Montogue

QUIZ GT504

Reviewed Solutions to Huang's *Pavement Analysis and Design*, 2nd Ed.

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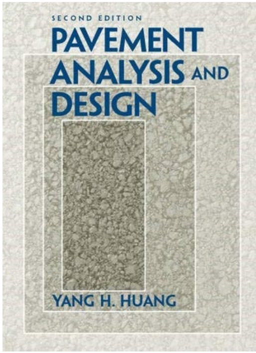
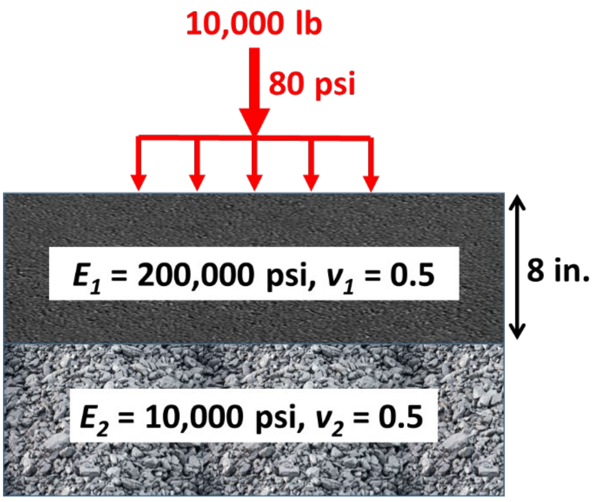


► Chapter 2: Stresses and Strains in Flexible Pavements

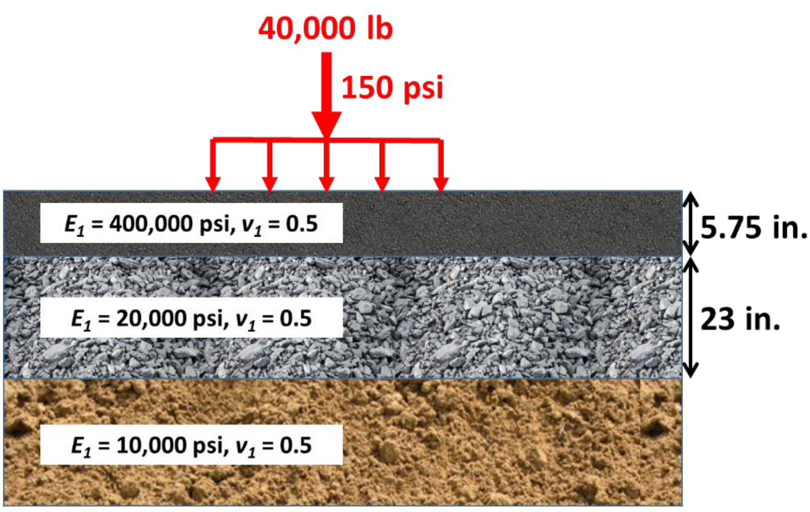
PROBLEM 2.4

A 10,000-lb wheel load exerting contact pressure of 80 psi is applied on an elastic two-layer system, as shown in Figure P2.4. Layer 1 has an elastic modulus of 200,000 psi and thickness 8 in. Layer 2 has elastic modulus of 10,000 psi. Both layers are incompressible, with Poisson ratio equal to 0.5. Assuming that the loaded area is a single circle, determine the maximum surface deflection, interface deflection, and interface stress.



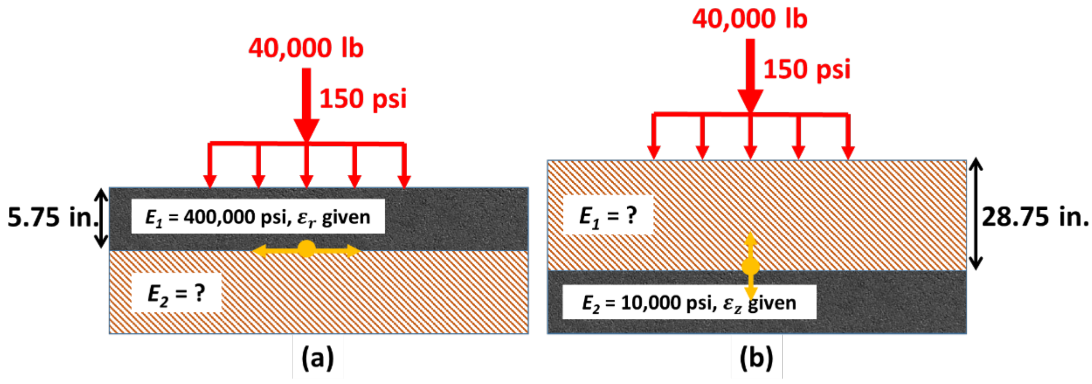
PROBLEM 2.6

Figure P2.6 shows a pavement structure composed of the following three layers: 5.75 in. HMA with elastic modulus 400,000 psi, 23 in. granular base with elastic modulus 20,000 psi, and a subgrade with elastic modulus 10,000 psi. All layers are assumed to have a Poisson ratio of 0.5. Calculate the maximum horizontal tensile strain at the bottom of HMA and the maximum vertical compressive strain on the top of subgrade under a 40,000-lb wheel load and 150-psi contact pressure, assuming that the contact area is a circle.



PROBLEM 2.7

In Problem 2-6, if the base and subgrade are combined as one layer, as shown in Figure P2.7*a*, what should be the equivalent elastic modulus of this combined layer so that the same tensile strain at the bottom of HMA can be obtained? If the HMA and base are combined as one layer with the same total thickness of 28.75 in., as shown in Figure 2.7*b*, what should be the equivalent elastic modulus of this combined layer so that the same compressive strain on the top of subgrade can be obtained?



▸ Chapter 6: Traffic Loading and Volume

PROBLEM 6.1

A set of dual tires is spaced at 34 in. center to center and carries a total load of 45,000 lb with a tire pressure of 100 psi. Assuming the pavement to be a homogeneous half-space, determine the equivalent single-wheel load (ESWL) for a pavement of 25 in. using
(*a*) The Boyd and Foster method;
(*b*) The Foster and Ahlvin method;
(*c*) Huang's chart based on equal contact radius.

