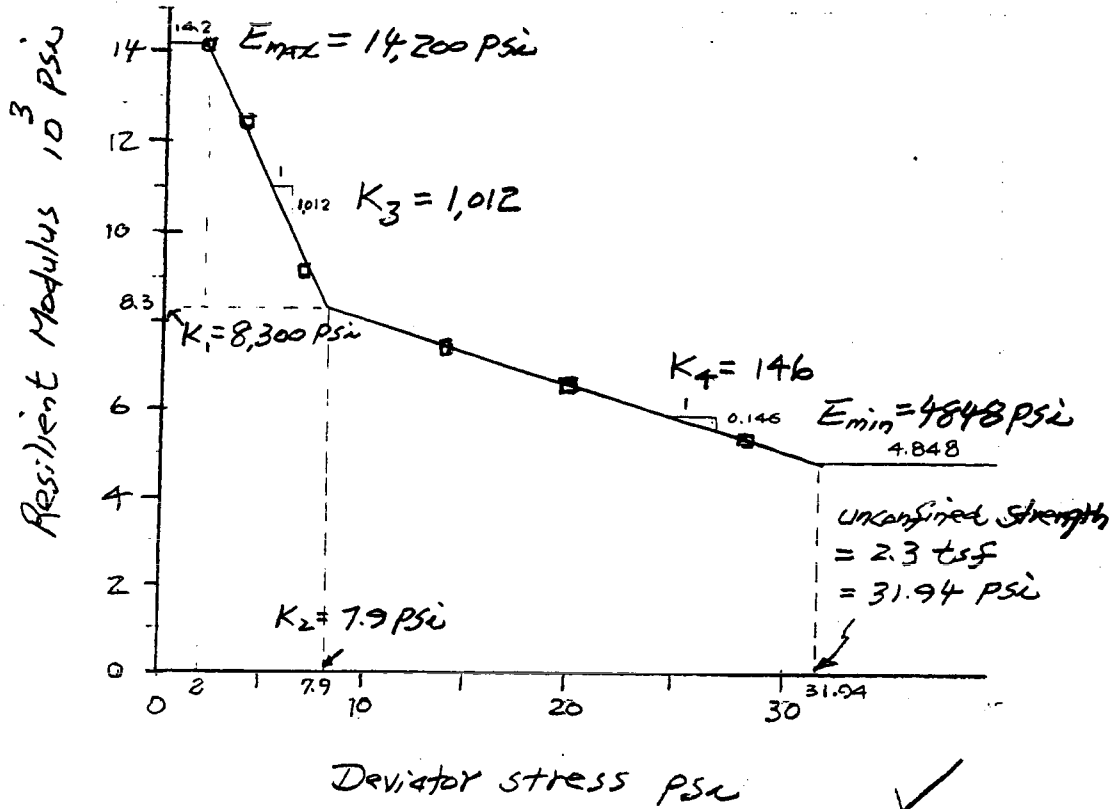
$MR = 1750$ Psi

Slope of the Regression line = $S = 0.7109$

Thus: $MR = 1750 \theta^{0.7109}$ ✓ See Page 52



7-2



7-3. The results of a series of fatigue tests on HMA are as follows:

Test	Stress (psi)	E_t (psi)
1	278	1×10^5
2	254	1.14×10^5
3	228	1.15×10^5
4	197	1.34×10^5
5	186	1.60×10^5
6	165	2.87×10^5
7	137	2.12×10^5
8	115	2.78×10^5
9	91	3.15×10^5

The values of $\log E_t$ & stress are plotted as shown

Based on regression analysis:

$$\log E_t = 5.7664 - 2.861 \times 10^{-3} \sigma$$

for $\sigma = 0 \rightarrow \log E_t = 5.7664$

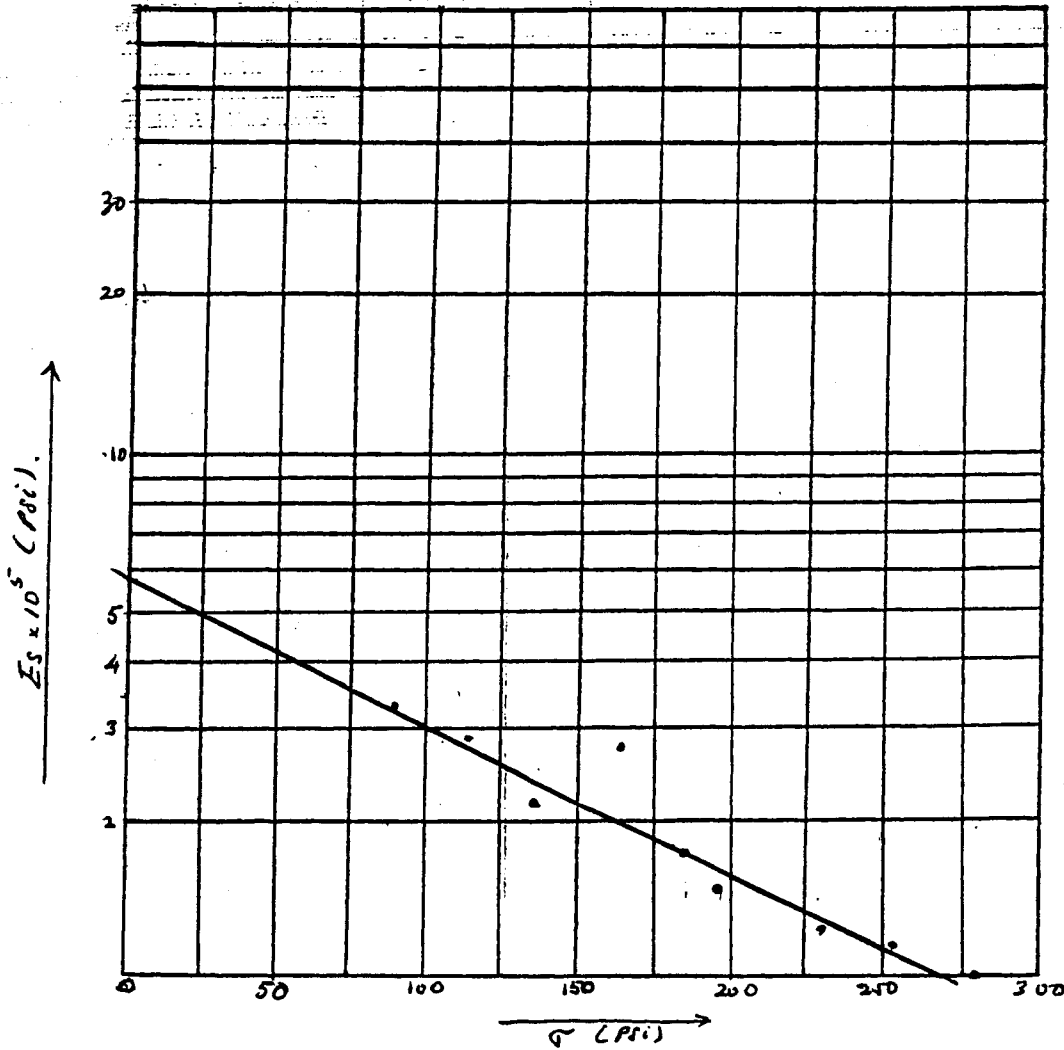
$$E_t = E_0 = 583983 \text{ psi}$$

From Eq. 7.11:

Dynamic Modulus (Complex Modulus) for $f = 8 \text{ Hz}$ is

$$|E^*| = 0.18089 f^{2.1476} E_0 \left(\frac{14.6218}{f^{0.01}} - 13.5739 \right)$$

$$= \underline{7.9 \times 10^5 \text{ psi}} \quad \checkmark$$



Based on Regression Analysis:

$$\log E_s = 5.7664 - 2.861 \times 10^{-5} \sigma$$

$$\sigma = 0 \rightarrow \log E_s = 5.7664 \rightarrow E_s = E_0 = 583983 \text{ psi}$$

Eq. 7.11:

$$|E^*| = 0.18089 f^{2.1476} E_0 \left(\frac{14.6218}{f^{0.01}} - 13.5739 \right)$$

$$= \underline{7.9 \times 10^5 \text{ psi}}$$

$f = 8 \text{ Hz}$

See also P. 52

7-4 See page 52

p7.1

log x	log y
1.079181	4.014730
1.477121	4.306854
1.778151	4.499398
2.079181	4.721250
1.079181	4

Regression Output:

Constant	3.243085
Std Err of Y Est	.0111520
R Squared(Adj,Raw)	.9987188 .9990391
No. of Observations	5
Degrees of Freedom	3
Coefficient(s)	.7109222 ← K ₂
Std Err of Coef.	.0127294

log K₁

$$M_R = K_1 \theta^{K_2}$$

$$\log M_R = \log K_1 + K_2 \log \theta$$

$$M_R = 1750 \theta^{0.711}$$

p7.3

x	log y
278	5
254	5.056905
228	5.060698
197	5.127105
185	5.204120
165	5.457882
137	5.346353
115	5.444045
91	5.498311

Regression Output:

Constant	5.773954
Std Err of Y Est	.0740420
R Squared(Adj,Raw)	.8558775 .8738928
No. of Observations	9
Degrees of Freedom	7
Coefficient(s)	-.002891
Std Err of Coef.	.0004151

log E₀

$$E_s = E_0 A_1^s$$

$$\log E_s = \log E_0 + s \log A_1$$

$$E_0 = 594,229$$

$$|E^x| = 0.18089 (8)^{2.1456} \times (5.942 \times 10^5) \frac{14.6918}{8^{0.01}} - 13.5739 = 8.0 \times 10^5 \text{ PSI}$$

p7.4

log x	log y
-2.50169	1.544068
-2.58336	1.875061
-2.60380	2
-2.71670	2.468347
-2.79860	2.531479
-2.89620	2.986772
-2.96257	3.212188
6	3.553033

Regression Output:

Constant	-7.17659
Std Err of Y Est	.0708248
R Squared(Adj,Raw)	.9896900 .9911629
No. of Observations	8
Degrees of Freedom	6
Coefficient(s)	-3.50710 ← f ₂
Std Err of Coef.	.1351934

log f₁

$$N_f = f_1 (E_t)^{f_2}$$

$$\log N_f = \log f_1 + f_2 \log E_0$$

$$N_f = 6.66 \times 10^{-8} (E_t)^{-3.507}$$

p7.9

log x	log y
-1	-4.93629
0	-4.45917
1	-3.93806
2	-3.50624
3	-3.20424

Regression Output:

Constant	-4.45050
Std Err of Y Est	.0751524
R Squared(Adj,Raw)	.9885204 .9913903
No. of Observations	5
Degrees of Freedom	3
Coefficient(s)	.4417041 ← S
Std Err of Coef.	.0237653

log I₁

$$\log E_p = \log I_1 + S \log t$$

$$S = 0.4417 \quad \alpha = 1 - 0.4417 = 0.5583$$

$$\log I = -4.4505 + 0.4417 \log 0.1 = -4.8922 \quad I = 1.28 \times 10^{-5}$$

$$\mu = \frac{1.28 \times 10^{-5} \times 0.442}{3.045 \times 10^{-5}} = 0.186$$

p7.10

log x	log y
0	-4.62709
1	-4.23426
2	-3.89371
2.301030	-3.85605
3	-3.70520
4	-3.44032
5	-3.13368

Regression Output:

Constant	-4.54931
Std Err of Y Est	.0578542
R Squared(Adj,Raw)	.9861963 .9884969
No. of Observations	7
Degrees of Freedom	5
Coefficient(s)	.2863923 ← S
Std Err of Coef.	.0138164

log I

$$\log E_p = \log I + S \log N$$

$$S = 0.2864 \quad \alpha = 1 - 0.2864 = 0.7136$$

$$\log I = -4.54931$$

$$I = 2.823 \times 10^{-5}$$

$$\mu = \frac{2.823 \times 10^{-5} \times 0.2864}{4.128 \times 10^{-5}} = 0.196$$

7-5

Asphalt Mixture : Asphalt Content = 7% ; Bulk S.G. = 2.24
 Asphalt : S.G. = 1.02 ; Penetration at 77°F = 50
 Aggregate : S.G. = 2.61 ; $T_{240} = 120^\circ\text{F}$.
 Determine $|E^*|$ at $T = 74^\circ\text{F}$ and loading time of 0.02 sec.

Note: $120^\circ\text{F} = 49^\circ\text{C}$; $77^\circ\text{F} = 25^\circ\text{C}$; $c = \frac{(F-32)}{9}$
 $74^\circ\text{F} = 23.3^\circ\text{C}$

Eq. 7.17: $A = \frac{\log \text{Pen}_{act} - \log 800}{T - T_{240}} = \frac{\log 50 - \log 800}{T - T_{240}}$
 $= \frac{\log 50 - \log 800}{25 - 49} = 0.0502$

Eq. 7.16: $PI = \frac{20 - 500A}{1 + 50A} = -1.453$

① Determination of Stiffness Modulus of Asphalt Binder

Fig. 7.19 for $t = 0.02$

$T_{diff} = 49 - 23.33 = 25.67$ } Stiff. Mod. = $2 \times 10^7 \text{ N/m}^2$
 $PI = -1.453$

② Determination of Stiff. Modulus of Asphalt Mixture :

$P_b = \text{asphalt content} = 7\% = 0.07$

$G_m = \text{S.G. of Mixture} = 2.24$

$G_s = \text{S.G. of aggregate} = 2.61$

% Volume of aggregate $V_g = \frac{100(1 - P_b)G_m}{G_s} = \frac{100(1 - 0.07)2.24}{2.61} = 79.816\%$

% Volume of Binder $V_b = \frac{100P_bG_m}{G_a} = \frac{100(0.07)2.24}{1.02} = 15.27\%$

% Volume of Void/Air $V_a = 100 - V_g - V_b = 100 - 79.8 - 15.2 = 4.8\%$

Fig. 7.20:

for: Stiff. Mod. of Binder = 2×10^7
 $V_b = 15.4$
 $V_g = 79.8$ } $|E^*|$ of Mixture = $2 \times 10^9 \text{ N/m}^2$

Using Eq. 7.29

for: $S_b = 7 \times 10^6 \text{ N/m}^2$

$\beta_1 = 10.82 - \frac{1.342(100 - V_g)}{V_g + V_b} = 10.82 - \frac{1.342(100 - 79.8)}{79.8 + 15.4} = 10.534$

$\beta_2 = 8.0 + 0.00588V_g + 0.0002135V_g^2 = 9.813$

$\beta_3 = 0.6 \log \left[\frac{1.37V_b^2 - 1}{1.23V_b - 1} \right] = 0.7325 \quad (V_b = 15.4)$

$\beta_4 = 0.7082 (\beta_1 - \beta_2) = 0.507$

for $5 \times 10^6 \text{ N/m}^2 < S_b < 10^9 \text{ N/m}^2$. ($S_b = 7.0 \times 10^6 \text{ N/m}^2$)

$$\begin{aligned} \log S_m &= \frac{\beta_4 + \beta_3}{2} (\log S_b - 8) + \frac{\beta_4 + \beta_3}{2} / \log S_b - 8 / + \beta_2 \\ &= \frac{0.547 + 0.734}{2} (\log 2 \times 10^7 - 8) + \frac{0.547 - 0.734}{2} / \log 2 \times 10^7 - 8 / + 9.815 \\ &= 9.301. \end{aligned}$$

$$S_m = 10^{9.301} = 2 \times 10^9 \text{ N/m}^2. \quad \checkmark$$

7-6 Given:

$$f = 8 \text{ Hz} \quad P_{77} = 75$$

$$T = 74 \text{ }^\circ\text{F}$$

$$P_{200} = 5 \%$$

$$\begin{aligned} \text{assume: } V_v &= 4.0\% & & = 100 - V_g - V_b \\ V_g &= \frac{100 \times (1 - 0.07) \times 2.24}{2.61} = 79.81 & & = \frac{100(1 - P_v) G_m}{G_g} \\ V_b &= \frac{100 \times 0.07 \times 2.24}{1.02} = 15.37 \% & & = \frac{100 P_v G_m}{G_b} \end{aligned}$$

$$\begin{aligned} \lambda &= 29508.2 \times (P_{77F})^{-2.1939} \\ &= 2.27 \times 10^6 \text{ poise} \end{aligned}$$

$$\begin{aligned} \beta_5 &= 1.3 + 0.49825 \log 5 \\ &= 1.3 + 0.49825 \log 8 \\ &= 1.75 \end{aligned}$$

$$\begin{aligned} \beta_4 &= 0.483 V_b = 0.483 \times 15.37 = \\ &= 7.42 \end{aligned}$$

$$\begin{aligned} \beta_3 &= 0.553833 + 0.028829 (P_{200} f^{-0.1703}) \\ &\quad - 0.03476 V_v + 0.070377 \lambda + 0.93157 f^{-0.02774} \\ &= 0.553833 + 0.028829 \times 5 \times 8^{-0.1703} \\ &\quad - 0.03476 \times 5 + 0.070377 \times 2.27 + 0.93157 f^{-0.02774} \\ &= 1.53 \end{aligned}$$

$$\begin{aligned} \beta_2 &= \beta_4^{0.5} (T P_5) \\ &= 7.42^{0.5} \times (74)^{1.75} = 5085.8 \end{aligned}$$

$$\begin{aligned} \beta_1 &= \beta_3 + 0.000005 \beta_2 - 0.00189 \beta_2 (f)^{-1.1} \\ &= 53 + 0.000005 \times 5085.8 - 0.00189 \times 5085.8 \times (8)^{-1.1} \\ &= 0.579 \end{aligned}$$

$$|E^*| = 100000 \times 10^{0.579} = \underline{3.793 \times 10^5} \text{ psi} \quad \checkmark$$