PROBLEM 6.2

A full-depth asphalt pavement is loaded by a set of dual wheels, each weighing 8000 lb and spaced at 20 in. on centers. The hot mix asphalt has a thickness of 10 in. and an elastic modulus of 250,000 psi; the subgrade has an elastic modulus of 10,000 psi. Both layers are incompressible with a Poisson ratio of 0.5. If the dual wheels and the equivalent single wheel have the same contact radius of 6 in., determine the equivalent single-wheel load (ESWL) based on (*a*) equal interface deflection and (*b*) equal tensile strain at the bottom of asphalt layer.

PROBLEM 6.3

A pavement is subjected to the single-axle loads shown in Table P6.3. Determine the ESAL for a design period of 20 years using (*a*) AI's equivalent axle load factors and (*b*) the equivalent axle load factors from equation 6.23.

Axle load (kip)	Number per day	Axle load (kip)	Number per day	Axle load (kip)	Number per day
12	200.0	20	47.2	28	2.9
14	117.4	22	21.4	30	1.2
16	84.5	24	12.9	32	0.7
18	61.4	26	6.1	34	0.3

PROBLEM 6.6

Estimate the equivalent 18-kip single-axle load applications (ESAL) for a four-lane pavement (two lanes in each direction) of a rural interstate highway with a truck count of 1000 per day (including 2-axle, 4-tire panel, and pickup trucks), an annual growth rate of 5%, and a design life of 20 years.

PROBLEM 6.7

Table P6.7 is abstracted from a W-4 table on tractor semitrailer combinations for a loadometer station from July 16 to August 8. It is assumed that the traffic during the recorded period represents the average over the entire year. If the pavement to be constructed has a structural number *SN* of 5, estimate the ESAL of the tractor semitrailer combinations during the first year in two directions over all lanes based on a p_t (terminal serviceability) of 2.5.

TABLE P6.7

Axle loads (lb)	3-axle	4-axle	5-axle	Tractor semitrailer combinations probable no.
Single axle under 3000	—	—	—	—
3000–6999	256	227	60	3188
7000–7999	148	243	85	2843
8000–11,999	345	939	363	9942
12,000–15,999	174	288	54	3111
16,000–17,999	67	225	12	1899
18,000–19,000	22	141	7	1078
19,001–19,999	8	54	5	423
20,000–21,999	5	80	9	598
22,000–23,999	1	29		144
24,000–25,999	—	1	—	6
26,000–29,999	—	1	—	6
Total single axles weighed	1026	2228	595	
Total single axles counted	5541	14,526	3171	23,238
Tandem axle under 6000	—	1	—	7
6000–11,999	—	237	173	2631
12,000–17,999	—	189	209	2541
18,000–23,999	—	218	150	2362
24,000–29,999	—	270	214	3103
30,000–31,500	—	62	52	703
31,501–31,999	—	11	11	141
32,000–33,999	—	36	43	503
34,000–35,999	—	26	35	388
36,000–37,999	—	16	28	280
38,000–39,999	—	12	27	247
40,000–41,999	—	10	19	183
42,000–43,999	—	14	11	160
44,000–45,999	—	2	6	51
46,000–49,999	—	5	5	64
50,000–53,999	—	1	—	7
Total tandem axles weighed		1110	983	—
Total tandem axles counted		7263	6135	13,398
Total vehicles counted	1847	7263	3087	12,197

PROBLEM 6.8

Same as Problem 6-7 but for a rigid pavement with a concrete thickness of 9 in.

PROBLEM 6.9

Based on the axles weighted and the axles and vehicles counted, as shown in Table P6.7, determine the truck factor of all tractor semitrailer combinations for a flexible pavement with $SN = 5$ and $p_t = 2.5$.

PROBLEM 6.10

Same as Problem 6-9 but for a rigid pavement with $D = 9$.

▸ Chapter 7: Material Characterization

PROBLEM 7.5

An asphalt mixture has an asphalt content of 7% and a bulk specific gravity of 2.24. The recovered asphalt has a specific gravity is 1.02, a ring and ball softening point of 120°F, and a penetration of 50 at 77°F. The specific gravity of the aggregate is 2.61. Determine the stiffness modulus of the mixture at a temperature of 74°F and a loading time of 0.02 s by the Shell nomographs shown in Figures 7.19 and 7.20. Check the result by equation 7.25.

PROBLEM 7.6

The asphalt mixture is the same as in Problem 7.5. The mineral aggregate has 5% passing through a No. 200 sieve, and the original asphalt has a penetration of 75 at 77°F. Determine the dynamic modulus at a temperature of 74°F and a loading frequency of 8 Hz by the AI equations.

PROBLEM 7.7

The asphalt mixture in Problem 7.5 is subjected to an initial tensile strain of 0.00015. Determine the number of repetitions to failure by the nomograph shown in Figure 7.26, using constant stress and constant strain tests, respectively, and check the results by using equations 7.33 and 7.35.

PROBLEM 7.8

The asphalt mixture in Problem 7-6 is subjected to an initial strain of 0.00015. Determine the number of repetitions to failure by equations (7.36) and (7.37).

PROBLEM 7.9

The results of incremental static test on a HMA specimen are shown in Table P7.9. If the creep strain at a time duration of 0.03 s is 3.045×10^{-5}, determine the permanent deformation parameters α and μ.

Load duration (s)	0.1	1	10	100	1000
Permanent strain (10^{-5})	1.158	3.474	11.533	31.172	62.483

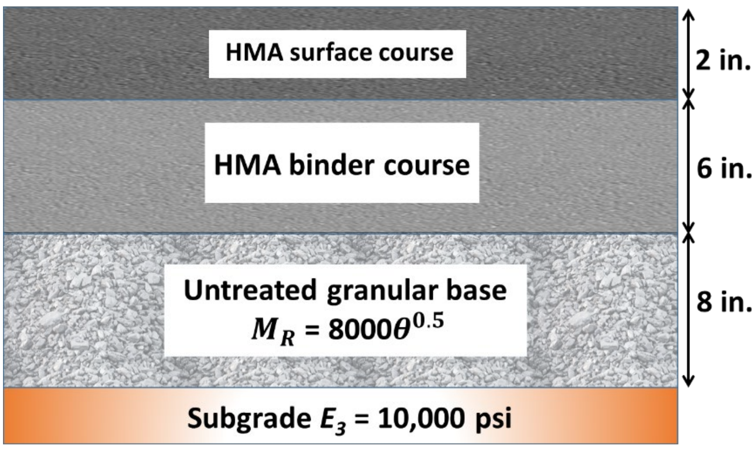
▸ Chapter 11: Flexible Pavement Design

PROBLEM 11.3

The fatigue equation for an asphalt pavement is $N_f = 5\times10^{-6}(\varepsilon_t)^{-3}$, where ε_t is the tensile strain. If the pavement is subjected to 5000 thermal cycles with a maximum tensile strain of 0.0005 in./in. and the coefficient of variation of N_f, $C[N_f]$, is 0.8, estimate the percent area cracked that is due to thermal fatigue cracking.

PROBLEM 11.4

Figure P11.4 shows an asphalt pavement with the thickness and the resilient moduli of the granular base and subgrade as indicated. The hot mix asphalt has a viscosity of 2.5×10^6 poise at 70°F, a bitumen volume of 11%, and a fine content of 5% passing No. 200, and is subjected to a loading frequency of 8 Hz. The air void content is 4% for the surface course and 7% for the binder course. The mean monthly air temperature is 68°F. By the Asphalt Institute procedure, as used in the DAMA program, determine (*a*) temperatures for surface and binder courses using equation (3.27); (*b*) dynamic moduli of surface and binder courses using equation (7.27); and (*c*) the modulus of the untreated base using equations (3.28) and (3.29).



PROBLEM 11.5

A six-lane (three in each direction) rural interstate highway has a truck count of 1885 per day (including two-axle, four-tire panel and pickup trucks) and an annual growth rate of 4%. The HMA will be laid on an untreated granular base, 8 in. thick, which is placed on a subgrade with a resilient modulus of 10,000 psi. (*a*) Referring to Tables 6.9 and 6.10, estimate the equivalent single-axle load (ESAL) for a design period of 20 years by the Asphalt Institute method. (*b*) Determine the HMA thickness required by the Asphalt Institute method. (*c*) If part of the HMA is replaced by emulsified asphalt mix type I, determine the thickness of HMA and of emulsified asphalt required.

PROBLEM 11.9

A 12-in. full-depth asphalt pavement is placed on a subgrade with an effective roadbed resilient modulus of 10,000 psi. Assuming a layer coefficient of 0.44 for the hot mix asphalt, a drop in PSI from 4.2 to 2.5, an overall standard deviation of 0.5, and a predicted ESAL of 3×10^7, determine the reliability of the design by the AASHTO equation, and check the result by the AASHTO design chart.

PROBLEM 11.10

An interstate highway pavement composed of a HMA surface course, a cement treated base course, and a sand-gravel subbase is to be designed for an ESAL of 1.2×10^6. The quality of drainage is considered fair because water can be removed from the subbase within a week. However, there is a large amount of precipitation, so more than 25% of the time the pavement will be exposed to moisture levels approaching saturation. The material properties are as follows: effective roadbed soil resilient modulus = 5500 psi, resilient modulus of subbase = 15,000 psi, unconfined compressive strength of cement-treated at 7 days = 500 psi (see Figure 7.15*c* for correlation), and resilient modulus of HMA = 4.3×10^5 psi. Assuming a minimum thickness for HMA, determine the thickness of the surface, base, and subbase courses required.

► Chapter 12: Rigid Pavement Design

PROBLEM 12.1

A 10-in. concrete pavement without concrete shoulders is placed on an untreated subbase having the *k* value 150 pci. Estimate the allowable corner deflection by the PCA erosion criterion if the pavement is subjected to 2 million applications of a given axle load.

PROBLEM 12.2

Same as Problem 12-1, but with concrete shoulders. Estimate the allowable corner deflection.

PROBLEM 12.3

Determine the thickness of a concrete pavement for a two-lane highway by the PCA method. The pavement has doweled joints and no concrete shoulders. The modulus of subgrade reaction is 200 pci and the concrete modulus of rupture is 650 psi. Assume a load safety factor of 1.1 and a design period of 20 years. The average daily traffic during the design period is 2500, of which 35% are trucks. Truck weight distribution data for single (*S*) and tandem (*T*) loads are tabulated in Table P12.3.

Axle loads (kip)	No. axles per 1000 trucks	Axle loads (kip)	No. axles per 1000 trucks
16 *S*	130.9	24 *T*	80.2
18 *S*	110.8	28 *T*	34.4
20 *S*	65.4	32 *T*	24.0
22 *S*	15.6	36 *T*	17.2
24 *S*	2.3	40 *T*	16.8
26 *S*	1.9	44 *T*	10.5
28 *S*	0.9	48 *T*	9.6

PROBLEM 12.4

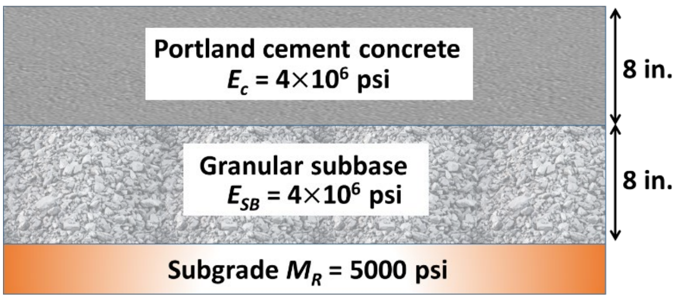
A concrete pavement has doweled joints and tied concrete shoulders. Given a concrete modulus of rupture of 650 psi, a modulus of subgrade reaction of 150 pci, a load safety factor of 1.2, a design period of 20 years, an average daily truck traffic of 3460 (excluding all two-axle, four-tire trucks) on the design lane during the design life, and an axle load distribution shown by category 3 in Table 12.13. Determine the slab thickness by the PCA method using the procedure similar to the worksheet shown in Figure 12.15. Check the result by the simplified procedure using Table 12.15.