7-7

$PI = -1.453$; $V_b = 15.4\%$ $f_m = 2 \times 10^9 \text{ N/m}^2 = 2.9 \times 10^5 \text{ psi}$ $E_t = 0.00015$
 from Fig. 7.26

$N_f = 8.7 \times 10^5 \text{ N/m}^2$ for constant stress test ✓
 $N_f = 9 \times 10^7 \text{ N/m}^2$ for constant strain test ✓

using Eq. 7.31:

$N_f = (0.0252 PI - 0.00126 \times PI \times V_b + 0.00672 V_b - 0.0167) \times E_t^{-1.4} \times f_m^{-1.4}$
 $= (0.0252(-1.453) - 0.00126(-1.453) \times 15.4 + 0.00672 \times 15.4 - 0.0167) \times 0.00015^{-1.4} \times (2.9 \times 10^5)^{-1.4}$
 $N_f = \underline{8.85 \times 10^5}$ (for constant stress test) ✓

$N_f = (0.17 \times PI - 0.0085 PI \times V_b + 0.0464 \times V_b - 0.112) \times E_t^{-1.8} \times f_m^{-1.8}$
 $= (0.17(-1.453) - 0.0085(-1.453) \times 15.4 + 0.0464 \times 15.4 - 0.112) \times 0.00015^{-1.8} \times (2.9 \times 10^5)^{-1.8}$
 $= \underline{8.13 \times 10^7}$ (for constant strain test) ✓

7-8

Given:

$|E^*| = 3.793 \times 10^5 \text{ psi}$ $E_t = 0.00015$
 $V_u = 4.8\%$
 $V_b = 15.37\%$

$M = 4.84 \left(\frac{V_b}{V_u + V_b} - 0.69 \right)$
 $= 4.84 \times \left(\frac{15.37}{15.37 + 4.8} - 0.69 \right)$
 $= 0.3486$

$C = 10^M = 2.23$

$N_f = 0.00432 \times C \times (E_t)^{-3.291} \times |E^*|^{-0.854}$
 $= \underline{636533}$ ✓

7-9

The results of incremental static test on a HMA specimen are plotted in Fig. below for 0.1, 1, 10, 100, and 1000 sec. duration. with permanent strain 1.18×10^{-5} , 3.44×10^{-5} , 11.53×10^{-5} , 31.17×10^{-5} & 62.48×10^{-5} respectively. based on regression analysis the relationship of strain and duration are well represented by:

$$\text{Log strain} = 0.4417 (\text{Log Duration}) + 0.5495$$

$$\text{for } d = 0.1 \text{ sec} \rightarrow \text{Strain} = 1.282 \times 10^{-5}$$

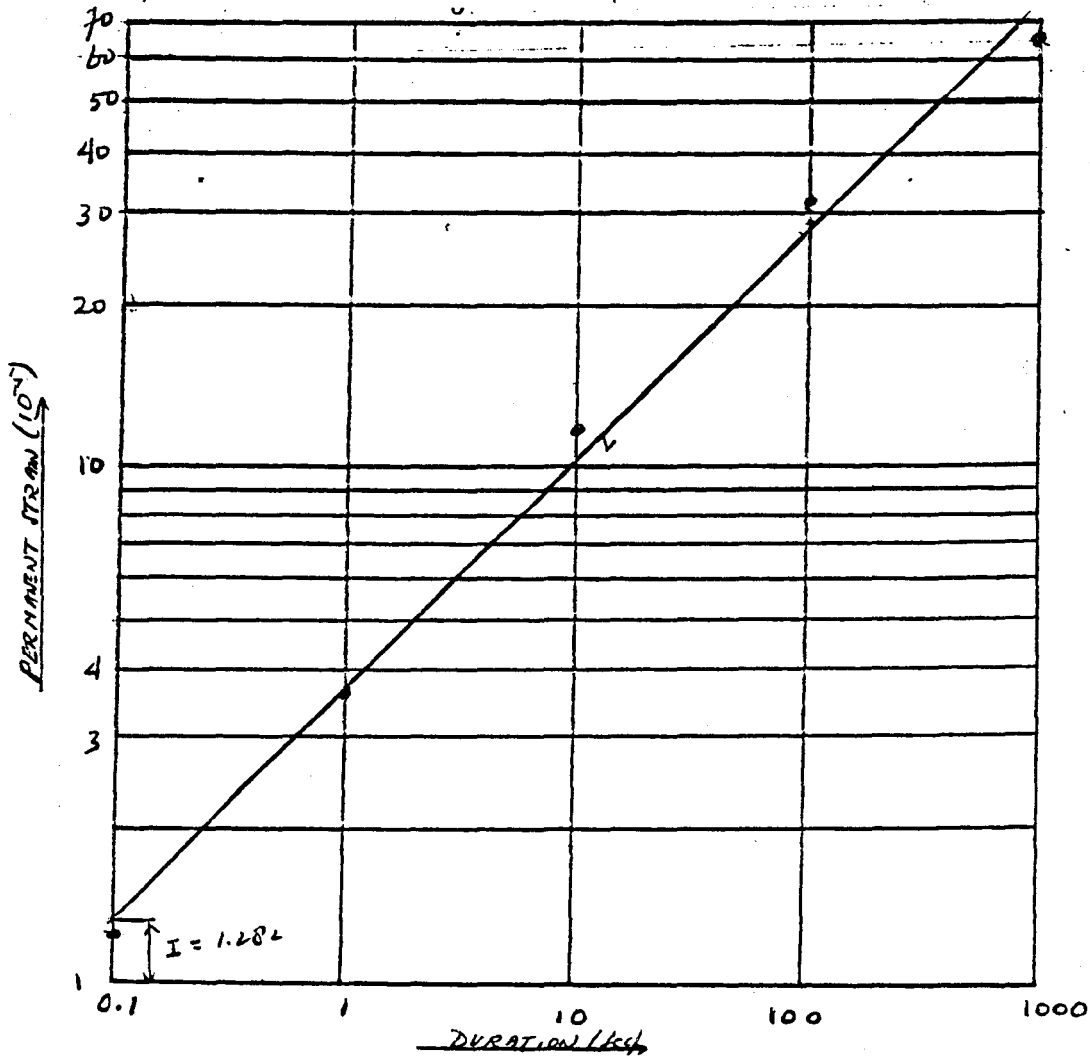
$$= I = \text{Intercept}$$

$$\text{slope of Regression line} = 0.4417 (10^{-5})$$

$$\text{from: Eq. 7.43 } \alpha = 1 - S = 1 - 0.4417 = \underline{0.5583} \quad \checkmark$$

$$\text{Eq. 7.44 } \beta = \frac{I \cdot S}{E} = \frac{1.282 \times 0.4417 \times 10^{-5}}{3.046 \times 10^{-5}} = \underline{0.186} \quad \checkmark$$

Note: $E = \text{Strain at } \omega \text{ max duration of } 0.03 = 3.56 \times 10^{-5}$

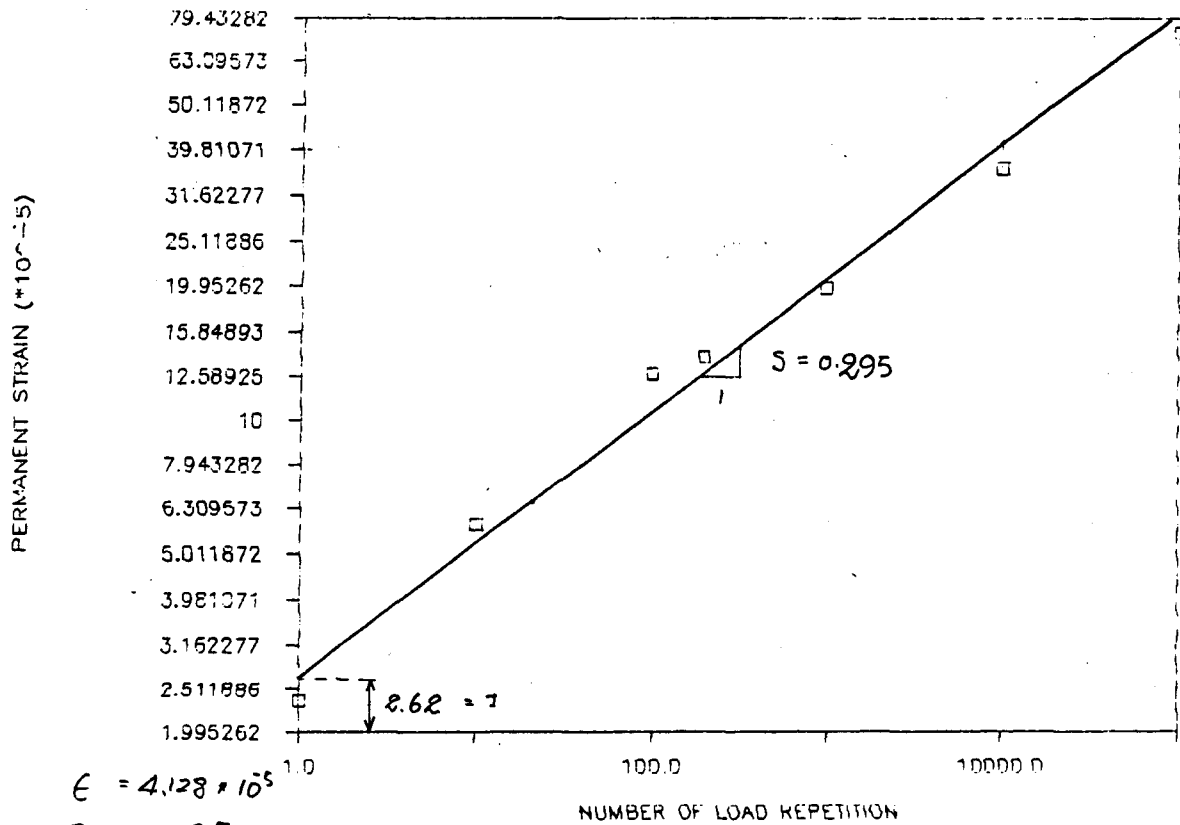


See page 52

7-10.

No. OF REPETITION	PERMANENT STRAIN (10 ⁻⁵)
1	2.36
10	5.813
100	12.773
200	13.93
1000	19.715
10000	36.281
100000	73.506

PROBLEM 7-10



$$\epsilon = 4.128 \times 10^5$$

$$S = 0.295$$

$$I = 2.62$$

$$\alpha = 1 - S = 1 - 0.295 = \underline{0.705} \quad \checkmark$$

$$\mu = \frac{IS}{\epsilon} = \frac{2.62 \times 0.295}{4.128} = \underline{0.187} \quad \checkmark$$

See also P. 52

Chapter 8 Drainage Design

P.8.1

Water is sprayed over a 400 ft^2 soil surface -
 Soil's permeability = 0.001 ft/min .
 2.99 gpm what is max. spray rate in gal/min. so that all water
 will be absorbed by the soil & there is no overland flow

$$(400 \text{ ft}^2)(0.001 \text{ ft/min}) = (0.4 \text{ ft}^3/\text{min}) \left(\frac{7.48 \text{ gal}}{\text{ft}^3} \right)$$

$$Q = UA$$

$$V = Ki \quad i = 1$$

$$\text{Spray rate} = \boxed{2.99 \text{ g/min}} \quad \checkmark$$

8.2
$$\log D_x = \log D_a + \frac{x-a}{b-a} \log \frac{D_b}{D_a}$$

a) $x = 15$ $D_x = ?$
 $a = 5.8$ $D_a = .094 \text{ " } \leftarrow \#8$
 $b = 32$ $D_b = .19 \text{ " } \leftarrow \#4$

$$\log D_x = \log .094 + \frac{15-5.8}{32-5.8} \log \frac{.19}{.094} = -0.92$$

$$D_x = .120 \text{ in} \quad \frac{2.54 \text{ cm}}{1 \text{ in}} \quad \frac{100 \text{ mm}}{1 \text{ cm}} = \boxed{D_x = 3.0 \text{ mm}} \quad \checkmark$$

b) $x = 85$ $D_{85} = ?$
 $a = 75$ $D_a = .5$
 $b = 100$ $D_b = .175$

$$\log D_{85} = \log .5 + \frac{85-75}{100-75} \log \frac{.175}{.5}$$

$$D_{85} = .588 \text{ in} \quad \frac{2.54 \text{ cm}}{1 \text{ in}} \quad \frac{10 \text{ mm}}{1 \text{ cm}} = \boxed{D_{85} = 15 \text{ mm}} \quad \checkmark$$

Problem 8-3

Soil A (filter)

Soil C (soil)

Clogging Criterion ($D_{15} \text{ filter} / D_{35} \text{ soil} \leq 5$)
 $0.375 / 0.0125 = 30$ Not satisfied

Permeability Criterion ($D_{15} \text{ filter} / D_{15} \text{ soil} \geq 5$)
 $0.375 / 0.000225 = 1667$ satisfied

Additional Criteria ($D_{50} \text{ filter} / D_{50} \text{ soil} \leq 25$)
 $0.7 / 0.00175 = 400$ Not satisfied

Soil A should not be used as a filter for soil C ✓

Soil A (filter)

Soil B (soil)

Clogging Criterion
 $0.375 / 0.25 = 1.5$ satisfied

Permeability Criterion
 $0.375 / 0.007 = 54$ satisfied

Additional Criteria
 $0.7 / 0.0375 = 19$ satisfied

$D_{60} \text{ filter} / D_{10} \text{ filter} \leq 25$
 $0.9 / 0.3 = 3$ satisfied

$D_5 \text{ filter} \geq 0.074 \text{ mm}$
 $0.225 \geq 0.074$ satisfied

Soil B (filter)

Soil C (soil)

Clogging Criterion
 $0.007 / 0.0125 = 0.56$ satisfied

Permeability Criterion
 $0.007 / 0.000225 = 31$ satisfied

Additional Criteria
 $0.0375 / 0.00175 = 21$ satisfied

$0.06 / 0.005 = 12$ satisfied

$0.0035 < 0.074$ Not satisfied ✓

This is important only when drainage layer is used

8-4. (a) Can geotextiles be used as a filter for soil C in Figure P8.3? Why?

Soil C is a clayed soil with 100% passing #200 sieve. Geotextiles cannot be used as a filter because the soil is too fine and will cause clogging.

(b) If geotextiles are used for soil B, what AOS do you recommend?

Soil B has 65% passing #200 sieve with $D_{85} = 0.25$ mm or #60.

If woven fabric is used, $AOS \leq D_{85}$ or $AOS \geq \#60$

(c) If geotextiles are used for soil A, what AOS do you recommend?

Soil C has less than 50% passing #200, so $AOS \leq B \times D_{85}$

$C_u = D_{60} / D_{10} = 0.9 / 0.3 = 3$, which is between 2 and 4, so $B = 0.5C_u = 1.5$

$D_{85} = 2$ mm, $AOS \leq 1.5 \times 2 = 3$ mm or $AOS \geq \#8$

8-5. (a) Estimate the permeability of soil B in Figure P8.3 by Eq. 8.3

From Figure P8.3, $D_{10} = 0.0052$ mm From Table 8.4, $C_k = 5$ to 8

From Eq. 8.3, $k = C_k D_{10}$ so

$$k = 5 (0.0052)^2 = 1.352 \times 10^{-4} \text{ mm/s} \left(\frac{1 \text{ ft}}{304.8 \text{ mm}} \right) \left(\frac{60 \times 60 \times 24 \text{ sec}}{1 \text{ day}} \right)$$

= 0.0383 ft/day (lower limit)

$k = 8 (0.0052)^2 = 2.163 \times 10^{-4} \text{ mm/s} = 0.0613 \text{ ft/day}$ (upper limit)

(b) Given $\gamma_{dry} = 110 \text{ lb/ft}^3$, estimate the permeability of soil B by Eq. 8.5a

$$\text{Assume } G_s = 2.7, \text{ from Eq. 8.5b, } n = 1 - \frac{110}{62.4 \times 2.7} = 0.3471$$

From Figure P8.3, percent passing #200 (0.075 mm) is $P_{200} = 65\%$

$$\text{From Eq. 8.5a, } k = \frac{6.214 \times 10^5 (0.0052)^{1.478} (0.3471)^{6.654}}{(65)^{0.597}} = 0.0189 \text{ ft/day}$$

8-6. Given $N = 2$, $W_p = 22$ ft, $C_s = 40$ ft, from Eq. 8.18

$$q = 0.1 \left(2 + 1 + \frac{22}{40} \right) = 0.355 \text{ ft}^3/\text{hr}/\text{linear ft of pavement}$$

$$= 0.355/22 = \underline{0.016} \text{ ft}^3/\text{hr}/\text{ft}^2 \text{ (by Eq. 8.18)}$$

From Figure 8.13, the 1-h duration/1-yr. frequency precipitation rate for Kentucky is 1.2 in./hr. Cedergren

recommended that the design infiltration rate be obtained by applying a coefficient varying from 0.33 to 0.50, so

$$q = \begin{cases} 0.33 \times 1.2 = 0.396 \text{ in./hr} = \underline{0.033} \text{ ft}^3/\text{hr}/\text{ft}^2 \\ 0.50 \times 1.2 = 0.6 \text{ in./hr} = \underline{0.050} \text{ ft}^3/\text{hr}/\text{ft}^2 \end{cases}$$

8-7. Given $K = 0.5$ ft/day, $H = 23$ ft, $H_0 = 15$ ft,

$W = 40$ ft. From Eq. 8.20, $L_i = 3.8(23-15) = 30.4$ ft

$$\text{So } \frac{L_i + 0.5W}{H_0} = \frac{30.4 + 0.5 \times 40}{15} = 3.36 \text{ and } \frac{W}{H_0} = \frac{40}{15}$$

$$= 2.67. \text{ From Fig. 8.14, } \frac{K(H-H_0)}{2q_2} = 1.2 \text{ so}$$

$$q_2 = \frac{0.5 \times (23-15)}{2 \times 1.2} = 1.67 \text{ ft}^2/\text{day} \text{ or}$$

$$q_g = \frac{2 \times 1.67}{40} = \underline{0.084} \text{ ft}^3/\text{day}/\text{ft}^2$$

$$\text{From Eq. 8.19 } q_1 = \frac{0.5(23-15)^2}{2 \times 30.4} = 0.53 \text{ ft}^2/\text{day}$$

$$\text{So } q_L = q_1 + q_2 = 0.53 + 1.67 = \underline{2.2} \text{ ft}^3/\text{day}/\text{ft}^2$$

8-8 For GW-GC with 4% passing 0.02 mm, from

Table 8.5, Heave rate = 2.5 mm/day

$$G_p = (145 \times 4 + 120 \times 10)/12 = 148 \text{ psf. From Fig. 8.15,}$$

$$\frac{q_m}{\sqrt{K}} = 0.3 \quad q_m = 0.3 \sqrt{0.05} = \underline{0.067} \text{ ft}^3/\text{day}/\text{ft}^2$$

8-9. Given $K = 10,000$ ft/day, $H = 8$ in., $S = 0.04$
 $L = 18$ ft, from Eq. 8.27, the steady-state capacity

$$q = KH \left(S + \frac{H}{2L} \right) = 10,000 \times \frac{8}{12} \left(0.04 + \frac{8}{2 \times 18 \times 12} \right)$$

$$= \underline{390 \text{ ft}^3/\text{day}/\text{ft}}$$

Given $n_e = 0.25$, from Eq. 8.28

$$t_{50} = \frac{n_e L^2}{2K(H+SL)} = \frac{0.25 \times (18)^2}{2 \times 10,000 (8/12 + 0.04 \times 18)}$$

$$= 0.00292 \text{ day} = \underline{0.07 \text{ hr.}}$$

From Eq. 8.30 $S_f = \frac{18 \times 0.04}{8/12} = 1.08$

From Fig. 8.18 $T_f = 1.5$ or

$$t_{95} = \frac{T_f \cdot n_e L^2}{KH} = \frac{1.5 \times 0.25 \times (18)^2}{10,000 \left(\frac{8}{12} \right)}$$

$$= 0.0182 \text{ day} = \underline{0.44 \text{ hr.}}$$

8-10. Given $n = 0.01$, $L_0 = 300$ ft, $S = 0.025$,
 $D = 4$ in., from Eq. 8.33

$$q_L = \frac{53 S^{0.5} D^{2.667}}{n L_0}$$

$$= \frac{53 (0.025)^{0.5} (4)^{2.667}}{0.01 \times 300} = \underline{112.7 \text{ ft}^3/\text{day}/\text{ft.}}$$

Chapter 9 Pavement Performance

9-1. Given $PSI = A_0 + A_1 \log(RI)$ and Table P9.1
Derive equations and find A_0 and A_1

$$E = \sum(PSR - PSI)^2 = \sum[PSR - A_0 - A_1 \log(RI)]^2$$

$$\frac{\partial E}{\partial A_0} = -2 \sum[PSR - A_0 - A_1 \log(RI)] = 0$$

$$\overline{PSR} = A_0 + A_1 \overline{\log(RI)} \dots\dots\dots(1)$$

$$\frac{\partial E}{\partial A_1} = -2 \sum\{[PSR - A_0 - A_1 \log(RI)] \log(RI)\} = 0$$

$$\sum(PSR) \log(RI) = A_0 \sum \log(RI) + A_1 \sum [\log(RI)]^2 \dots\dots\dots (2)$$

Eqs. 1 and 2 can be used to solve A_0 and A_1

$$\overline{PSR} = (1 + 2 + 3 + 4 + 5)/5 = 2.5$$

$$\overline{\log(RI)} = (\log 800 + \log 300 + \log 200 + \log 150 + \log 80)/5 =$$

$$(2.903 + 2.477 + 2.301 + 2.176 + 1.903)/5 = 11.76/5 = 2.352$$

$$\text{From Eq. 1 } 2.5 = A_0 + 2.352 A_1 \dots\dots\dots(3)$$

$$\text{From Eq. 2 } 1 \times 2.903 + 2 \times 2.477 + 2.5 \times 2.301 + 3 \times 2.176 + 4 \times 1.903$$

$$= 11.76 A_0 + [(2.903)^2 + (2.477)^2 + (2.301)^2 + (2.176)^2 + (1.903)^2] A_1$$

$$27.75 = 11.76 A_0 + 28.214 A_1 \dots\dots\dots(4)$$

$$\text{Solve Eqs. 3 and 4 } 27.75 - 2.5 \times 11.76 = (28.214 - 2.352 \times 11.76) A_1$$

$$-1.65 = 0.554 A_1 \quad \text{or} \quad A_1 = -2.98$$

$$A_0 = 2.5 - 2.352 \times (-2.98) = 9.5$$

$$\underline{PSI = 9.5 - 2.98 \log(RI)}$$

9-2. Given Table P9.2
 Develop equation for PSI

Section No.	$\log(1+\overline{SV})$ R_1	\overline{RD}^2 R_2	$\sqrt{C+P}$ D_1	PSR	$R_1 - \overline{R}_1$	$R_2 - \overline{R}_2$	$D_1 - \overline{D}_1$	PSR - \overline{PSR}
1	0.580	0.0036	0	4.3	-0.519	-0.0139	-2.994	1.34
2	0.833	0.0100	1	3.8	-0.266	-0.0075	-1.994	0.84
3	1.076	0.0121	3.606	3.2	-0.023	-0.0054	0.612	0.24
4	1.250	0.0256	4.796	2.4	0.151	0.0081	1.802	-0.56
5	1.756	0.0361	5.568	1.1	0.657	0.0186	2.574	-1.86
Average	1.099	0.0175	2.994	2.96				

From Eq. 9.9

$$2.96 = A_0 + 1.099 A_1 + 0.0175 A_2 + 2.994 B_1 \dots\dots\dots(1)$$

From Eq. 9.11

$$\begin{aligned} & [(-0.519)^2 + (-0.266)^2 + (-0.023)^2 + (0.151)^2 + (0.657)^2] A_1 + [(-0.519) \\ & (-0.0139) + (-0.266)(-0.0075) + (-0.023)(-0.0054) + (0.151)(0.0081) + \\ & (0.657)(0.0186)] A_2 + [(-0.519)(-2.994) + (-0.266)(-1.994) + (-0.023)(0.612) \\ & + (0.151)(1.802) + (0.657)(2.574)] B_1 = (-0.519)(1.34) + (-0.266)(0.84) + \\ & (-0.023)(0.24) + (0.151)(-0.56) + (0.657)(-1.86) \text{ or} \\ & 0.7951 A_1 + 0.0228 A_2 + 4.033 B_1 = -2.231 \dots\dots\dots(2) \end{aligned}$$

From Eq. 9.12

$$\begin{aligned} & 0.0228 A_1 + [(-0.0139)^2 + (-0.0075)^2 + (-0.0054)^2 + (0.0081)^2 + \\ & (0.0186)^2] A_2 + [(-0.0139)(-2.994) + (-0.0075)(-1.994) + (-0.0054)(0.612) \\ & + (0.0081)(1.802) + (0.0186)(2.574)] B_1 = (-0.0139)(1.34) + (-0.0075)(0.84) \\ & + (-0.0054)(0.24) + (0.0081)(-0.56) + (0.0186)(-1.86) \text{ or} \\ & 0.0228 A_1 + 0.00069 A_2 + 0.1152 B_1 = -0.0654 \dots\dots\dots(3) \end{aligned}$$

From Eq. 9.13

$$4.033 A_1 + 0.1152 A_2 + [(-2.994)^2 + (-1.994)^2 + (0.612)^2 + (1.802)^2 +$$

$$(2.574)^2] B_1 = [(-2.994)(1.34) + (-1.994)(0.84) + (0.612)(0.24) + (1.802)$$

$$(-0.56) + (2.574)(-1.86)] \quad \text{or}$$

$$4.033 A_1 + 0.1152 A_2 + 23.187 B_1 = -11.337 \quad \dots\dots\dots (3)$$

From Eqs. 2, 3, and 4

$$A_1 = -1.70, \quad A_2 = -38.09, \quad \text{and} \quad B_1 = -0.004$$

$$\text{From Eq. 1} \quad A_0 = 2.96 - 1.099(-1.7) + 0.0175(-38.09) - 2.994(-0.004)$$

$$A_0 = 5.51 \quad \underline{PSI = 5.51 - 1.70 \log(1 + 5V) - 38.09 \overline{RD}^2 - 0.004 \sqrt{C+P}}$$

9-3. Derive Eq. 9.29

$$F = ma \quad \text{Average speed} = \frac{V}{2} \quad \text{Time to stop} = \frac{2S}{V}$$

$$a = \frac{V}{\frac{2S}{V}} = \frac{V^2}{2S} \quad \mu W = \frac{W}{g} \cdot \frac{V^2}{2S} \quad \underline{\mu = \frac{V^2}{2gS} \dots\dots\dots (9.29)}$$

9-4. Given volume of beads = 2 in.³, diameter of patch = 10 in., and SN₄₀ = 40

Determine SN₂₀ and SN₆₀

$$MTD = \frac{2}{\frac{1}{4}\pi(10)^2} = 0.0255 \text{ in.}$$

$$\text{From Eq. 9.33} \quad PNG = 0.157 (0.0255)^{-0.47} = 0.881$$

$$\text{From Eq. 9.31} \quad 40 = SN_0 \exp\left(-\frac{0.881}{100} \times 40\right) \quad SN_0 = 56.9$$

$$\text{When } V = 20 \text{ mph} \quad SN_{20} = 56.9 \times \exp(-0.881 \times 0.2) = \underline{47.7}$$

$$\text{When } V = 60 \text{ mph} \quad SN_{60} = 56.9 \times \exp(-0.881 \times 0.6) = \underline{33.5}$$

```

1 (1) NPROB
PROBLEM 9.5
1 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
3 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
4 12 (6) TH
0.35 0.35 0.45 (7) PR
0 (8) ZC
1 (9) NBOND
500000 35000 9000 (11) E
0 (13) LOAD
6 79.5775 (14) CR CP
7 (16) NR
0 8 12 24 48 72 96 (17) RC

```

← These are E_1 , E_2 , and E_3 obtained by trial & error.

```

1 (1) NPROB
PROBLEM 9.6
2 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
3 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
4 12 (6) TH
0.35 0.35 0.45 (7) PR
0 (8) ZC
1 (9) NBOND
500000 35000 9000 (11) E
0 (13) LOAD
6 79.5775 (14) CR CP
7 (16) NR
0 8 12 24 48 72 96 (17) RC
1 15 (25) NOLAY ITENOL
2 0 (26) LAYNO NCLAY
7 (27) ZCNOL
0 0 0 0 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
145 135 0 (30) GAM
0.5 0.6 (31) K2 K0
8000 8000 (33) PHI K1

```

$E_1 = 500,000 \text{ Psi}$
 $E_3 = 9,000 \text{ Psi}$
 $K_1 = 8000$

↑ K_1

```

1 (1) NPROB
PROBLEM 9.7
2 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
8 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
4 2 2 2 2 2 2 (6) TH
0.35 0.35 0.35 0.35 0.35 0.35 0.35 0.45 (7) PR
0 (8) ZC
1 (9) NBOND
500000 35000 35000 35000 35000 35000 35000 9000 (11) E
0 (13) LOAD
6 79.5775 (14) CR CP
7 (16) NR
0 8 12 24 48 72 96 (17) RC
6 15 (25) NOLAY ITENOL
2 0 3 0 4 0 5 0 6 0 7 0 (26) LAYNO NCLAY
5 7 9 11 13 15 (27) ZCNOL
3 0 0 0.25 0.01 (28) RCNOL XCNOL YCNOL SLD DELNOL
0.5 (29) RELAX
145 135 135 135 135 135 135 0 (30) GAM
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0.5 0.6 (31) K2 K0
0 8000 (33) PHI K1
0 8000 (33) PHI K1
0 8000 (33) PHI K1
0 8000 (33) PHI K1
0 8000 (33) PHI K1
0 8000 (33) PHI K1

```

$E_1 = 500,000 \text{ psi}$
 $E_3 = 9,000 \text{ psi}$
 $K_1 = 8,000$

```

1 (1) NPROB
PROBLEM 9.8
1 0 1 1 (3) MATL NDAMA NPY NLG
0.001 (4) DEL
3 1 80 1 0 (5) NL NZ ICL NSTD NUNIT
8 12 (6) TH
0.35 0.35 0.45 (7) PR
0 (8) ZC
1 (9) NBOND
240000 19200 4800 (11) E
0 (13) LOAD
6 80 (14) CR CP
5 (16) NR
0 12 24 36 48 (17) RC

```

use a realistic E_3 of 4800 psi

$q = 100 \text{ psi}$, $a = 6 \text{ in.}$, $E_3 = 4800 \text{ psi}$, $E_2 = 19,200 \text{ psi}$,
 $E_1 = 240,000 \text{ psi}$, $W_n^c = \frac{80 \times 6}{4800} f_n = 0.1 f_n$, so
 $f_n = 10 W_n^c$ W_n^c are the surface deflections of
0.02971, 0.02427, 0.01907, 0.01530, and 0.01125 in.,
as computed by KENLAYER.

9-9. Given $W_0 = 0.0047$ in., $W_1 = 0.004$ in., $W_2 = 0.0035$ in.
and $W_3 = 0.0026$ in., from Eq. 9.45

$$\text{AREA} = 6 \left[1 + 2 \left(\frac{0.004}{0.0047} \right) + 2 \left(\frac{0.0035}{0.0047} \right) + \frac{0.0026}{0.0047} \right]$$

$$= 28.468$$

From Figure 9.39, $l = 29$ in.

From Figure 9.40, $d_0 = 0.123$, $d_1 = 0.111$, $d_2 = 0.091$, $d_3 = 0.068$

From Eq. 9.42 $K = \frac{P d_i}{W_i l^2} = \frac{9,000}{(29)^2} \left(\frac{d_i}{W_i} \right) = 10.7 \left(\frac{d_i}{W_i} \right)$

Based on d_0 and W_0 , $K = 10.7 \left(\frac{0.123}{0.0047} \right) = 280.0$ pci

" d_1 and W_1 , $K = 10.7 \left(\frac{0.111}{0.004} \right) = 296.9$ pci

" d_2 and W_2 , $K = 10.7 \left(\frac{0.091}{0.0035} \right) = 278.2$ pci

" d_3 and W_3 , $K = 10.7 \left(\frac{0.068}{0.0026} \right) = 279.8$ pci

Average $K = \underline{283.7}$ pci, say 285 pci

Given $E_c = 4.7 \times 10^6$ psi, from Eq. 9.48

$$h^3 = \frac{12 [1 - (0.15)^2] \times 283.7 \times (29)^4}{4.7 \times 10^6} = 500.8 \text{ in}^3$$

$h = \underline{7.94}$ in., say 8 in.

9-10.

From Fig. 9.39, $l = 14$ in.