PROBLEM 12.5

Same as Problem 12-4, but with no concrete shoulders. Determine the slab thickness by the regular PCA procedure, and check the result with the simplified procedure.

PROBLEM 12.7

Figure P12.7 shows a concrete pavement with the thicknesses and elastic moduli as indicated. Assume a modulus of rupture of 650 psi, a load transfer coefficient of 3.2, a serviceability loss from 4.5 to 2.0, and poor drainage with 5% of time near saturation. Determine the performance traffic by equation (12.21) without the reliability term and check the result by the AASHTO design chart.



PROBLEM 12.8

A 8.5-in. (216-mm) concrete slab is placed directly on a subgrade. The relationship between the resilient modulus and *k* value is indicated by equation (12.22). The monthly subgrade resilient moduli from January to December are tabulated below. Determine the effective modulus of subgrade reaction.

Month	Subgrade resilient modulus	Month	Subgrade resilient modulus
January	15,900	July	2340
February	27,300	August	3060
March	38,700	September	3780
April	50,000	October	4500
May	900	November	4500
June	1620	December	4500

PROBLEM 12.9

Same as Problem 12-8, except that the relationship between the resilient modulus and *k* is indicated by equation (5.7). Assuming that the concrete has an elastic modulus of 4,000,000 psi and a Poisson ratio of 0.15 and the subgrade has a Poisson ratio of 0.45, determine the effective modulus of subgrade reaction.

▸ SOLUTIONS

P.2.4 ■ Solution

We first determine the radius of the loaded area,

$$\frac{10,000}{\pi a^2} = 80 \rightarrow a = \sqrt{\frac{10,000}{\pi \times 80}} = 6.31\,\text{in.}$$

Now, the vertical surface deflection is given by

$$w_0 = \frac{1.5qa}{E_2} F_2$$

where F_2 is the deflection factor, which is a function of the ratio of Young moduli, E_1/E_2, and the dimension ratio, h_1/a, as shown in Fig. 2.17. In the case at hand,

$$\frac{E_1}{E_2} = \frac{200,000}{10,000} = 20 \;\; ; \;\; \frac{h_1}{a} = \frac{8}{6.31} = 1.27$$

so that F_2 can be read to be ~0.34. Substituting in the formula for w_0 brings to

$$w_0 = \frac{1.5 \times 80 \times 6.31}{10,000} \times 0.34 = \boxed{0.0257\,\text{in.}}$$

The vertical surface deflection is close to 0.026 inches.

Next, to compute the vertical interface deflection, we write

$$w = \frac{qa}{E_2} F$$

Here, F can be determined from Figure 2.19. Since there is no chart for a Young moduli ratio E_1/E_2 = 20, the best we can do is to interpolate the values of F read from the chart for E_1/E_2 = 25 and the chart for E_1/E_2 = 10. First, we enter h_1/a = 1.27 and r/a = 0 into the chart for E_1/E_2 = 10 to read F = 0.59. Then, we enter the same ratio into the chart for E_1/E_2 = 25 to read F = 0.43. Interpolating between the two results, we obtain F = 0.483.

E_1/E_2	F
10	0.59
25	0.43
20	0.483 (interpolated)

We are now in position to compute the interface deflection,

$$w = \frac{qa}{E_2} F = \frac{80 \times 6.31}{10,000} \times 0.483 = \boxed{0.0244\,\text{in.}}$$

The interface deflection is close to 0.024 inches.

Next, we compute the vertical interface stress σ_c. The ratio σ_c/q can be read by entering a/h_1 = 6.31/8 = 0.789 and the Young moduli ratio E_1/E_2 into Figure 2.15. There is no curve for E_1/E_2 = 20, so the best we can do is interpolate between the curves for E_1/E_2 = 10 and E_1/E_2 = 25. The results are tabulated below.

E_1/E_2	F
10	0.22
25	0.13
20	0.160 (interpolated)

Accordingly,

$$\frac{\sigma_c}{q} = 0.16 \rightarrow \sigma_c = 0.16q$$

$$\therefore \sigma_c = 0.16 \times 80 = \boxed{12.8\,\text{psi}}$$

P.2.6 ■ Solution

First of all, a is given by

$$a = \sqrt{\frac{40,000}{\pi \times 150}} = 9.21\,\text{in.}$$

We proceed to determine k_1, k_2, A, and H,

$$k_1 = \frac{E_1}{E_2} = \frac{400,000}{20,000} = 20\ ;\ k_2 = \frac{E_2}{E_3} = \frac{20,000}{10,000} = 2$$

$$A = \frac{a}{h_2} = \frac{9.21}{23} = 0.400\ ;\ H = \frac{h_1}{h_2} = \frac{5.75}{23} = 0.25$$

With k_1 = 20 and k_2 = 2, we refer to Figure 2.31(c) and read (*RR1* – *ZZ1*)/2 = 2.0. Using eq. (2.25), the radial strain is calculated as

$$\varepsilon_r = -\frac{q}{E}\underbrace{\left(\frac{RR1 - ZZ1}{2}\right)}_{=2.0} = \frac{150}{40,0000} \times 2.0 = \boxed{-7.5 \times 10^{-4}}$$

One could make use of Table 2.3 instead. Entering k_1 = 20, k_2 = 2, H = 0.25, and A = 0.4, we obtain (*ZZ1* – *RR1*) = 3.86779. It follows that

$$\varepsilon_r = -\frac{150}{40,0000} \times \left(\frac{3.86779}{2}\right) = \boxed{-7.25 \times 10^{-4}}$$

There is little difference relatively to the result obtained graphically.