From Fig. 9.41, $d_0 = 0.182$, $d_1 = 0.152$, $d_2 = 0.108$, $d_3 = 0.078$

From Eq. 9.47, $E_f = \frac{2 [1 - (0.4)^2] \times 9,000 d_i}{14 W_i} = 1080 \left(\frac{d_i}{W_i} \right)$

Based on d_0 and W_0 , $E_f = 1080 \left(\frac{0.182}{0.0047} \right) = 41,821$ psi

" d_1 and W_1 , $E_f = 1080 \left(\frac{0.152}{0.004} \right) = 41,040$ psi

Based on d_2 and W_2 , $E_f = 1080 \left(\frac{0.108}{0.0035} \right) = 33,326 \text{ psi}$

" d_3 and W_3 , $E_f = 1080 \left(\frac{0.078}{0.0026} \right) = 32,400 \text{ psi}$

Average $E_f = \underline{37,147} \text{ psi}$

From Eq. 9.49 $h^3 = \frac{6 [1 - (0.15)^2] \times 37,147 \times (14)^3}{[1 - (0.4)^2] \times 4.7 \times 10^6} = 151.4 \text{ in}^3$

$h = \underline{5.4} \text{ in.}$

9-11. Given: $h = 4 \text{ in.}$, $a = 6 \text{ years}$, $S_{bit} = 200 \text{ kg/cm}^2$,
 $d = 3 \text{ (10mm)}$, $m = 20^\circ\text{C}$

Required: Cracking index I for low temperature cracking

Solution: From Eq. 9.52b

$$I = 30.3974 + (6.7966 - 0.8741 \times 4 + 1.3388 \times 6) \log(0.1 \times 200) \\ - 2.1516 \times 3 - 1.2496 \times 20 + 0.06026 \times 200 \log 3 \\ = 19.5 \text{ ft/500 ft} \text{ OR } 39 \text{ ft/1000 ft}$$

9-12. From Eq. 9.54a

$$\text{FAULT} = (20)^{0.528} [0.1204 + 0.04048(3)^{0.3388} \\ - 0.1492(1)^{0.05911}] = 0.089 \text{ in.}$$

9-13. From Eq. 9.56a

$$\text{JTSPALL} = (15)^{2.178} \left[0.0221 - 0.0135 \times \begin{Bmatrix} 0 \\ 1 \end{Bmatrix} - 0.0419 \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \right] \\ + 0.0000362 \times 1,000 \\ = \begin{cases} 6.0 \text{ joints per mile for preformed seal} \\ 16.3 \text{ joints per mile for liquid seal} \end{cases}$$

Chapter 10 Reliability

10-1. Given: $f(x) = \begin{cases} 1/3 & x=0 \\ 1/2 & x=1 \\ 1/6 & x=2 \end{cases}$ Find: expectation and variance of x

From Eq. 10.2a, $E[x] = 0x \frac{1}{3} + 1x \frac{1}{2} + 2x \frac{1}{6} = \frac{5}{6} = \underline{0.833}$

From Eq. 10.7b,

$$V[x] = \left(0 - \frac{5}{6}\right)^2 x \frac{1}{3} + \left(1 - \frac{5}{6}\right)^2 x \frac{1}{2} + \left(2 - \frac{5}{6}\right)^2 x \frac{1}{6} = \underline{0.472}$$

10-2. Given: $f(t) = te^{-\frac{t^2}{2}}$ when $t \geq 0$
 $= 0$ when $t < 0$

Find: Mean and variance of x

$$E[t] = \int_{-\infty}^{\infty} t f(t) dt = \int_0^{\infty} t^2 e^{-\frac{t^2}{2}} dt$$

From mathematical handbook, we can find the following definite integral

$$\int_0^{\infty} x^2 e^{-x^2} dx = \frac{\sqrt{\pi}}{4} \text{ so } E[t] \text{ must be transformed to the same form, or}$$

$$\begin{aligned} E[t] &= 2\sqrt{2} \int_0^{\infty} \left(\frac{t}{\sqrt{2}}\right)^2 e^{-\left(\frac{t}{\sqrt{2}}\right)^2} d\left(\frac{t}{\sqrt{2}}\right) = 2\sqrt{2} \left(\frac{\sqrt{\pi}}{4}\right) \\ &= \sqrt{\frac{\pi}{2}} = \underline{1.253} \end{aligned}$$

From Eq. 10.8

$$\begin{aligned} V[t] &= E[t^2] - (E[t])^2 \\ E[t^2] &= \int_0^{\infty} t^3 e^{-\frac{t^2}{2}} dt = \frac{1}{2} \int_0^{\infty} t^2 e^{-\frac{t^2}{2}} d(t^2) \end{aligned}$$

From mathematical handbook, we can find the following integral

$$\int x e^{ax} dx = \frac{e^{ax}}{a^2}(ax - 1)$$

With $x = t^2$ and $a = -\frac{1}{2}$,

$$E[t^2] = \frac{1}{2} \left[\frac{e^{-\frac{t^2}{2}}}{\left(-\frac{1}{2}\right)^2} \left(-\frac{t^2}{2} - 1\right) \right]_0^\infty = 2 \left[e^{-\frac{t^2}{2}} \left(-\frac{t^2}{2} - 1\right) \right]_0^\infty$$

When $t = \infty$, the value is 0 because the exponential term predominates.

When $t = 0$, the value is -2 . so $E[t^2] = 0 - (-2) = 2$. $V[x] = 2 - (1.253)^2 = \underline{0.429}$

10-3. Given: $f(x, y) = \begin{cases} \frac{1}{4} & x=1 & y=2 \\ \frac{1}{4} & x=2 & y=3 \\ \frac{1}{2} & x=3 & y=4 \end{cases}$ Find: $\text{Cov}(x, y)$, $\rho(x, y)$, $V[x + y]$

From Eq. 10.2a

$$E[x] = 1x \frac{1}{4} + 2x \frac{1}{4} + 3x \frac{1}{2} = 2.25 \quad E[Y] = 2x \frac{1}{4} + 3x \frac{1}{4} + 4x \frac{1}{2} = 3.25$$

From Eq. 10.15b

$$\begin{aligned} \text{Cov}[x, y] &= (1 - 2.25)(2 - 3.25)x \frac{1}{4} + (2 - 2.25)(3 - 3.25)x \frac{1}{4} + \\ &\quad (3 - 2.25)(4 - 3.25)x \frac{1}{2} = \underline{0.6875} \end{aligned}$$

From Eq. 10.7b

$$V[x] = (1 - 2.25)^2 \times 0.25 + (2 - 2.25)^2 \times 0.25 + (3 - 2.25)^2 \times 0.5 = 0.6875$$

$$V[y] = (2 - 3.25)^2 \times 0.25 + (3 - 3.25)^2 \times 0.25 + (4 - 3.25)^2 \times 0.5 = 0.6875$$

$$\text{From Eq. 10.18} \quad \rho(x, y) = \frac{0.6875}{\sqrt{0.6875 \times 0.6875}} = \underline{1}$$

$$\text{From Eq. 10.21} \quad V[x, y] = 0.6875 + 0.6875 + 2 \times 0.6875 = \underline{2.75}$$

10-4. Given: $f(x, y) = 6xy(2-x-y)$ $x \leq x \leq 1, \quad 0 \leq y \leq 1$
 $= 0$ otherwise

Find: $\text{Cov}[x, y]$ and $\rho[x, y]$

Note $\text{Cov}[x, y] = E[x, y] - E[x]E[y]$, so it is necessary to compute $E[x, y]$,

$E[x]$, and $E[y]$.

$$\begin{aligned} E[x, y] &= \int_0^1 \int_0^1 xy(12xy - 6x^2y - 6xy^2) dx dy \\ &= \int_0^1 \int_0^1 (12x^2y^2 - 6x^3y^2 - 6x^2y^3) dx dy \\ &= \int_0^1 \left[4x^3y^2 - \frac{6}{4}x^4y^2 - 2x^3y^3 \right]_0^1 dy \\ &= \left[\frac{4}{3}y^3 - \frac{3}{2}y^3 - 2y^4 \right]_0^1 = \frac{4}{3} - \frac{3}{2} - 2 = -\frac{1}{6} \end{aligned}$$

$$\begin{aligned} E[x] &= \int_0^1 \int_0^1 x(12xy - 6x^2y - 6xy^2) dx dy \\ &= \int_0^1 \int_0^1 (12x^2y - 6x^3y - 6x^2y^2) dx dy \\ &= \int_0^1 \left[4x^3y - \frac{6}{4}x^4y - 2x^3y^2 \right]_0^1 dy \\ &= \left[2y^2 - \frac{3}{4}y^2 - \frac{2}{3}y^3 \right]_0^1 = 2 - \frac{3}{4} - \frac{2}{3} = \frac{7}{12} \end{aligned}$$

Because of symmetry of x and y , $E[y] = E[x] = 7/12$

$$\text{Cov}[x, y] = \frac{1}{3} - \frac{7}{12} \times \frac{7}{12} = -\frac{1}{144}$$

Since $\rho[x, y] = \frac{\text{Cov}[x, y]}{\sqrt{V[x]V[y]}}$, it is necessary to determine $V[x]$ and $V[y]$.

Because $V[x] = V[y] = E[x^2] - (E[x])^2$, $E[x^2]$ must be determined first.

$$\begin{aligned}
E[x^2] &= \int_0^1 \int_0^1 x^2 (12xy - 6x^2y - 6xy^2) dx dy \\
&= \int_0^1 \int_0^1 (12x^3y - 6x^4y - 6x^3y^2) dx dy \\
&= \int_0^1 \left[3x^4y - \frac{6}{5}x^5y - \frac{6}{4}x^4y^2 \right]_0^1 dy \\
&= \left[\frac{3}{2}y^2 - \frac{3}{5}y^2 - \frac{2}{4}y^3 \right]_0^1 = \frac{3}{2} - \frac{3}{5} - \frac{1}{2} = \frac{2}{5}
\end{aligned}$$

Because of symmetry of x and y, $E[y] = E[x] = 2/5$

$$V[x] = V[y] = \frac{2}{5} - \left(\frac{7}{12}\right)^2 = \frac{2}{5} - \frac{49}{144} = \frac{43}{720}$$

$$\rho[x, y] = \frac{\text{Cov}[x, y]}{\sqrt{V[x]V[y]}} = \frac{-\frac{1}{144}}{\sqrt{\frac{43}{720} \times \frac{43}{720}}} = -\frac{5}{43}$$

10-5. Given $t = (0.25 + 0.125 \log n) \left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right] \sqrt[3]{\frac{E}{E_p}}$

$t = 6.5$ in., $n = 100,000$, $P = 9000$ lb, $E = 10,000$ psi, $a = 6$ in., and $E_p = 400,000$ psi.

The coefficients of variation of all the above variables are 10 %

Find: Reliability of t based on Taylorseries expansion.

(a) Variance of t due to n

After substituting the values of all variables, except n, the following equation is obtained.

$$t = 6.03266(0.25 + 0.125 \log n)$$

$$\begin{aligned} \frac{\partial t}{\partial n} &= 6.03266 \times 0.125 \times \frac{\log e}{n} \\ &= 7.5408 \times 10^{-6} \times 0.4343 = 3.275 \times 10^{-6} \end{aligned}$$

$$\begin{aligned} V[t]_n &= \left(\frac{\partial t}{\partial n} \right)^2 V[n] \\ &= (3.275 \times 10^{-6})^2 (100,000 \times 0.1)^2 = 1.0726 \times 10^{-3} \end{aligned}$$

(b) Variance of t due to P

$$\begin{aligned} t &= 0.25585 \sqrt{5.6993 \times 10^{-6} P^2 - 36} \\ \frac{\partial t}{\partial P} &= \frac{0.25585}{2} (5.6993 \times 10^{-6} P^2 - 36)^{-0.5} \times 11.3986 P \\ &= 6.36 \times 10^{-4} \end{aligned}$$

$$V[t]_P = (6.36 \times 10^{-4})^2 (9000 \times 0.1)^2 = 0.328$$

(c) Variance of t due to E

$$\begin{aligned} t &= 0.0119 \sqrt[3]{E} \sqrt{4.616 \times 10^{10} E^{-2} - 36} \\ \frac{\partial t}{\partial E} &= 0.0119 (4.616 \times 10^{10} E^{-2} - 36)^{0.5} \times \frac{1}{3} (E)^{-\frac{2}{3}} \\ &\quad + 0.0119 \sqrt[3]{E} \left(\frac{1}{2} \right) (4.616 \times 10^{10} E^{-2} - 36)^{-0.5} (-9.232 \times 10^{10} E^{-3}) \\ &= 1.76314 \times 10^{-4} - 6.21 \times 10^{-3} (-9.232 \times 10^{-2}) = -3.9699 \times 10^{-4} \\ V[t]_E &= (-3.9699 \times 10^{-4})^2 (10,000 \times 0.1)^2 = 0.1576 \end{aligned}$$

(d) Variance of t due to a

$$\begin{aligned} t &= 0.2559 \sqrt{461.64 - a^2} \\ \frac{\partial t}{\partial a} &= 0.2559 \times 0.5 (461.64 - a^2)^{-0.5} (-2a) = -7.442 \times 10^{-2} \\ V[t]_a &= (-7.442 \times 10^{-2})^2 (6 \times 0.1)^2 = 0.1994 \times 10^{-3} \end{aligned}$$

(e) Variance of t due to E_p

$$t = 388.917(E_p)^{-\frac{1}{3}}$$

$$\frac{\partial t}{\partial a} = -\frac{388.917}{3}(E_p)^{-\frac{4}{3}} = -4.399 \times 10^{-6}$$

$$V[t]_{E_p} = (-4.399 \times 10^{-6})^2 (400000 \times 0.1)^2 = 0.031$$

Variance of t

$$\begin{aligned} V[t] &= V[t]_n + V[t]_P + V[t]_E + V[t]_a + V[t]_{E_p} \\ &= 0.0011 + 0.328 + 0.1576 + 0.002 + 0.031 = 0.5197 \end{aligned}$$

Standard deviation of t

$$S_t = \sqrt{V[t]} = \sqrt{0.5297} = 0.721$$

$$E[t] = (0.25 + 0.125 \log n) \left[\sqrt{\left(\frac{75P}{\pi E} \right)^2 - a^2} \right] \sqrt[3]{\frac{E}{E_p}}$$

$$= [0.25 + 0.125 \log(100000)] \left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000} \right)^2 - 36} \right] \sqrt[3]{\frac{10,000}{400000}}$$

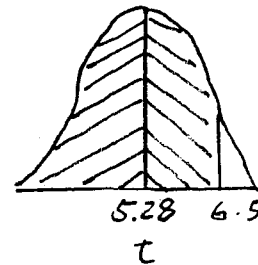
$$= 0.875 \times 20.631 \times 0.2924 = 5.28 \text{ in.}$$

$$Z = \frac{6.5 - 5.28}{0.721} = 1.692$$

From Table 10.1

Area under normal curve = 0.5 + 0.455 = 0.955

Reliability = 95.5%



$$10-6 \text{ Given } t = (0.25 + 0.125 \log n) \left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right] \sqrt[3]{\frac{E}{E_p}}$$

$$n = 100,000 \pm 10,000 = 110,000 \text{ and } 90,000$$

$$P = 9,000 \pm 900 = 9,900 \text{ and } 8,100 \text{ lb}$$

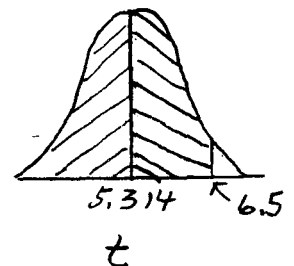
$$E = 10,000 \pm 1,000 = 11,000 \text{ and } 9,000 \text{ PSI}$$

$$a = 6 \pm 0.6 = 6.6 \text{ and } 5.4 \text{ in.}$$

$$E_p = 400,000 \pm 40,000 = 440,000 \text{ and } 360,000 \text{ PSI}$$

By using Excel spreadsheet and arranging variables in groups of 16, 8, 4, 2, 1, the following results were obtained:

n	P (lb)	E (psi)	a (in.)	Ep (PSI)	t (in.)	(t) ² (sq. in.)
110000	9900	11000	6.6	440000	5.262368	27.69251
110000	9900	11000	6.6	360000	5.626408	31.65647
110000	9900	11000	5.4	440000	5.352226	28.64632
110000	9900	11000	5.4	360000	5.722482	32.7468
110000	9900	9000	6.6	440000	6.118354	37.43425
110000	9900	9000	6.6	360000	6.541609	42.79265
110000	9900	9000	5.4	440000	6.186164	38.26863
110000	9900	9000	5.4	360000	6.614111	43.74646
110000	8100	11000	6.6	440000	4.193347	17.58416
110000	8100	11000	6.6	360000	4.483434	20.10118
110000	8100	11000	5.4	440000	4.305574	18.53796
110000	8100	11000	5.4	360000	4.603425	21.19152
110000	8100	9000	6.6	440000	4.921882	24.22492
110000	8100	9000	6.6	360000	5.262368	27.69251
110000	8100	9000	5.4	440000	5.005926	25.05929
110000	8100	9000	5.4	360000	5.352226	28.64632
90000	9900	11000	6.6	440000	5.197236	27.01126
90000	9900	11000	6.6	360000	5.556771	30.8777
90000	9900	11000	5.4	440000	5.285982	27.94161
90000	9900	11000	5.4	360000	5.651656	31.94122
90000	9900	9000	6.6	440000	6.042628	36.51335
90000	9900	9000	6.6	360000	6.460645	41.73993
90000	9900	9000	5.4	440000	6.109599	37.3272
90000	9900	9000	5.4	360000	6.532249	42.67028
90000	8100	11000	6.6	440000	4.141446	17.15158
90000	8100	11000	6.6	360000	4.427943	19.60668
90000	8100	11000	5.4	440000	4.252284	18.08192
90000	8100	11000	5.4	360000	4.546449	20.6702
90000	8100	9000	6.6	440000	4.860964	23.62897
90000	8100	9000	6.6	360000	5.197236	27.01126
90000	8100	9000	5.4	440000	4.943968	24.44282
90000	8100	9000	5.4	360000	5.285982	27.94161
			Sum		170.0449	920.5796