0.04381	0.00530	0.63215	0.00962	0.00909
0.14282	0.02091	1.83766	0.03781	0.03269
0.37882	0.07933	3.86779	0.14159	0.10684
0.75904	0.26278	5.50796	0.44710	0.30477
0.98743	0.61673	4.24281	0.90115	0.66786
1.00064	0.91258	1.97494	0.93254	0.98447

Also from Table 2.3, we read *ZZ2* – *RR2* = 0.14159, giving

$$\sigma_{z2} - \sigma_{r2} = q\left(ZZ2 - RR2\right) = 150 \times 0.14159 = 21.2\,\text{psi}$$

so that

$$\sigma_{z2} - \sigma'_{r2} = \frac{\sigma_{z2} - \sigma_{r2}}{k_2} = \frac{21.2}{2} = 10.6\,\text{psi}$$

The corresponding compressive strain is

$$\varepsilon_z = \frac{\sigma_{z2} - \sigma'_{r2}}{E_3} = \frac{10.6}{10,000} = \boxed{1.06 \times 10^{-3}}$$

P.2.7 ■ Solution

From the previous problem, $\varepsilon_r = -7.25\times10^{-4}$, $\varepsilon_z = 1.06\times10^{-3}$, and a = 9.21 in. The base and subgrade are combined as one layer. We first solve equation (2.17) for strain factor F_e,

$$e = \left|\varepsilon_r\right| = \frac{q}{E_1}F_e \to F_e = \frac{\varepsilon_r E_1}{q}$$

$$\therefore F_e = \frac{\left|\varepsilon_r\right| E_1}{q} = \frac{\left(7.25 \times 10^{-4}\right) \times 400,000}{150} = 1.93$$

Further, h_1/a = 5.75/9.21 = 0.624. From Figure 2.17, E_1/E_2 = 20, so that

$$E_2 = \frac{E_1}{20} = \frac{400,000}{20} = \boxed{20,000\,\text{psi}}$$

In the second combination of layers, trial-and-error can be used to yield E_1 = 35,000 psi. Indeed, when E_1 = 35,000 psi, and noting that $\varepsilon_r = 0.5\varepsilon_z$ = 0.5 × 0.00106 = 0.00053, we have

$$F_e = \frac{0.00053 \times 35,000}{150} = 0.124$$

Further, h_1/a = 28.75/9.21 = 3.12. Entering the two foregoing results into Figure 2.21, we read E_1/E_2 = 3.5, giving

$$E_1 = 3.5E_2 = 3.5 \times 10,000 = \boxed{35,000\,\text{psi}}$$

P.6.1 ■ Solution

In the Boyd and Foster method, the ESWL is computed with equation (6.1),

$$\log(\text{ESWL}) = \log P_d + \frac{0.301\log(2z/d)}{\log(4S_d/d)}$$

In the present case, the load on one of the dual tires is P_d = 45,000/2 = 22,500 lb; the pavement thickness is z = 25 in.; the center-to-center spacing between dual tires is S_d = 34 in.; and the clearance between dual tires is $d = S_d - 2a$, where

$$a = \sqrt{\frac{P_d}{\pi p}} = \sqrt{\frac{(45,000/2)}{\pi \times 100}} = 8.46\,\text{in.}$$

so that

$$d = S_d - 2a = 34 - 2 \times 8.46 = 17.1\,\text{in.}$$

Accordingly,

$$\log(\text{ESWL}) = \log(22,500) + \frac{0.301\log(2 \times 25/17.1)}{\log(4 \times 34/17.1)} = 4.51$$

Resolving the logarithm,

$$\log(\text{ESWL}) = 4.51 \rightarrow ESWL = 10^{4.51}$$

$$\therefore ESWL = 10^{4.51} = \boxed{32,400\,\text{lb}}$$

Point No.	Left wheel		Right wheel		Sum
	r/a	*F**	*r/a*	*F**	
1	0	0.48	4	0.22	0.70
2	1	0.42	3	0.27	0.69
3	2	0.35	2	0.35	0.70
*Values read from Figure 2.6 with z/a = 25/8.46 = 2.96.					

Noting that F_d = 0.70 (red cell in the table above) and F_s = 0.48 (blue cell), we resort to equation (6.6) to obtain

$$ESWL = \frac{F_d}{F_s}P_d = \frac{0.70}{0.48} \times 22,500 = \boxed{32,800\,\text{lb}}$$

We now turn to the solution by Huang's method. Since the chart in Figure 6.4 is designed for a tire spacing different from 48 in. and a contact radius different from 16 in., we must apply the alternative method recommended in Figure 6.4. We first compute the corrected values

$$a' = \frac{48}{S_d} a = \frac{48}{34} \times 8.46 = 11.9\,\text{in.}$$

$$h_1' = \frac{48}{S_d} h_1 = \frac{48}{34} \times 25 = 35.3\,\text{in.}$$

Further, E_1/E_2 = 1. Entering this ratio and h_1' into Figure 6.4, we read L_1 = 1.40 (upper chart) and L_2 = 1.34 (lower chart). Substituting into equation (6.10) brings to

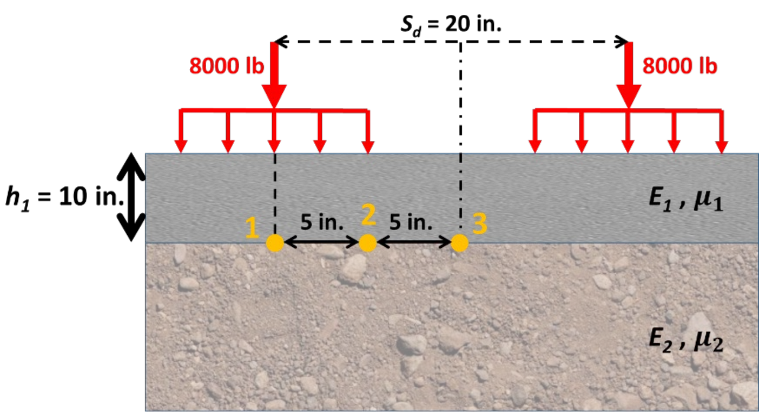
$$L = L_1 - (L_1 - L_2)\frac{a'-6}{10} = 1.40 - (1.40 - 1.34) \times \frac{11.9-6}{10} = 1.36\,\text{in.}$$

so that, from equation (6.7*b*),

$$ESWL = \frac{2P_d}{L} = \frac{2 \times 22,500}{1.36} = \boxed{33,100\text{ lb}}$$

P.6.2 ■ Solution

Let us first analyze the problem per the equal interface deflection criterion. The upper layer, which is constituted of hot mix asphalt, has thickness h_1 = 10 in, whence we have the ratio h_1/a = 10/6 = 1.67. Further, E_1/E_2 = 250,000/10,000 = 25. Refer to the illustration below.