$$E[t] = 170.0449 / 32 = 5.314, \quad E[t^2] = 920.5796 / 32 = 28.768$$

$$\text{From Eq. 10.61, } V[t] = 28.768 - (5.314)^2 = 0.529, \quad S_t = 0.727$$

$$\text{Given } t = 6.5, \quad z = \frac{6.5 - 5.314}{0.727} = 1.631 \text{ From Table 10.1}$$

$$\text{Area under normal curve} = 0.448 + 0.5 = 0.948$$

$$\text{Reliability} = \underline{94.8\%}$$

10-7. Find reliability based on n by Taylor's series expansion

$$t = (0.25 + 0.125 \log n) \left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right] \sqrt[3]{\frac{E}{E_p}}$$

$$\log n = \frac{8t}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right] \sqrt[3]{\frac{E}{E_p}}} - 2$$

$$\frac{\partial \log n}{\partial t} = \frac{8}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right]^2 \sqrt[3]{\frac{E}{E_p}}} = \frac{8}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right]^2 \sqrt[3]{\frac{10,000}{400,000}}} = 1.326$$

$$\frac{\partial \log n}{\partial p} = \left(-\frac{1}{2}\right) \frac{8t \left(\frac{75}{\pi E}\right)^2 (2p)}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right]^3 \sqrt[3]{\frac{E}{E_p}}} = -\frac{8 \times 6.5 \left(\frac{75}{\pi \times 10,000}\right)^2 (9000)}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right]^3 \sqrt[3]{\frac{10,000}{400,000}}} = -1.0388 \times 10^{-3}$$

$$\begin{aligned} \frac{\partial \log n}{\partial E} &= \frac{-\frac{8t}{3} \sqrt[3]{\frac{E_p}{E^4}}}{\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2}} + \frac{8t \left(\frac{75P}{\pi}\right)^2 \sqrt[3]{\frac{E_p}{E^{10}}}}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right]^3} \\ &= \frac{-\frac{8 \times 6.5}{3} \sqrt[3]{\frac{400,000}{10,000^4}}}{\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2}} + \frac{8 \times 6.5 \left(\frac{75 \times 9000}{\pi}\right)^2 \sqrt[3]{\frac{400,000}{10,000^{10}}}}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right]^3} \end{aligned}$$

$$= -2.873 \times 10^{-4} + 9.349 \times 10^{-4} = 6.476 \times 10^{-4}$$

$$\frac{\partial \log n}{\partial a} = \frac{8ta}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right]^3 \sqrt[3]{\frac{E}{E_p}}} = \frac{8 \times 6.5 \times 6}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right]^3 \sqrt[3]{\frac{10,000}{400,000}}} = 0.1215$$

$$\frac{\partial \log n}{\partial E_p} = \frac{\frac{8}{3}t}{\left[\sqrt{\left(\frac{75P}{\pi E}\right)^2 - a^2} \right] \sqrt[3]{EE_p^2}} = \frac{\frac{8}{3} \times 6.5}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right] \sqrt[3]{10,000 \times 400,000^2}} = 7.183 \times 10^{-6}$$

$$V[\log n]_t = \left(\frac{\partial \log n}{\partial t} \right)^2 (tC[t])^2$$

$$V[\log n]_t = (1.326)^2 + (6.5 \times 0.1)^2 = 0.7429$$

$$V[\log n]_p = (-1.0388 \times 10^{-3})^2 + (9000 \times 0.1)^2 = 0.8741$$

$$V[\log n]_E = (6.476 \times 10^{-4})^2 + (10,000 \times 0.1)^2 = 0.4194$$

$$V[\log n]_a = (0.1215)^2 + (6 \times 0.1)^2 = 0.005314$$

$$V[\log n]_{E_p} = (7.183 \times 10^{-6})^2 + (400,000 \times 0.1)^2 = 0.08255$$

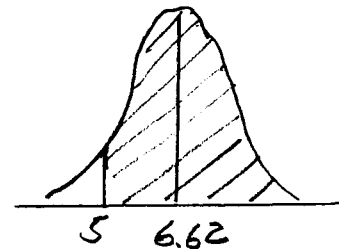
$$V[\log n] = 0.7429 + 0.8741 + 0.4194 + 0.005314 + 0.08255 = 2.1242$$

$$S[\log n] = \sqrt{V[\log n]} = 1.4574$$

$$E[\log n] = \frac{8 \times 6.5}{\left[\sqrt{\left(\frac{75 \times 9000}{\pi \times 10,000}\right)^2 - 6^2} \right] \sqrt[3]{\frac{10,000}{400,000}}} - 2 = 6.62$$

$$\log n_T = \log 100,000 = 5$$

$$z = \frac{\log n_T - E[\log n]}{S[\log n]} = \frac{5 - 6.62}{1.4572} = -1.1116$$

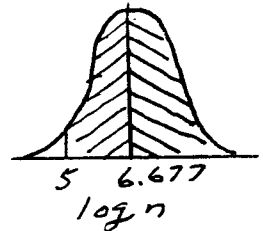


Reliability = 86.75%

$$10-8. \text{ Given } \log n = \frac{8t}{\left[\sqrt{\left(\frac{75P}{\pi E} \right)^2 - a^2} \right] \sqrt{\frac{E}{E_p}}} - 2$$

$t = 6.5 \pm 0.65 = 7.15$ and 5.85 , by Excel spreadsheet, the following results were obtained

t	P (lb)	E (psi)	a (in.)	Ep (PSI)	log n	(log n) ²
7.15	9900	11000	6.6	440000	7.567168	57.26204
7.15	9900	11000	6.6	360000	6.948153	48.27683
7.15	9900	11000	5.4	440000	7.406546	54.85692
7.15	9900	11000	5.4	360000	6.797923	46.21175
7.15	9900	9000	6.6	440000	6.228677	38.79642
7.15	9900	9000	6.6	360000	5.696265	32.44743
7.15	9900	9000	5.4	440000	6.138478	37.68091
7.15	9900	9000	5.4	360000	5.611901	31.49344
7.15	8100	11000	6.6	440000	10.00615	100.1231
7.15	8100	11000	6.6	360000	9.229329	85.18051
7.15	8100	11000	5.4	440000	9.693206	93.95824
7.15	8100	11000	5.4	360000	8.936631	79.86337
7.15	8100	9000	6.6	440000	8.229006	67.71654
7.15	8100	9000	6.6	360000	7.567168	57.26204
7.15	8100	9000	5.4	440000	8.057272	64.91964
7.15	8100	9000	5.4	360000	7.406546	54.85692
5.85	9900	11000	6.6	440000	5.827683	33.96189
5.85	9900	11000	6.6	360000	5.321216	28.31534
5.85	9900	11000	5.4	440000	5.696265	32.44743
5.85	9900	11000	5.4	360000	5.1983	27.02233
5.85	9900	9000	6.6	440000	4.732554	22.39707
5.85	9900	9000	6.6	360000	4.296944	18.46373
5.85	9900	9000	5.4	440000	4.658754	21.70399
5.85	9900	9000	5.4	360000	4.227919	17.8753
5.85	8100	11000	6.6	440000	7.823215	61.2027
5.85	8100	11000	6.6	360000	7.187633	51.66207
5.85	8100	11000	5.4	440000	7.567168	57.26204
5.85	8100	11000	5.4	360000	6.948153	48.27683
5.85	8100	9000	6.6	440000	6.369187	40.56654
5.85	8100	9000	6.6	360000	5.827683	33.96189
5.85	8100	9000	5.4	440000	6.228677	38.79642
5.85	8100	9000	5.4	360000	5.696265	32.44743
Sum					215.128	1517.269



$$E[\log n] = \frac{215.128}{32} = 6.723 \quad E[(\log n)^2] = \frac{1517.269}{32} = 47.415$$

$$\text{From Eq. 10.61, } V[\log n] = 47.415 - (6.723)^2 = 2.216$$

$$S_{\log n} = \sqrt{2.216} = 1.489 \quad \text{Given } n = 100000 \text{ or } \log n = 5$$

$$z = \frac{5 - 6.723}{1.489} = -1.157 \quad \text{From Table 10.1, Area under}$$

$$\text{normal curve} = 0.376 + 0.5 = 0.876 \text{ so Reliability} = \underline{87.6\%}$$

10-9. Given

$$N_f = f_1(\varepsilon_t)^{-f_2}$$

$$f_1 = 0.00462, C[f_1] = 30\%$$

$$f_2 = 2.69, C[f_2] = 5\%$$

$$\varepsilon_t = 0.0021, C[\varepsilon_t] = 10\%$$

$$\rho(f_1, f_2) = -0.867$$

Find Expectation and variance of N_f based on the first order Taylor series expansion.

First order approximation of expectation or mean is $E[g] = E[\mu]$

$$E[N_f] = 0.00462 (0.0021)^{-2.69} = \underline{73,769}$$

$$V[N_f] = V[N_f]_{\varepsilon_t} + V[N_f]_{f_1} + V[N_f]_{f_2} + 2\left(\frac{\partial N_f}{\partial f_1}\right)\left(\frac{\partial N_f}{\partial f_2}\right)\text{Cov}[f_1, f_2]$$

(a) $V[N_f]_{\varepsilon_t}$

$$\frac{\partial N_f}{\partial \varepsilon_t} = f_1(-f_2)(\varepsilon_t)^{-f_2-1} = -0.00462 \times 2.69 \times (0.0021)^{-3.69} = -94,494,180$$

$$V[N_f]_{\varepsilon_t} = \left(\frac{\partial N_f}{\partial \varepsilon_t}\right)^2 V[\varepsilon_t] = (-94,494,180)^2 (0.0021 \times 0.1)^2 = 3.94 \times 10^8$$

(b) $V[N_f]_{f_1}$

$$\left(\frac{\partial N_f}{\partial f_1}\right) = (\varepsilon_t)^{-f_2} = (0.0021)^{-2.69} = 0.1597 \times 10^8$$

$$V[N_f]_{f_1} = \left(\frac{\partial N_f}{\partial f_1}\right)^2 V[f_1] = (0.1597 \times 10^8)^2 (0.00462 \times 0.3)^2 \\ = 4.899 \times 10^8$$

(c) $V[N_f]_{f_2}$

$$\begin{aligned}\frac{\partial N_f}{\partial f_2} &= -f_1[\ln(\epsilon_t)](\epsilon_t)^{-f_2} = -0.00462[\ln(0.0021)](0.0021)^{-2.69} \\ &= 4.55 \times 10^5\end{aligned}$$

$$\begin{aligned}V[N_f]_{f_2} &= \left(\frac{\partial N_f}{\partial f_2}\right)^2 V[f_2] = (4.55 \times 10^5)^2 (2.69 \times 0.05)^2 \\ &= 37.45 \times 10^8\end{aligned}$$

(d) Cross - Product

$$\text{Cov}[f_1, f_2] = \rho(f_1, f_2) \sqrt{V[f_1]} \sqrt{V[f_2]}$$

$$\sqrt{V[f_1]} = 0.00462 \times 0.3 = 0.001386$$

$$\sqrt{V[f_2]} = 2.69 \times 0.05 = 0.1345$$

$$\text{Cov}[f_1, f_2] = -0.867 \times 0.001386 \times 0.1345 = -1.616 \times 10^{-4}$$

$$\begin{aligned}\left(\frac{\partial N_f}{\partial N_{f_1}}\right) \left(\frac{\partial N_f}{\partial N_{f_2}}\right) \text{Cov}[f_1, f_2] &= 0.1597 \times 10^8 \times 4.55 \times 10^5 \times (-1.616 \times 10^{-4}) \\ &= -11.75 \times 10^8\end{aligned}$$

$$\begin{aligned}V[N_f] &= 3.94 \times 10^8 + 4.899 \times 10^8 + 37.45 \times 10^8 - 2 \times (11.75 \times 10^8) \\ &= \underline{2.28 \times 10^9}\end{aligned}$$

10-10. Serviceability index

$$PSI = p_1 - 1.91 \log(1 + SV) - 1.38 RD^2 - 0.01 \sqrt{C}$$

(a) The expected value of PSI using second order Taylor series

$$E[g] = g(\mu) + \frac{1}{2} \sum_{i=1}^n \frac{\partial^2 g}{\partial x_i^2} V[x_i] \quad g(x_1, x_2, x_3, x_4) = PSI(p_1, SV, RD, C)$$

$$\frac{\partial PSI}{\partial p_1} = 1 \quad \frac{\partial^2 PSI}{\partial p_1^2} = 0$$

$$\frac{\partial PSI}{\partial SV} = -\frac{1.91}{1+SV} \left(\frac{1}{\ln 10} \right) = -\frac{1.91}{1+1.572} \left(\frac{1}{\ln 10} \right) = -0.323$$

$$\frac{\partial^2 PSI}{\partial SV^2} = \frac{1.91}{(1+SV)^2} \left(\frac{1}{\ln 10} \right) = \frac{1.91}{(1+1.572)^2} \left(\frac{1}{\ln 10} \right) = 0.125$$

$$\frac{\partial PSI}{\partial RD} = -1.38 \times 2 \times RD = 1.38 \times 2 \times 0.284 = -0.784 \quad \frac{\partial^2 PSI}{\partial RD^2} = -1.38 \times 2 = -2.76$$

$$\frac{\partial PSI}{\partial C} = -0.01 \left(\frac{1}{2} \right) \frac{1}{\sqrt{C}} = -0.01 \left(\frac{1}{2} \right) \frac{1}{\sqrt{120}} = 0.000456$$

$$\frac{\partial^2 PSI}{\partial C^2} = -0.01 \left(\frac{1}{2} \right) \left(-\frac{1}{2} \right) \frac{1}{\sqrt{C}^3} = 0.01 \left(\frac{1}{4} \right) \frac{1}{\sqrt{120}^3} = 0.0000019$$

$$E[PSI] = 4.2 - 1.91 \log(1+1.572) - 1.38 \times (0.284)^2 - 0.01 \sqrt{120} + 0.5(0 \times 0.06 + 0.125 \times 0.32 - 2.76 \times 0.003 + 0.0000019 \times 0) = \underline{\underline{3.211}}$$

(b) Variance

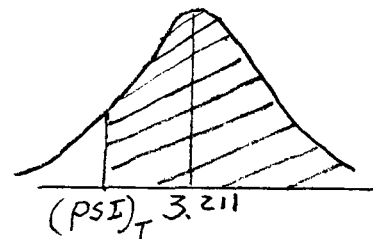
$$V(g) = \sum_{i=1}^n \left(\frac{\partial g}{\partial x_i} \right)^2 V[x_i]$$

$$V[PSI] = 1 \times 0.06 + (-0.323)^2 \times 0.32 + (-0.784)^2 \times 0.003 + (0.000456)^2 \times 0 = \underline{\underline{0.09522}}$$

(c) Terminal serviceability index for 95 % reliability

From Table 8.1, $u = 1.645$ for 95% reliability

$$\frac{(PSI)_T - E[PSI]}{\sqrt{V[PSI]}} = -1.645$$



$$\frac{(\text{PSI})_T - 3.211}{\sqrt{0.04522}} = -1.645 \quad \text{or} \quad (\text{PSI})_T = \underline{2.703}$$

10-11. Given $g = \frac{1-2r}{1+r} + \frac{2+r}{3+6r+r^2} + \frac{r}{(4+r^2)(6+r)}$ Find $V[g]$ when $r=1$, $C[r]=0.2$

$$V[r] = (0.2 \times 1)^2 = 0.04$$

$$\frac{\partial g}{\partial r} = \frac{(1+r)(-2) - (1-2r)(1)}{(1+r)^2} + \frac{(3+6r+r^2)(1) - (2+r)(6+2r)}{(3+6r+r^2)^2} + \frac{(4+r^2)(6+r)(1) - r(4+12r+3r^2)}{[(4+r^2)(6+r)]^2}$$

For $r = 1$, $\frac{\partial g}{\partial r} = -\frac{3}{4} + 0.14 + 0.0131 = -0.5969$

$$V[g] = \left(\frac{\partial g}{\partial r}\right)^2 V[r] = (-0.5969)^2 (0.04) = \underline{0.01425}$$

10-12. Given $g = \frac{1-2r-s}{1+rs} + \frac{r+s}{3+6s+r^2} + \frac{rs}{(r+s)^2}$, Find $V[g]$ when $r = \sqrt{r} = 10$, $s = \sqrt{s} = 20$

$$\frac{\partial g}{\partial r} = \frac{(1+rs)(-2) - (1-2r-s)(s)}{(1+rs)^2} + \frac{(3+6s+r^2)(1) - (r+s)(2r)}{(3+6s+r^2)^2} + \frac{(r+s)^2(s) - rs(2r+2s)}{(r+s)^2(r+s)^2} =$$

$$\frac{(1+200)(-2) - (1-20-20)(20)}{(1+20 \times 10)^2} + \frac{(3+6 \times 20+10^2) - (30) \times 2 \times 10}{3+120+100)^2} + \frac{(10+20)^2 \times 20 - 20 \times 10(2 \times 10 + 2 \times 20)}{(30)^2(30)^2}$$

$$= 0.00936 - 0.00758 + 0.00741 = 0.00919$$

$$\frac{\partial g}{\partial s} = \frac{(1+rs)(-1) - (1-2r-s)(r)}{(1+rs)^2} + \frac{(3+6s+r^2)(1) - (r+s) \times 6}{(3+6s+r^2)^2} + \frac{(r+s)^2 r - rs(2s+2r)}{(r+s)^2(r+s)^2}$$

$$= \frac{-201 - (-39)(10)}{(201)^2} + \frac{223 - 180}{(223)^2} + \frac{900 \times 10 - 200(40+20)}{900 \times 900}$$

$$= 0.004678 + 0.000865 - 0.003704 = 0.001839$$

$$V(g) = \left(\frac{\partial g}{\partial r}\right)^2 V[r] + \left(\frac{\partial g}{\partial s}\right)^2 V[s]$$

$$V[g] = (0.00919)^2 \times 10 + (0.001839)^2 \times 20 = \underline{0.00139}$$

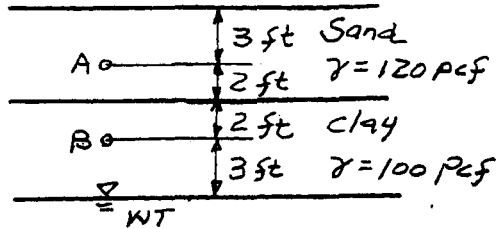
Chapter 11 Flexible Pavement Design

11-1 Find moisture content at Points A and B.