At point 1, which is directly below the central axis of the left wheel, we have r = 0 and r/a = 0. Entering this ratio and h_1/a = 1.67 into the chart of Figure 2.19 corresponding to E_1/E_2 = 25, we read F = 0.35. Proceeding similarly with other points, we draw up the following table.

Point No.	Left wheel		Right wheel		Sum
	r/a	F*	r/a	F*	
1	0/6 = 0	0.35	20/6 = 3.33	0.23	0.58
2	5/6 = 0.833	0.32	15/6 = 2.5	0.29	0.61
3	10/6 = 1.67	0.3	10/6 = 1.67	0.3	0.61
*Values read from Figure 2.19 with h_1/a = 1.67 and E_1/E_2 = 25.					

Accordingly, F_d = 0.61 and F_s = 0.35, so that, from equation (6.6),

$$ESWL = \frac{F_d}{F_s} P_d = \frac{0.61}{0.35} \times 8000 = \boxed{13,900\,\text{lb}}$$

Next, we assess the ESWL with the equal tensile strain at the bottom of asphalt layer. The charts in Figure 2.23 are meant for center-to-center spacing between dual tires and contact radii different from those in the system at hand; we must use the extrapolation procedure presented under topic *Dual Wheels* of section 2.2.1. We first estimate the modified radius a' and the modified thickness h_1',

$$a' = \frac{24}{S_d} a = \frac{24}{20} \times 6 = 7.2\,\text{in.}\ ;\ h_1' = \frac{24}{S_d} h_1 = \frac{24}{20} \times 10 = 12\,\text{in.}$$

Then, we enter this modified thickness and the ratio E_1/E_2 = 25 into Figure 2.23 to read coefficients C_1 = 1.27 and C_2 = 1.38; interpolation is needed because there are no curves for E_1/E_2 = 25. Substituting into equation (2.19) gives

$$C = C_1 + 0.2(a' - 3)(C_2 - C_1)$$
$$\therefore C = 1.27 + 0.2 \times (7.2 - 3) \times (1.38 - 1.27) = 1.36$$

Substituting into equation (6.14) brings to

$$ESWL = CP_d = 1.36 \times 8000 = \boxed{10{,}900\,\text{lb}}$$

P.6.3 ■ Solution

The data for this traffic load analysis are processed in the following table. Columns [1] and [4] are reproduced from the given dataset. Column [2] contains the EALF's read from Table 6.4. Column [3] is obtained by substituting the load value L_x into equation (6.23), namely

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

Columns [5] and [6] list the products of the EALF's and the numbers-per-day of column [4]. The sums of the computed values are listed at the end of these two columns.

[1]	[2]	[3]	[4]	[5]	[6]
Axle load (kip)	EALF from Table 6.4	EALF from Eq. 6.23	No. per day	[2] × [4]	[3] × [4]
12	0.189	0.198	200	37.80	39.51
14	0.36	0.366	117.4	42.26	42.96
16	0.623	0.624	84.5	52.64	52.75
18	1	1.000	61.4	61.40	61.40
20	1.51	1.524	47.2	71.27	71.94
22	2.18	2.232	21.4	46.65	47.75
24	3.03	3.160	12.9	39.09	40.77
26	4.09	4.353	6.1	24.95	26.55
28	5.39	5.855	2.9	15.63	16.98
30	6.97	7.716	1.2	8.36	9.26
32	8.88	9.989	0.7	6.22	6.99
34	11.18	12.730	0.3	3.35	3.82
			Sum =	409.63	420.69

Noting that 20 years amount to 20 × 365 days, the corresponding EAL's are, for the data extracted from Table 6.4,

$$EAL = \sum F_i n_i \times 365 \times 20 = 409.63 \times 365 \times 20 = \boxed{2.99 \times 10^6}$$

while, for the data produced using equation (6.23),

$$EAL = \sum F_i n_i \times 365 \times 20 = 420.69 \times 365 \times 20 = \boxed{3.07 \times 10^6}$$

P.6.6 ■ Solution

The expression to use is equation (6.30), namely

$$ESAL = (ADT)_0 (T)(T_f)(G)(D)(L)(365)(Y)$$

Since the truck count is 1000 per day, $(ADT)_0(T)$ = 1000. For the general truck mix in question, T_f = 0.52 can be read from Table 6.10. For an annual growth rate r = 0.05 and a design life of 20 years, equation (6.33) gives

$$(G)(Y) = \frac{(1+r)^Y - 1}{r} = \frac{(1+0.05)^{20} - 1}{0.05} = 33.1$$

For a four-lane pavement, $(D)(L) = 0.45$ is read from Table 6.15. Gleaning our data and substituting into the equation for *ESAL*, we find that

$$ESAL = 1000 \times 0.52 \times 33.1 \times 0.45 \times 365 = \boxed{2.83 \times 10^6}$$

P.6.7 ■ Solution

The data are processed below. Column [1] is simply the load-range data from Table P6.7; column [2] is the average load corresponding to each loading range in [1]; column [3] is EALF data read from Table 6.4 and may require interpolation for some of the average loads in [2]; column [4] is No. per day data read from the rightmost column of Table P6.7; column [5] is ESAL data obtained by multiplying [3] and [4].