From Eq. 11.2 $u = S + \alpha p$

$$u = -z \gamma_w$$

$$S = -z \gamma_w - \alpha p$$



At Point A with sand, $\alpha = 0$,

$$S = -z \gamma_w = -7 \times 62.4 = -463.8 \text{ psf} = -3.033 \text{ psi}$$

From Fig. P11.1 $w = \underline{10\%}$

At Point B with clay, $\alpha = 0.5$,

$$P = 5 \times 120 + 2 \times 100 = 800 \text{ psf}$$

$$S = -3 \times 62.4 - 0.5 \times 800 = -587.2 \text{ psf} = -4.08 \text{ psi}$$

From Fig. 11.1 $w = \underline{21\%}$

11-2. Estimate the coefficients of permanent deformation (a, b, and m) in the Ohio State Model in Eq. 11.16 based on the test results in Figs. 11.4 and 11.5.

$$\epsilon_p = a(\epsilon)^b (N)^{1-m} = a \left(\frac{M_R}{\sigma_d} \right)^b (N)^{1-m}$$

$$\text{Let } A = a \left(\frac{M_R}{\sigma_d} \right)^b \text{ or } \log A = \log a - b \log \left(\frac{M_R}{\sigma_d} \right)$$

From Fig. 11.5, when $A = 0.0002$, $M_R/\sigma_d = 10^4$, when $A = 0.0006$, $M_R/\sigma_d = 3000$

$$\log(0.0002) = \log a - b \log(10^4) \text{ or } -3.69897 = \log a - 4b$$

$$\log(0.0006) = \log a - b \log(3000) \text{ or } -3.22185 = \log a - 3.47712b$$

Solving a and b $a = \underline{0.89324}$, $b = \underline{0.9125}$

Fig. 11.4 shows a straight line relationship between $\log(\epsilon_p/N)$, thus m is a constant, which is equal to the slope of the straight line

From Fig. 11.4

$$m = \frac{\log(2 \times 10^{-5}) - \log(2 \times 10^{-7})}{\log 10,000 - \log 70} = \underline{0.79}$$

$$\epsilon_p = 0.8932(\epsilon)^{0.9125}(N)^{0.21}$$

11-3. Given: $N_f = 5 \times 10^{-6}(\epsilon_t)^{-3}$, $\epsilon_t = 0.0005$, and $C[N_f] = 0.8$.

Find: Percent area cracked if the pavement is subjected to 5000 thermal cycles.

$$N_f = 5 \times 10^{-6}(0.0005)^{-3} = 40,000$$

$$V[N_f] = (0.8 \times 40,000)^2 = 1.024 \times 10^9$$

$$\text{Cracking Index } c = n/N_f = 5000/40,000 = 0.125$$

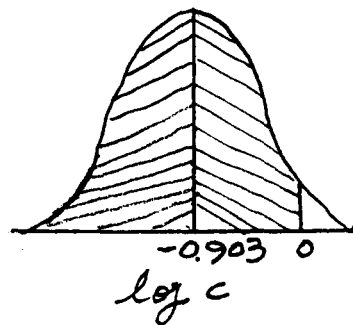
$$V[c] = \left[-\frac{n}{(N_f)^2} \right]^2 V[N_f] = \left[-\frac{5000}{(40,000)^2} \right]^2 \times 1.024 \times 10^9 = 0.01$$

$$V[\log c] = \frac{0.1886}{c^2} V[c] = \frac{0.1886}{(0.125)^2} \times 0.01 = 0.1207$$

$$S_{\log c} = \sqrt{0.1207} = 0.3474$$

$$\log c = \log(0.125) = -0.903$$

$$Z = \frac{0 + 0.903}{0.3474} = 2.6$$



From Table 10.1, Area under normal curve = 0.5 + 0.495 or

Reliability = 99.5 % Or Area cracked = 100 - 99.5 = 0.5 %

11-4.

$$(a) M_p = 68 \left(1 + \frac{1}{0.67+4} \right) - \frac{34}{0.67+4} + 6 = \underline{81.3^\circ F} \text{ surface}$$

$$M_p = 68 \left(1 + \frac{1}{4+4} \right) - \frac{34}{4+4} + 6 = \underline{78.3^\circ F} \text{ binder}$$

$$(b) B_3 = 1.3 + 0.49825 \log 8 = 1.74996 \checkmark$$

$$B_4 = 0.483 \times 11 = 5.313 \checkmark$$

$$B_3 = 0.553833 + 0.028829 \times 5 \times (8)^{-0.1703} + 0.070377 \times 2.5 \text{ Surface}$$

$$+ 0.931757 (8)^{-0.02774} - 0.03476 \sqrt{V_a} = 1.71046 - \square = 1.571425$$

↓
1.46714
↑
binder

$$B_2 = (5.313)^{0.5} \left(\frac{81.3}{78.3} \right)^{1.74996} = 5072.8$$

$$= 4749.8$$

$$B_1 = \frac{1.571425}{1.46714} + 0.000005 \times (5072.8) - 0.00189 \times (4749.8)^{-1.1} (8)$$

$$= \frac{0.623346}{0.57943}$$

$$|E|_* = 100,000 \times 10^{(0.623346 / 0.57943)} = \frac{4.2 \times 10^5 \text{ psi surface}}{3.8 \times 10^5 \text{ psi binder}}$$

$$E_1 = \left\{ \frac{2 \times (4.2)^{\frac{1}{3}} + 6 (3.8)^{\frac{1}{3}}}{8} \right\}^3 = 3.9 \times 10^5 \text{ psi}$$

$$E_2 = 10.47 (8)^{-0.471} (8)^{-0.04} (3.9 \times 10^5)^{-0.139} (10000)^{0.267} (8000)^{0.868} \text{ psi} = \underline{29,700}$$

11-5.

$$(a) \text{ From Eq. 6.30 } ESAL = (ADT)_0 (T) (T_f) (G) (D) (L) (365) (Y)$$

$$\text{Given: } (ADT)_0 (T) = 1885, \quad T_f = 0.52 \text{ (see Table 6.10)}$$

$$(D) (L) = 0.4 \text{ (see Table 6.15), and from Eq. 6.33}$$

$$(G) (Y) = \frac{(1 + 0.04)^{20} - 1}{0.04} = 29.78$$

$$ESAL = 1885 \times 0.52 \times 29.78 \times 0.4 \times 365 = \underline{4.26 \times 10^6}$$

(b) With 8" of untreated aggregate base, $M_R = 10^4$ psi, $ESAL = 4.26 \times 10^6$, from Fig. 11.17 $h = 10$ in.

(c) First, use Figures 11.11 and 11.12 to determine the substitution ratio of 1" HMA to 1" of Type I emulsified asphalt mix.

From Fig. 11.11, the thickness of full-depth HMA is 11.5 in.

From Fig. 11.12, the combined thickness of HMA and emulsified asphalt mix is 12 in.

Assume a minimum HMA of 2 in.

$$\text{Substitution Ratio} = \frac{12 - 2}{11.5 - 2} = 1.053$$

If use 2 in. of HMA, thickness of emulsified asphalt base = $(10 - 2) \times 1.053 \approx 8.5$ in.

If use 3.5 in. of HMA, thickness of emulsified asphalt base = $(10 - 3.5) \times 1.053 \approx 7$ in.

11.6. Stage Construction :

1st stage = 5 yrs
 2nd stage = 10 yrs
 3rd stage = 15 yrs } 30 yrs

Design traffic = 30,000 ESAL
 $r = 3\frac{1}{2}\%$

$$DT = 0.5; 0.75; 1$$

$$\therefore \text{1st stage (5 yrs)} \quad GY = \frac{(1+0.035)^5 - 1}{0.035} = 5.36$$

$$\text{2nd stage (10 yrs)} \quad GY = \frac{(1+0.035)^{10} - 1}{0.035} = 19.296$$

$$\text{3rd stage (30 yrs)} \quad GY = 51.623$$

* The first stage:

$$R_1 = 30000 \times 5.36 = 160800 \checkmark$$

$$S_{p1} = 11.4: N_1 = \frac{R_1}{D_r} = \frac{160800}{0.5} = 321600 = 0.322 \times 10^6 \checkmark$$

fig 11.10 $\rightarrow R_1 \approx \underline{8.25 \text{ in.}}$ use 8.5 in.

* The second stage:

$$R_2 = 30000 (19.246 - 5.36) = 418080 = 0.418 \times 10^6$$

$$N_2 = \frac{418080}{(0.75 - 0.5)} = 1.67 \times 10^6 \checkmark$$

$R_2 \approx \underline{10.6 \text{ in.}}$ use 11 in.
or overlay of 2.5 in.

* The third stage:

$$R_3 = 30000 (57.623 - 19.246) = 970620$$

$$N_3 = \frac{970620}{1 - 0.75} = 3.88 \times 10^6 \checkmark$$

$R_3 \approx \underline{12.5 \text{ in.}}$ or overlay of $\underline{1.5 \text{ in.}}$

11-7

$$\beta_2 = (5.313)^{0.5} (70)^{1.74996} = 3904.07$$

surface

$$\beta_1 = \left(\frac{1.571425}{1.46714} \right) + \left(0.000005 - 0.00189 \times 8^{-11} \right) \times 3904.07 = 0.84178$$

$$E^* = 100,000 (10)^{0.73749} = 6.9467 \times 10^5$$

$$E_1 = \left\{ \frac{2 \times (6.95)^{\frac{1}{3}} + 6 (5.46)^{\frac{1}{3}}}{8} \right\}^3 = 5.4637 \times 10^5$$

binder

$$E_2 = 10.447 (8)^{-0.471} (8)^{-0.041} (5.8 \times 10^5)^{-0.139} (10,000)^{0.287} (8,000)^{0.868} \text{ psi} = 19,560$$

$$a_2 = 0.249 \log 19,560 - 0.977 = 0.0916$$

$$SN = 8 \times 0.48 + 8 \times 0.0916 = \underline{4.6 \text{ in.}}$$

11-8.

MAAT = 45°F ; Normal Modulus = 22500 PSI.

determine the effective modulus for asphalt modulus based on the normal modulus (Table 11.10).

Month	MR (PSI)	U_i
JAN	29400	0.00507
FEB	36300	0.00311
MAR	43100	0.00209
APR	50000	0.00148
MAY	15800	0.02145
JUNE	17100	0.01784
JULY	18500	0.01486
AUG.	19800	0.01269
SEPT.	21200	0.01083
OCT.	22500	0.00944
NOV.	22500	0.00944
DEC.	22500	0.00944
Σ		0.11772

$$U_f = 1.18 \times 10^{-8} MR^{-2.32}$$

$$\Sigma U_f = 0.11772$$

$$\bar{U}_f = \frac{0.11772}{12} = 0.00981$$

$$\text{Effective MR} = \frac{\bar{U}_f}{MR^{-2.32}} = \frac{\bar{U}_f}{1.18 \times 10^{-8}}$$

$$MR^{-2.32} = 8.3136 \times 10^{-11}$$

$$MR = \underline{\underline{22167 \text{ PSI}}} \checkmark$$

11-9. 12 in full depth asphalt pavement on subgrade with effective MR = 10,000 PSI

$$a = a_1 = 0.44 \text{ (for MMA)}$$

$$\Delta \text{PSI} = 4.20 - 2.5 = 1.7 ; S_o = 0.5 ; W_{18} = 3 \times 10^7$$

$$\text{For full depth asphalt } SN = a_1 D_1 = 0.44 \times 12 = 5.28$$

$$\text{Eqn. 11-34: } \log W_{e18} = 9.36 \log (SN+1) - 0.20 + \frac{\log \left[\frac{4.2 - P_e}{4.2 - 1.5} \right]^{1.7}}{0.4 + \frac{1094}{(SN+1)^{1.19}}} + 2.32 \log MR - 8.07$$

$$\log W_{e18} = 7.4689 - 0.20 - 0.41942 + 9.28 - 8.07 = 8.05948 \checkmark$$

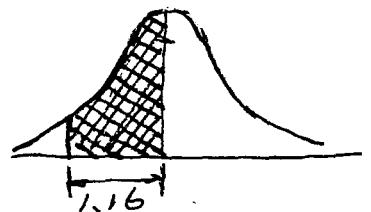
$$W_{e18} = \underline{\underline{1.147 \times 10^8}} \checkmark$$

$$Z_R = \frac{\log W_{18} - \log W_{e18}}{S_o} = \frac{\log (3 \times 10^7) - \log (1.147 \times 10^8)}{0.5}$$

$$= -1.16473 \checkmark$$

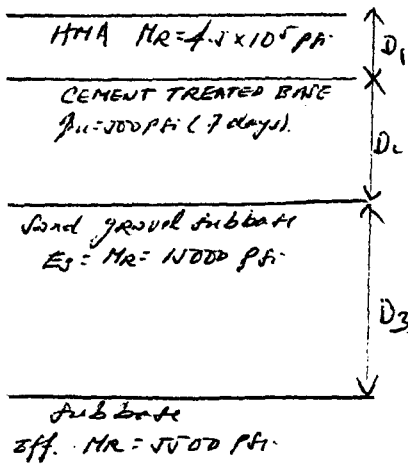
From Table 10.1, with $Z = 1.16$, the area under the normal curve, as shown by the cross hatched area, is 0.377 so

$$R = 0.5 + 0.377 = 0.877 \text{ or } \underline{\underline{88\%}}$$



11-10:

Design ESAL = 1.2×10^6 ; APSI = 2



Drainage: fair, 25% of the time of the pavement will be expected to moisture levels approaching saturation.

HMA: $MR = 4.5 \times 10^5$ psi \rightarrow Fig. 11.26
 $a_1 = 0.44$

CTB: Fig. 7.12C \rightarrow $MR = 6.5 \times 10^5$ psi
 $a_2 = 0.17$

Granular subbase:
 $a_3 = 0.227(\log MR) - 0.839$ (Eq. 11.46)
 $a_3 = 0.109$

Drainage coeff = 0.80 (Table 11.20)

• Thickness of HMA:

AASHTO Method unapplicable because $MR = 6.5 \times 10^5 \gg 40000$

Let take $D_1 = 3$ in (minimum thickness required).

• Thickness of CTB:

Subbase \rightarrow $ESAL = 1.2 \times 10^6$
 $MR = 15000$ psi } From Fig 11.24 $SN_2 = 2.3$
 $APSI = 2$

$SN_2 = a_1 D_1 + a_2 D_2 m_2$

Assume that CTB is unfusceptible to moisture change $\rightarrow m_2 = 1$

$2.3 = 3 \times 0.44 + 0.17 D_2 \times 1$

$D_2 = 5.8 \approx 6$ in \checkmark

• Thickness of Subbase:

$ESAL = 1.2 \times 10^6$
 $MR = 5500$ psi } $SN_3 = 3.1$
 $APSI = 2$

$SN_3 = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$

$3.1 = 0.44 \times 3 + 6 \times 0.17 + 0.109 \times D_3 \times 0.8$

$R = 50\%$, $D_3 = 8.7 \approx 9$ in \checkmark

11-11. Given $W_{18} = 5 \times 10^6$, $MR = 5,000$ psi, and $APSI = 1.7$, from Fig. 11.25
 SN for main line pavement = 4.2

Given $P_e = 2.5\%$ and $P_p = 0.02\%$, $W_{18} = 5 \times 10^6 (0.025 + 0.0002)$
 $= 0.126 \times 10^6$, from Fig. 11.25
 SN for shoulder pavement = 2.4

Chapter 12 Rigid Pavement Design

12-1. Given: a concrete pavement on untreated subbase without concrete shoulders.
 $h = 10$ in., $k = 150$ pci, and $n = 2 \times 10^6$ repetitions.