Single Axle				
[1]	[2]	[3]	[4]	[5]
Axle load range (lb)	Average load (lb)	EALF from Table 6.4	No. per day	ESAL
< 3000	1500	0.0001	0	0.000
3000 - 6999	5000	0.005	3188	15.940
7000 - 7999	7500	0.02695	2843	76.619
8000 - 11999	10000	0.0877	9942	871.913
12000 - 15999	14000	0.360	3111	1119.960
16000 - 17999	17000	0.796	1899	1511.604
18000 - 19000	18500	1.120	1078	1207.360
19001 - 19999	19500	1.375	423	581.625
20000 - 21999	21000	1.830	598	1094.340
22000 - 23999	23000	2.580	144	371.520
24000 - 25999	25000	3.530	6	21.180
26000 - 29999	28000	5.390	6	32.340
Tandem Axle				
< 6000	3000	0	7	0.000
6000 - 11999	9000	0	2631	0.000
12000 - 17999	15000	0.036	2541	91.476
18000 - 23999	21000	0.148	2362	349.576
24000 - 29999	27000	0.426	3103	1321.878
30000 - 31500	30750	0.72925	703	512.663
31501 - 31999	31750	0.831	141	117.171
32000 - 33999	33000	0.971	503	488.413
34000 - 35999	35000	1.23	388	477.240
36000 - 37999	37000	1.53	280	428.400
38000 - 39999	39000	1.89	247	466.830
40000 - 41999	41000	2.29	183	419.070
42000 - 43999	43000	2.76	160	441.600
44000 - 45999	45000	3.27	51	166.770
46000 - 49999	48000	4.17	64	266.880
50000 - 53999	52000	5.63	7	39.410
			Sum =	12491.778

Noting that the period of July 16 to August 8 spans 24 days and that 1 year = 365.25 days, the ESAL during the first year is calculated to be

$$ESAL \text{ during first year} = \frac{12,491.778 \times 365.25}{24} = \boxed{190,109}$$

P.6.8 ■ Solution

The only difference between the present problem and Problem 6.8 is that EALFs are to be read from Table 6.7 instead of Table 6.4. The calculations are tabulated below.

Single Axle				
[1]	[2]	[3]	[4]	[5]
Axle load range (lb)	Average load (lb)	EALF from Table 6.7	No. per day	ESAL
< 3000	1500	0.0000	0	0.000
3000 - 6999	5000	0.006	3188	19.128
7000 - 7999	7500	0.02650	2843	75.340
8000 - 11999	10000	0.0820	9942	815.244
12000 - 15999	14000	0.341	3111	1060.851
16000 - 17999	17000	0.802	1899	1522.998
18000 - 19000	18500	1.143	1078	1231.615
19001 - 19999	19500	1.428	423	603.833
20000 - 21999	21000	1.955	598	1169.090
22000 - 23999	23000	2.850	144	410.400
24000 - 25999	25000	4.015	6	24.090
26000 - 29999	28000	6.290	6	37.740
Tandem Axle				
< 6000	3000	0.0003	7	0.002
6000 - 11999	9000	0.009	2631	23.679
12000 - 17999	15000	0.065	2541	165.165
18000 - 23999	21000	0.257	2362	607.034
24000 - 29999	27000	0.736	3103	2283.808
30000 - 31500	30750	1.271	703	893.513
31501 - 31999	31750	1.446	141	203.886
32000 - 33999	33000	1.705	503	857.615
34000 - 35999	35000	2.175	388	843.900
36000 - 37999	37000	2.73	280	764.400
38000 - 39999	39000	3.385	247	836.095
40000 - 41999	41000	4.145	183	758.535
42000 - 43999	43000	5.015	160	802.400
44000 - 45999	45000	6.005	51	306.255
46000 - 49999	48000	7.73	64	494.720
50000 - 53999	52000	10.6	7	74.200
			Sum =	16885.535

Noting that the period of July 16 to August 8 spans 24 days and that 1 year = 365.25 days, the ESAL during the first year is calculated to be

$$ESAL\text{ during first year} = \frac{16{,}885.535\times 365.25}{24} = \boxed{256{,}977}$$

P.6.9 ■ Solution

Table P6.7 shows that 12,197 vehicles were counted over the course of 24 days. The equivalent total vehicle count is

$$\text{Equivalent total vehicle count} = 12{,}197\times\frac{365}{24} = 185{,}496$$

Problem 6.7 gave us a total EAL of 190,109; it follows that the truck factor is

$$\text{Truck factor} = \frac{190{,}109}{185{,}496} = \boxed{1.025}$$

P.6.10 ■ Solution

In Problem 6.9, the equivalent total vehicle count was calculated to be 185,496. Problem 6.8 gave us a total EAL equal to 256,977, so that

$$\text{Truck factor} = \frac{256{,}977}{185{,}496} = \boxed{1.385}$$

P.7.5 ■ Solution

For convenience, we first convert the temperature values involved to Celsius: 74ºF = 23.3ºC; 77ºF = 25ºC; and 120ºF = 49ºC. Observing that the mixture has a penetration of 50 at 25ºC (77ºF) and that the ring and ball softening point corresponds to a temperature of 49ºC (120ºF), we substitute into (7.18) to determine the temperature susceptibility *A*,

$$A = \frac{\log(\text{pen at } T) - \log 800}{T - T_{R\&B}} = \frac{\log 50 - \log 800}{25 - 49} = 0.0502$$

Then, substituting *A* into (7.16) gives the penetration index *PI*,

$$PI = \frac{20 - 500A}{1 + 50A} = \frac{20 - 500 \times 0.0502}{1 + 50 \times 0.0502} = -1.45$$

Entering a loading time of 0.02 s, a temperature difference T_{diff} = 49 – 23.3 = 25.7ºC, and *PI* = −1.45 into Figure 2.19, we read a stiffness modulus ≈ 2×10^7 N/m^2 for the asphalt binder.

Per the problem statement, asphalt content P_b = 0.07, bulk specific gravity G_m = 2.24, and aggregate specific gravity G_g = 2.61. Substituting into (7.20) gives

$$V_g = \frac{100(1 - P_b)G_m}{G_g} = \frac{100 \times (1 - 0.07) \times 2.24}{2.61} = 79.82\%$$

In turn, the percent volume of bitumen follows from equation (7.21),

$$V_b = \frac{100 P_b G_m}{G_b} = \frac{100 \times 0.07 \times 2.24}{1.02} = 15.37\%$$

Subtracting the two percent volume values above from 100, we obtain the percent volume of air void,

$$V_a = 100 - V_g - V_b = 100 - 79.82 - 15.37 = 4.81\%$$

Entering the binder stiffness modulus 2×10^7 N/m^2, the percent volume of binder V_b = 15.37%, and the percent volume of aggregate V_a = 4.81% into Figure 7.20, the stiffness modulus of the asphalt mixture is found to be ≈2×10^9 N/m^2.