Estimate: Allowable corner deflection.

$$\text{From Eq. 12.9} \quad \% \text{ erosion damage} = 100 \sum \frac{C_2 n_i}{N_i}$$

When damage is 100 %, allowable number of repetitions $N = C_2 n$

$C_2 = 0.06$ for pavements with concrete shoulders, so

$$N = 0.06 \times 2 \times 10^6 = 0.12 \times 10^6$$

$$\text{From Eq. 12.7} \quad \log N = 14.524 - 6.777(C_1 P - 9.0)^{0.103}$$

$C_1 = 1$ for untreated subbase

$$\log(0.12 \times 10^6) = 14.524 - 6.777(P - 9.0)^{0.103}$$

$$P = 34.0946 \quad \text{From Eq. 12.8}$$

$$P = 268.7 \frac{p^2}{hk^{0.73}}$$

$$p = \sqrt{\frac{Phk^{0.73}}{268.7}} = \sqrt{\frac{34.0946 \times 10 \times (150)^{0.73}}{268.7}} = 7.014 \text{ psi}$$

$$w = \frac{p}{k} = \frac{7.014}{150} = \underline{0.04676 \text{ in.}}$$

12-2. Same as Problem 12-1 but with concrete shoulders.

$$C_2 = 0.94, \text{ so } N = 0.94 \times 2 \times 10^6 = 1.88 \times 10^6$$

$$\log(1.88 \times 10^6) = 14.524 - 6.777(P - 9.0)^{0.103}$$

$$P = 15.7485 \quad \text{From Eq. 12.8} \quad p = 4.767 \text{ psi} \quad \text{or} \quad w = 4.767/150 = \underline{0.0318 \text{ in.}}$$

12-3. Total number of trucks during design period on design lane

$$= 2500 \times 365 \times 20 \times 0.35 \times 0.5 = 3,193,750$$

Calculation of Pavement Thickness

Project Problem 12-3

Trial thickness 8 in Doweled joints: yes no
 Subbase-subgrade k 200 pci Concrete shoulder: Yes no
 Modulus of rupture, MR 650 psi Design period 20 years
 Load safety factor, LSF 1.1

Axle load kips	Multiplied by LSF	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue damage %	Allowable repetitions	Erosion damage %
1	2	3	4	5	6	7

8. Equivalent stress 242 10. Erosion factor 2.80
 9. Stress ratio factor 0.372

Single Axles

28	30.8	2874	19,000	15.1	900,000	0.3
26	28.6	6068	45,000	13.5	1,400,000	0.4
24	26.4	7346	160,000	9.6	2,100,000	0.4
22	24.2	99823	800,000	6.2	3,500,000	1.4
20	22.0	208,871	-		7,200,000	2.9
18	19.8	353,868	-		16,000,000	2.2
16	17.6	418,062	-		40,000,000	1.0

11. Equivalent stress 208 13. Erosion factor 2.93
 12. Stress ratio factor 0.320

Tandem Axles

48	52.8	30,660	10,000,000	0.3	950,000	3.2	
44	48.4	33,534	-		1,600,000	2.1	
40	44.0	53,655	-		2,600,000	2.1	
36	39.6	54,933	-		5,600,000	1.0	
32	35.2	76,650	-		12,000,000	0.6	
28	30.8	109,865	-		40,000,000	0.3	
24	26.4	256,139	-		-		
Total				39.7	Total		17.9

12-4. Determine the thickness of a concrete pavement using the PCA procedure and check the result by the simplified procedure.

Trial thickness = 8.5 in.
 K = 150 pci
 MR = 650 psi
 LSF = 1.2

Doweled joints: yes
 Shoulders: yes
 Design period = 20 years

Total no. of trucks on the design lane during the design period = $3460 \times 365 \times 20$
 = 25,258,000

Load kips	Multiplied by LSF	Expected Repetition	Fatigue Analysis		Erosion Analysis	
			Allowable R.	% Damage	Allowable R.	% Damage

Single Axle

30	36	11,383	110,000	11.4	680,000	1.67
28	33.6	21,500	300,000	7.17	1,200,000	1.79
26	31.2	45,024	1,750,000	2.57	2,000,000	2.25
24	28.8	131,784			5,000,000	2.63
22	26.4	198,562			15,000,000	1.32
20	24	413,059				
18	21.6	636,157				
16	19.2	804,871				
14	16.8	1,207,306				
12	14.4	4,604,105				

Eq. Stress = 191
 Stress Ratio F = 0.29
 Erosion Factor = 2.32

Tandem Axles

52	62.4	30,100			680,000	4.43
48	57.6	73,607			1,300,000	5.66
44	52.8	202,609			3,000,000	6.75
40	48	539,026			8,000,000	6.74
36	43.2	1,422,816				
32	38.4	2,621,269				
28	33.6	3,066,199				
24	28.8	1,834,863				
20	24	2,173,809				
16	19.2	2,512,756				
				Total	21.1	33.2

Eq. Stress = 166
 Stress Ratio F = 0.26
 Erosion Factor = 2.45

For $h = 8.0$ in., the fatigue damage is greater than 100 %, so $h = \underline{8.5}$ in.

For the simplified procedure, from Table 12.15, the allowable ADTT is 5,700 for an 8-in. slab with medium support, which is greater than the actual ADTT of 3460, so the thickness required is 8 in.

12-5. Same as Problem 12-4 but without concrete shoulder

Trial thickness = 9.5 in.

K = 150 pci

MR = 650 psi

LSF = 1.2

Total no. of trucks on the design lane during the design period = 25,258,000

Doweled joints: yes

Concrete shoulders: no

Design period = 20 years

From Table 12.15, a thickness of 9.5 in. is required. A 9-in. slab is not adequate because an allowable ADTT of 2700 is smaller than the actual ADTT of 3460.

Trial thickness = 9.5 in.

Load kips	Multiplied by LSF	Expected Repetition	Fatigue Analysis		Erosion Analysis	
			Allowable R	% Damage	Allowable R	% Damage

Single Axle

30	36	11,383	40,000	28.5	1,400,000	0.81
28	33.6	21,500	120,000	17.92	2,000,000	1.08
26	31.2	45,024	400,000	11.26	3,400,000	1.32
24	28.8	131,784	3,000,000	4.4	5,800,000	2.27
22	26.4	198,562			10,000,000	1.99
20	24	413,059			21,000,000	1.97
18	21.6	636,157			60,000,000	1.06
16	19.2	804,871				
14	16.8	1,207,306				
12	14.4	4,604,105				

Eq. Stress = 200

Stress Ratio F = 0.308

Erosion Factor = 2.59

Tandem Axes

52	62.4	30,100	4,000,000	0.75	900,000	3.34
48	57.6	73,607			1,400,000	5.26
44	52.8	202,609			2,100,000	9.65
40	48	539,026			4,000,000	13.48
36	43.2	1,422,816			8,000,000	17.79
32	38.4	2,621,269			20,000,000	13.11
28	33.6	3,066,199			80,000,000	3.83
24	28.8	1,834,863				
20	24	2,173,809				
16	19.2	2,512,756				
Total				62.83		76.96

Eq. Stress = 183

Stress Ratio F = 0.282

Erosion Factor = 2.775

12-6. Given: $W_{18}^* = 5 \times 10^6 [(1.04)^Y - 1]$, $\Delta PSI_{FH} = 0.08(Y)^{0.6}$

$R = 90\%$, $S_o = 0.4$, $D = 8$ in, $\Delta PSI = 2.0 - \Delta PSI_{FH}$,

$S_c = 600$ psi, $C_d = 1.05$, $J = 3.2$, $E_c = 5 \times 10^6$, 40% $K = 100$ pci

From Table 11.15, $Z_R = -1.282$ From Eq. 12.21

$$\log W_{18} = -1.282 \times 0.4 + 7.35 \log(8+1) - 0.06 + \frac{\log(\Delta PSI/3)}{1 + 1.624 \times 10^7 / (8+1)^{8.46}}$$

$$+ (4.22 - 0.32 \times 2.5) \log \left\{ \frac{600 \times 1.05 [(8)^{0.75} - 1.132]}{215.63 \times 3.2 [(8)^{0.75} - \frac{18.42}{(\frac{5 \times 10^6}{100})^{0.25}}]} \right\}$$

$$\log W_{18} = 6.347 + 0.879 \log \left(\frac{\Delta PSI}{3} \right)$$

(a) Assume $Y = 8.5$ years, $W_{18}^* = 5 \times 10^6 [(1.04)^{8.5} - 1] = 1.98 \times 10^6$

$\Delta PSI_{FH} = 0.08(8.5)^{0.6} = 0.289$, $\Delta PSI = 2 - 0.289 = 1.711$

$\log W_{18} = 6.347 + 0.879 \log \frac{1.711}{3} = 6.1326$, or $W_{18} = 1.36 \times 10^6$

$1.36 \times 10^6 = 5 \times 10^6 [(1.04)^Y - 1]$, or $(1.04)^Y = 1.272$

$Y = \frac{\log 1.272}{\log 1.04} = 6.2$ years

(b) Assume $Y = 6.2$ years

$W_{18}^* = 5 \times 10^6 [(1.04)^{6.2} - 1] = 1.38 \times 10^6$

$\Delta PSI_{FH} = 0.08(6.2)^{0.6} = 0.239$, $\Delta PSI = 2 - 0.239 = 1.761$

$\log W_{18} = 6.347 + 0.879 \log \frac{1.761}{3} = 6.144$, $W_{18} = 1.39 \times 10^6$

The actual ESAL of 1.38×10^6 is slightly smaller than the allowable ESAL of 1.39×10^6 so a performance period of 6.2 years is satisfactory.

12-7. Given a concrete pavement with $S_c = 650$ psi, $J = 3.3$, $\Delta PSI = 4.5 - 2.0 = 2.5$, and poor drainage with 5% of time near saturation.

Determine W_{18} by Eq. 12.21 without the reliability term and compare the result with Figure 11.25.

From Table 12.20, $C = 0.9$ for poor drainage with 5% of time near saturation.

With $D_{SB} = 8$ in., $M_R = 5000$ psi, $E_{SB} = 30,000$ psi, from Figure 12.18, the composite modulus of subgrade reaction $k = 350$ pci. From Eq. 12.21

$$\log W_{18} = 7.35 \log(8+1) - 0.06 + \frac{\log\left(\frac{2.5}{3}\right)}{1 + \frac{1.624 \times 10^7}{(8+1)^{8.46}}} +$$

$$(4.22 - 0.32 \times 2.0) \log \left[\frac{650 \times 0.9 (8^{0.75} - 1.132)}{215.63 \times 3.2 \left[8^{0.75} - \frac{18.42}{\left(\frac{4 \times 10^6}{350}\right)^{0.25}} \right]} \right]$$

$$\log W_{18} = 7.01368 - 0.06 - 0.069621 + 0.050309 = 6.9343678$$

$$W_{18} = \underline{8,597,413}$$

By assuming a reliability of 50% and drawing a line along the scale of overall standard deviation, from the AASHTO design chart, $W_{18} = \underline{8.5 \times 10^6}$. Both solutions check very closely.

12-8. Given $D = 8.5$ in. and the subgrade modulus, M_R , for each month Determine the effective modulus, k_{eff} , by assuming $k = M_R / 19.4$

$$U_r = (D^{0.75} - 0.39 k^{0.25})^{3.24}$$

The computed k and U_r are listed below:

Month	MR (psi)	k (pci)	Ur (%)
JAN	15,900	819.6	31.2
FEB	27,300	1407.2	21.8
MAR	38,700	1994.8	16.4
APR	50,000	2577.3	12.9
MAY	900	46.4	86.4
JUN	1,620	83.5	75.5
JUL	2,340	120.6	68.5
AUG	3,060	157.7	63.2
SEP	3,780	194.8	59.0
OCT	4,500	232.0	55.6
NOV	4,500	232.0	55.6
DEC	4,500	232.0	55.6
		Sum	601.8

$$\bar{U}_r = 60.18/12 = 50.15 \quad 50.15 = [8.5^{0.75} - 0.39 (k_{\text{eff}})^{0.25}]^{3.24} \text{ or } k_{\text{eff}} = \underline{305 \text{ pci}}$$

12-9. Same as Problem 12-8 except that the relationship between M_R and k is

$$k = 0.95 \left(\frac{E_f}{E} \right)^{\frac{1}{3}} \frac{E_f}{(1 - \nu_f^2) h}$$

with $E = E_c = 4 \times 10^6$, $\nu_f = 0.45$, and $h = D = 8.5$ in.

The computed k and U_r are listed below:

Month	MR (psi)	k (pci)	Ur (%)
JAN	15,900	353.0	47.3
FEB	27,300	725.7	33.4
MAR	38,700	1155.6	25.1
APR	50,000	1626.2	19.5
MAY	900	7.7	115.3
JUN	1,620	16.8	103.6
JUL	2,340	27.4	95.6
AUG	3,060	39.2	89.4
SEP	3,780	52.0	84.4
OCT	4,500	65.6	80.1
NOV	4,500	65.6	80.1
DEC	4,500	65.6	80.1
		Sum	853.9

$$\bar{U}_r = 853.9/12 = 71.16 \quad 71.16 = [8.5^{0.75} - 0.39 (k_{\text{eff}})^{0.25}]^{3.24} \text{ or } k_{\text{eff}} = \underline{105 \text{ pci}}$$

12-10.

(a) Determine thickness of slab

Given $K = 75 \text{ pci}$, $E_c = 4 \times 10^6 \text{ psi}$, $S_c = 650 \text{ psi}$, $J = 2.9$
 $C_d = 1.05$, $R = 95\%$, $S_o = 0.3$, $ESAL = 10 \times 10^6$,
 and $\Delta PSI = 2$, from Figure 12.17

Thickness of slab $D = 9.5 \text{ in.}$

(b) Determine number of No. 5 bar per 12-ft lane

Given $D = 9.5 \text{ in.}$, wheel load due to construction traffic = 18,000 lb, and $K = 75$, from Fig. 12.22

$$S_w = 235 \text{ psi}$$

The minimum amount of steel P_{min} must satisfy the following three criteria: $\bar{X} < 8 \text{ ft}$, $CW < 0.04 \text{ in.}$, and

$$S_s < 62,000 \text{ psi}$$

Given $f_t = 0.86 S_c = 559 \text{ psi}$, $\alpha_s = 5 \times 10^{-6} / ^\circ\text{F}$,

$\alpha_c = 3.8 \times 10^{-6} / ^\circ\text{F}$ (Limestone coarse aggregate, see Table 12.23)

$$\phi = \frac{5}{8} \text{ in.} = 0.625 \text{ in.} \quad Z = 0.00036 \text{ (see Table 12.2)}$$

$$P_{min} = \frac{1.062 (1 + \frac{559}{1000})^{1.457} (1 + \frac{5 \times 10^{-6}}{2 \times 3.8 \times 10^{-6}})^{0.25} (1 + 0.625)^{0.476}}{(8)^{0.217} (1 + \frac{235}{1000})^{1.13} (1 + 1000 \times 0.00036)^{0.389}} - 1$$

$$= \frac{2.8997}{2.2465} - 1 = 0.29 \%$$

From Eq. 12.34 (based on $CW = 0.04 \text{ in.}$)

$$P_{min} = \frac{0.358 (1 + \frac{559}{1000})^{1.435} (1 + 0.625)^{0.484}}{(0.04)^{0.220} (1 + \frac{235}{1000})^{1.079}} - 1$$

$$= \frac{0.8564}{0.6186} - 1 = 0.38 \%$$

From Eq. 12.35 (Based on $G_s = 62,000$ psi, $DT_D = 60^\circ\text{F}$)

$$P_{\min} = \frac{50.834 \left(1 + \frac{60}{100}\right)^{0.155} \left(1 + \frac{559}{1000}\right)^{1.493}}{(62,000)^{0.365} \left(1 + \frac{235}{1000}\right)^{1.146} (1 + 1000 \times 0.00036)^{0.180}} - 1$$
$$= \frac{106.099}{75.563} - 1 = 0.40\%$$

Use $P_{\min} = \underline{0.4\%}$

The maximum amount of steel P_{\max} should be based on a crack spacing not less than 3.5 ft.

From Eq. 12.33 (Based on $\bar{X} = 3.5$ ft)

$$P_{\max} = \frac{1.062 (1.559)^{1.435} (1.658)^{0.25} (1.625)^{0.476}}{(3.5)^{0.217} (1.235)^{1.13} (1.36)^{0.389}} - 1$$
$$= \frac{2.8716}{1.8776} - 1 = \underline{0.53\%}$$

$$N_{\min} = 0.01273 \times 0.4 \times 12 \times 12 \times 9.5 / (0.625)^2 = 17.8$$

Use a minimum of 18 bars per 12-ft lane

$$N_{\max} = 0.01273 \times 0.53 \times 12 \times 12 \times 9.5 / (0.625)^2 = 23.6$$

Use a maximum of 24 bars per 12-ft lane.

Calculation of Pavement Thickness

Project Problem 12-11

Trial thickness 8.5 in

Doweled joints: yes no

Subbase-subgrade k 150 pci

Concrete shoulder: Yes no

Modulus of rupture, MR 650 psi

Design period 20 years

Load safety factor, LSF 1.2

Axle load kips	Multiplied by LSF	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue damage %	Allowable repetitions	Erosion damage %
1	2	3	4	5	6	7

8. Equivalent stress 234 10. Erosion

Single Axles

9. Stress ratio factor 0.36 factor 2.73

30	36	227	2400	9.5	610,000	0.0
28	33.6	429	8000	5.4	850,000	0.1
26	31.2	900	23,000	3.9	1,400,000	0.1
24	28.8	2632	52,000	5.1	2,100,000	0.1
22	26.4	3966	300,000	1.3	2,400,000	0.2
20	24.0	8249	4,000,000	0.2	7,000,000	0.1
18	21.6	12,705	-		14,000,000	0.1
16	19.2	16,074	-		39,000,000	0.0
14	16.8	24,111	-		-	
12	14.4	91,949	-		-	

11. Equivalent stress 208 13. Erosion

Tandem Axles

12. Stress ratio factor 0.32 factor 2.90

52	62.4	601	190,000	0.3	430,000	0.1	
48	57.6	1470	800,000	0.2	630,000	0.2	
44	52.8	4046	10,000,000	0	1,000,000	0.4	
40	48.0	10,765	-		1,900,000	0.6	
36	43.2	28,415	-		3,800,000	0.7	
32	38.4	52,350	-		8,000,000	0.7	
28	33.6	61,235	-		20,000,000	0.3	
24	28.8	36,644	-		100,000,000	0	
20	24	43,413	-		-		
16	19.2	50,183	-		-		
				Total	25.9	Total	3.7

Calculation of Pavement Thickness

Project Problem 12-12

Trial thickness 7 in. Doweled joints: yes no

Subbase-subgrade k 150 pci Concrete shoulder: yes no

Modulus of rupture, MR 650 psi Design period 20 years

Load safety factor, LSF 1.2

Axle load, kips	Multiplied by LSF	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue, percent	Allowable repetitions	Damage, percent
1	2	3	4	5	6	7

8. Equivalent stress 248 10. Erosion factor 2.54

9. Stress ratio factor 0.382

Single Axles

30	36	228	730	31.2	150,000	0.15
28	33.6	430	2,600	16.5	220,000	0.20
26	31.2	900	7,800	11.5	320,000	0.28
24	28.8	2,636	30,000	8.8	1,520,000	0.51
22	26.4	3,971	100,000	4.0	1,000,000	0.40
20	24.0	8,261	600,000	1.4	2,500,000	0.33
18	21.6	12,723			7,000,000	0.18
16	19.2	16,097				
14	16.8	24,146				
12	14.4	92,082				

11. Equivalent stress 210 13. Erosion factor 2.62

12. Stress ratio factor 0.323

Tandem Axles

52	62.4	602	140,000	0.43	180,000	0.33
48	57.6	1,472	700,000	0.21	280,000	0.53
44	52.8	4,052			500,000	0.81
40	48.0	10,781			1,000,000	1.07
36	43.2	28,446			2,000,000	1.42
32	38.4	52,425			10,000,000	0.52
28	33.6	61,324				
24	28.8	39,697				
20	24.0	43,476				
16	19.2	50,255				
			Total	<u>74.0</u>	Total <u>6.7</u>	

Chapter 13
Design of Overlays

13-1.

(a) With mean pavement temperature of 80°F and a granular base of 12 in., from Fig. 13.3 $F = 0.95$

Given $\bar{\delta} = 0.034$ in. and $S = 0.0041$ in., from Eq. 13.7

$$\delta_{\text{rrd}} = (0.034 + 2 \times 0.0041) \times 0.95 \times 1 = 0.04 \text{ in.}$$

With $\text{ESAL} = 10,000,000$, from Fig. 13.5,

HMA overlay thickness = 4.5 in. (By design chart)

(b) Check by Eqs. 13.9 and 13.10

$$E_2 = \frac{1.5 \times 70 \times 6.4}{0.04} = 16,800 \text{ psi} \quad \text{From Eq. 13.9}$$

$$\begin{aligned} \delta_a &= \frac{1.5 \times 70 \times 6.4}{16,800} \left(\left\{ 1 - \left[1 + 0.8 \left(\frac{4.5}{6.4} \right)^2 \right]^{-0.5} \right\} \times \frac{16,800}{500,000} \right. \\ &\quad \left. + \left\{ 1 + \left[0.8 \times \frac{4.5}{6.4} \left(\frac{500,000}{16,800} \right)^{\frac{1}{3}} \right]^2 \right\}^{-0.5} \right) \\ &= 0.04 (0.00516 + 0.4996) = 0.02011 \end{aligned}$$

From Eq. 13.10

$$\log 0.02011 = \log 1.0363 - 0.2438 \log \text{ESAL}$$

$\text{ESAL} = 10,529,707$, which is slightly greater than the 10,000 given, so the use of 4.5 in. is satisfactory. If the computed ESAL is smaller than 10,000,000, a larger thickness by trial and error should be used.

13-2.

Given $\delta_{\text{rrd}} = 0.055$ in., from Eq. 13.11

$$(\text{ESAL})_r = \left(\frac{1.0363}{0.055} \right)^{4.1017} = 169,891$$

Given annual growth rate of 6% and a design period of 5 years, from Table 6.13, growth factor = 5.64

$$\text{From Eq. 13.12, } (ESAL)_0 = \frac{167,891}{5.64} = \underline{30,123}$$

13-3

Given a slab length of 10 ft and a temperature differential of 80°F, from Figure 13.7, a minimum overlay thickness of 4 in. should be used.

$$\begin{aligned} \text{Deflection after overlay} &= 0.0007 - 4 \times 0.05 \times 0.0007 \\ &= 0.00056 \quad (\text{Assume each inch of HMA can reduce} \\ &\quad \text{deflection by 20\%}) \end{aligned}$$

Because the deflection is less than 0.0006 in., no undersealing is required.

13-4 (a) Bonded Case

$$\begin{aligned} \bar{f}_c &= \frac{1}{12} (500 + 453 + 554 + 450 + 513 + 488 + 512 \\ &\quad + 468 + 532 + 520 + 420 + 556) = 497.2 \text{ psi} \\ \sqrt{[f_c]} &= \sqrt{[(2.8)^2 + (44.2)^2 + (56.8)^2 + (47.2)^2 + (15.8)^2 \\ &\quad + (9.2)^2 + (14.8)^2 + (29.2)^2 + (34.8)^2 + (22.8)^2 + (77.2)^2 \\ &\quad + (58.8)^2]} / 11 = 1814.76 \\ S &= \sqrt{1814.76} = 42.6 \text{ psi} \end{aligned}$$

From Eq. 13.13

$$f_{te} = 497.2 - 1.65 \times 42.6 = 426.9 \text{ psi}$$

$$\text{From Eq. 13.14 } S_c = 1.45 \times 0.9 \times 426.9 = 557 \text{ psi}$$

So curve 1 in Fig. 13.14 should be used.

From Fig. 13.14, Combined thickness = 11.5 in.

So thickness of bonded overlay = $11.5 - 8 = \underline{3.5}$ in.

(b) Unbonded case

Use Fig. 13.12 for case 3 (existing pavement in good condition) overlay thickness = 9 in.

13-5.

(a) Determine SN_f for new pavement From Eq. 13.22

$$M_R = \frac{0.24 \times 9000}{0.00608 \times 36} = 9868 \text{ psi} \quad M_R = 0.33 \times 9868 = 3257 \text{ psi}$$

Given $R = 95\%$, $S_o = 0.45$, $ESAL = 100,000$, $M_R = 3.3 \text{ ksi}$

and $\Delta PSI = 4.2 - 2.5 = 1.7$, from Fig. 11.25

$SN_f = 3.4$ (For more accurate results, solve Eq. 11.37 by trial and error, and $SN_f = \underline{3.47}$)

(b) Determine D_{OL} by NDT method

Given $d_o = 16.1 \text{ mil}$, $M_R = 9868 \text{ psi}$, $P = 9000 \text{ lb}$,

and $D = 7.5 \text{ in.}$, $M_R d_o / P = 9868 \times 16.1 / 9000 = 17.7$

From Fig. 13.17, $E_p / M_R = 50$ or $E_p = 9868 \times 50$

$= 493,400 \text{ psi}$. From Eq. 13.26

$SN_{eff} = 0.0045 \times 7.5 \sqrt[3]{493,400} = 2.67$. From Eq. 13.32,

$$D_{OL} = \frac{3.47 - 2.67}{0.44} = 1.82 \text{ in. use } \underline{1.9} \text{ in.}$$

(c) Determine D_{OL} by condition survey

$$SN_{eff} = 0.35 \times 1.5 + 0.25 \times 6 = 2.03$$

$$D_{OL} = \frac{3.47 - 2.03}{0.44} = 3.27 \text{ in. use } \underline{3.3} \text{ in.}$$

(d) Determine D_{OL} by remaining life

$$SN = 0.44 \times 1.5 + 0.33 \times 6 = 2.64 \quad \text{From Eq. 11.37}$$

$$\begin{aligned} \log N_{1.5} &= 0 + 9.36 \log(2.61 + 1) - 0.2 + 0 + 2.32 \log 3257 - 8.07 \\ &= 5.218 - 0.2 + 8.150 - 8.07 = 5.098 \end{aligned}$$

$$N_{1.5} = 125.314 \quad \text{From Eq. 13.30}$$

$$RL = 100 \left(1 - \frac{95,000}{125,314} \right) = 24.19 \quad \text{From Fig. 13.23}$$

$$CF = 0.78 \quad \text{From Eq. 13.31} \quad SN_{\text{eff}} = 0.78 \times 2.64 = 2.06$$

$$D_{OL} = \frac{3.47 - 2.06}{0.44} = \underline{3.2 \text{ in.}}$$

13-6.

$$(a) \text{ From Eq. 13.22 } M_R = \frac{0.24 \times 9000}{0.0027 \times 36} = 22,222 \text{ psi}$$

$$\text{With } M_R d_o / p = 22,222 \times 4.1 / 9000 = 10.12 \text{ and } D = 16 \text{ in.}$$

$$\text{From Fig. 13.17, } E_p / M_R = 39 \text{ or } E_p = 39 \times 22,222 = 866,658 \text{ psi}$$

$$\text{With } \frac{d_o M_R}{8a} = \frac{0.0041 \times 22,222}{\frac{9000}{\pi(5.9)^2} \cdot 5.9} = 0.188 \text{ and } \frac{D}{a} = \frac{16}{5.9} = 2.71$$

$$\text{From Fig. 13.20 } E_p / M_R = 50 \text{ or } E_p = 50 \times 22,222 = \underline{1,111,100 \text{ psi}}$$

$$(b) \text{ With } C = 0.167, M_R = 0.167 \times 22,222 = 3711 \text{ psi}$$

$$\text{With } R = 95\%, S_o = 0.49, W_{18} = 6,700,000, M_R = 3711 \text{ psi,}$$

$$\text{and } \Delta PSI = 2.0, \text{ from Fig. 11.25 } SN_s = \underline{6}$$

$$(c) SN_{\text{eff}} = 0.25 \times 10 + 0.05 \times 6 = 2.8$$

$$D_{OL} = \frac{6.0 - 2.8}{0.44} = 7.27 \text{ in. Use } \underline{7.3 \text{ in.}}$$

13-7 (a) Determine E_c and Static K -value

$$\text{AREA} = 6 \left[1 + 2 \left(\frac{4.5}{5.2} \right) + 2 \left(\frac{3.5}{5.2} \right) + \frac{2.9}{5.2} \right] = 27.81$$

From Fig. 13.21, dynamic $K = 300 \text{ pci}$, so

Static $K = 150 \text{ pci}$, From Fig 13.22, with $K = 300 \text{ pci}$

$$E_c D^3 = 1.75 \times 10^9 \quad E_c = \frac{1.75 \times 10^9}{8^3} = \underline{3.4 \times 10^6} \text{ psi}$$

(b) Determine D_{OL}

$$\text{From Eq. 7.56a} \quad S_c = \frac{43.5 \times 3.4 \times 10^6}{106} + 488.5 = 636.4 \text{ psi}$$

With $K = 150 \text{ pci}$ $E_c = 3.4 \times 10^6$, $S_c = 636 \text{ psi}$, $J = 2.2$,

$C_d = 1$, $\Delta \text{PSI} = 2.0$, $R = 95\%$, $S_o = 0.3$, and $W_{18} = 80 \times 10^6$

from Fig. 12.17 $D_f = 11.6 \text{ in.}$ $D_{\text{eff}} = 8 \times 0.95 \times 0.95 = 7.22 \text{ in.}$

$$D_{OL} = 11.6 - 7.22 = 4.38 \text{ in. of PCC.}$$

$$\text{From Eq. 13.36} \quad A = 2.2233 + 0.0099 \times (438)^2 - 0.1534 \times 438$$

$$= 1.741 \quad D_{OL} = 1.741 \times 4.38 = \underline{7.6} \text{ in.}$$

13-8. From Eq. 13.37, with $F_{jc} = 0.8$, $F_{aur} = 0.8$, and $F_{ac} = 0.85$

$$D_{\text{eff}} = 0.8 \times 0.8 \times 7 + (3 - 0.75) \times 0.5 \times 0.85 = 5.44 \text{ in.}$$

With $K = 362/2 = 181 \text{ pci}$, $E_c = 2.1 \times 10^6 \text{ psi}$, $J = 2.6$, $C_d = 1$

$$S_c = \frac{43.5 \times 3.1 \times 10^6}{106} + 488.5 = 623 \text{ psi}, \Delta \text{PSI} = 2$$

$R = 95\%$, $S_o = 0.35$, and $W_{18} = 1,000,000$, from Fig. 12.17

$$D_f = 9.5 \text{ in.}$$

$$D_{OL} = 9.5 - 5.44 = 4.06$$

$$A = 2.2233 + 0.0099 (4.06)^2 - 0.1534 \times 4.06 = 1.764$$

$$D_{OL} = 1.764 \times 4.06 = 7.16 \text{ in. Use } \underline{7.2} \text{ in.}$$

13-9. From previous problem $D_f = 9.5$ in.

$$D_{eff} = 0.9 \times 7 = 6.3 \text{ in.}$$

$$D_{OL} = \sqrt{(9.5)^2 - (6.3)^2} = 7.11 \text{ in. use } \underline{7.2 \text{ in.}}$$

13-10.

(a) Determine E_c and static K

$$AREA = 6 \left[1 + 2 \left(\frac{3.08}{3.68} \right) + 2 \left(\frac{2.64}{3.68} \right) + \frac{2.23}{3.68} \right] = 28.3$$

From Figure 13.21, with $d_o = 3.68 \times 9,000 / 8,500 = 3.9$ mil

dynamic $K = 380$ pci so static $K = \underline{190}$ pci

From Figure 13.22 $E_c D^3 = 2.5 \times 10^9$ $E_c = \underline{4.6 \times 10^6}$ psi

(b) Determine D_{OL}

With $K = 190$ pci, $E_c = 4.6 \times 10^6$ psi, $J = 4$, $C_d = 1$

$$S_c = \frac{43.5 \times 4.6 \times 10^6}{106} + 488.5 = 688.6 \text{ psi, } \Delta PSI = 2$$

and $W_{18} = 11,000,000$, $R = 95\%$ and $S_o = 0.35$,

from Fig. 12.17 $D_f = 11.6$ in.

$$D_{eff} = 8.2 \times 0.95 = 7.8 \text{ in.}$$

$$D_{OL} = 11.6 - 7.8 = \underline{3.8 \text{ in.}}$$

13-11. From previous problem $D_f = 11.6$ in.

$$D_{eff} = 0.98 \times 8.2 = 8.04 \text{ in.}$$

$$D_{OL} = \sqrt{(11.6)^2 - (8.04)^2} = 8.36 \text{ in. Use } \underline{8.4 \text{ in.}}$$

13-12.

Given $r = 36$ in. $d_r = 0.00445$ in. From Eq. 13.22

$$M_R = \frac{0.24 \times 9000}{0.00445 \times 36} = 13,483 \text{ psi}$$

With $M_R d_o / P = 13,483 \times 24.1 / 9000 = 36.1$ and

$$D = 5.5 + 12 = 17.5 \text{ in.}, \text{ from Fig. 13.17}$$

$$E_p / M_R = 3 \quad \text{or} \quad E_p = 3 \times 13,843 = 41,500 \text{ psi}$$

With $D_{SB} = 17.5$ in. From Fig. 12.18 dynamic $K = 900$ pci

Static $K = 450$ pci.

With $K = 450$ pci, $E_c = 4.2 \times 10^6$ psi, $S_c = 690$ psi

$J = 3.2$, $C_d = 1$, $\Delta PSI = 2$, $R = 95\%$, $S_o = 0.35$ and

$W_{18} = 4,200,000$, from Fig. 12.17, $D = \underline{8.3}$ in.

From Eq. 12.21

$$\begin{aligned} \log W_{18} &= -1.645 \times 0.35 + 7.35 \log(8.3+1) - 0.06 \\ &+ \frac{\log 0.6667}{1 + 1.624 \times 10^7 / (8.3+1)} 8.46 + (4.22 - 0.32 \times 2.5) \times \\ &\log \left\{ \frac{690 \times 1 (8.3^{0.75} - 1.132)}{215.63 \times 3.2 [(8.3)^{0.75} - 18.42 / (4.2 \times 10^6 / 450)]^{0.25}} \right\} \\ &= -0.576 + 7.118 - 0.06 - 0.159 + 0.327 \\ &= 6.65 \end{aligned}$$

$W_{18} = 4,466,836$ which checks with the given traffic of 4,200,000



Upper Saddle River, NJ 07458
www.prenhall.com

ISBN 0-13-184244-7



9 780131 842441



99991