Let's see how this stiffness modulus compares to the result given by equation (7.25). We first substitute the pertaining quantities into equations (7.24*a*) through (7.24*d*), giving

$$\beta_1 = 10.82 - \frac{1.342(100 - V_g)}{V_g + V_b} = 10.82 - \frac{1.342 \times (100 - 79.82)}{79.82 + 15.37} = 10.54$$

$$\beta_2 = 8.0 + 0.00568 V_g + 0.0002135 V_g^2 = 8.0 + 0.00568 \times 79.82 + 0.0002135 \times 79.82^2$$

$$\therefore \beta_2 = 9.82$$

$$\beta_3 = 0.6 \log\left(\frac{1.37 V_b^2 - 1}{1.33 V_b - 1}\right) = 0.6 \times \log\left(\frac{1.37 \times 15.37^2 - 1}{1.33 \times 15.37 - 1}\right) = 0.732$$

$$\beta_4 = 0.7582(\beta_1 - \beta_2) = 0.7582 \times (10.54 - 9.82) = 0.546$$

Now, since the stiffness modulus of the bitumen $S_b = 2\times10^7$ N/m^2 falls into the interval [5×10^6, 10^9], the stiffness modulus S_m of the mixture can be estimated with equation (7.25*a*),

$$\log S_m = \frac{\beta_4 + \beta_3}{2}(\log S_b - 8) + \frac{\beta_4 - \beta_3}{2}\left|\log S_b - 8\right| + \beta_2$$

$$\therefore \log S_m = \frac{0.546 + 0.732}{2}\left[\log(2\times10^7) - 8\right] + \frac{0.546 - 0.732}{2}\left|\log(2\times10^7) - 8\right| + 9.82$$

$$\therefore \log S_m = 9.31$$

$$\therefore S_m = 10^{9.31} = \boxed{2.04\times10^{9}\ \text{N/m}^2}$$

The result obtained from equation (7.25) deviates very little from our graphical estimate of 2×10^9 N/m^2.

P.7.6 ■ Solution

If the penetration at 77ºF is equal to 75, we can estimate the viscosity from equation (7.28),

$$\lambda = 29{,}508.2\left(P_{77^\circ\text{F}}\right)^{-2.1939} = 29{,}508.2\times75^{-2.1939} = 2.27\times10^{6}\ \text{poise}$$

Let us compute the β_i coefficients, starting with β_5; the load frequency is f = 8 Hz, the volume of bitumen is V_b = 15.37%, the percent passing through a No. 200 sieve is P_{200} = 5%, the air void volume is V_a = 4.81%, and the operation temperature is 74ºF, giving

$$\beta_5 = 1.3 + 0.49825\log f = 1.3 + 0.49825\log 8 = 1.75$$

$$\beta_4 = 0.483V_b = 0.483\times15.37 = 7.42$$

$$\beta_3 = 0.553833 + 0.028829\left(P_{200}f^{-0.1703}\right) - 0.03476V_v$$
$$+0.070377\lambda + 0.931757f^{-0.02774}$$

$$\therefore \beta_3 = 0.553833 + 0.028829\times\left(5\times8^{-0.1703}\right) - 0.03476\times4.81$$
$$+0.070377\times2.27 + 0.931757\times8^{-0.02774} = 1.53$$

$$\beta_2 = \beta_4^{0.5}T^{\beta_5} = 7.42^{0.5}\times74^{1.75} = 5090$$

$$\beta_1 = \beta_3 + 5\times10^{-5}\beta_2 - 0.00189\beta_2 f^{-1.1} = 1.53 + \left(5\times10^{-6}\right)\times5090 - 0.00189\times5090\times8^{-1.1} = 0.579$$

Lastly, substituting β_1 into equation (7.27*a*) yields the dynamic modulus $|E^*|$,

$$\left|E^*\right| = 100{,}000\times10^{\beta_1} = 100{,}000\times10^{0.579} = \boxed{379{,}000\ \text{psi}}$$

P.7.7 ■ Solution

To establish the number of cycles to failure, refer to Figure 7.26. Enter a penetration index PI = −1.45, a volume of bitumen V_b = 15.37%, a stiffness modulus S_m = 2×10^9 N/m^2 = 2.9×10^5 psi, and an initial tensile strain ε_r = 0.00015; in doing so, we find a number of cycles to failure $N_f \approx$ 8.7×10^5 for constant stress test and $N_f \approx$ 9×10^7 for constant strain test. The number of repetitions to failure for constant stress can also be estimated from equation (7.33),

$$N_f = \left[0.0252PI - 0.00126PI\left(V_b\right) + 0.00673V_b - 0.0167\right]^5 \varepsilon_t^{-5}S_m^{-1.4}$$

$$\therefore N_f = \left[0.0252\times(-1.45) - 0.00126\times(-1.45)\times15.37 + 0.00673\times15.37 - 0.0167\right]^5\times0.00015^{-5}\times\left(2.9\times10^{5}\right)^{-1.4}$$

$$\therefore \boxed{N_f = 8.72\times10^{5}}$$

which agrees fairly well with our graphical estimate. Likewise, the number of repetitions to failure for constant strain can be estimated from equation (7.35),

$$N_f = \left[0.17PI - 0.0085PI\left(V_b\right) + 0.0454V_b - 0.112\right]^5 \varepsilon_t^{-5}S_m^{-1.8}$$

$$\therefore N_f = \left[0.17\times(-1.45) - 0.0085\times(-1.45)\times15.37 + 0.0454\times15.37 - 0.112\right]^5\times0.00015^{-5}\times\left(2.9\times10^{5}\right)^{-1.8}$$

$$\therefore \boxed{N_f = 8.01\times10^{7}}$$

Again, this result agrees reasonably well with the graphical estimate.

P.7.8 ■ Solution

Equation (7.36) gives the number of cycles to failure for a constant stress criterion,

$$N_f = 0.00432 C \varepsilon_1^{-3.291} |E^*|^{-0.854}$$

Here, factor $C = 10^M$, where M is given by equation (7.37*b*),

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right) = 4.84 \times \left(\frac{15.37}{4.81 + 15.37} - 0.69\right) = 0.347$$

so that

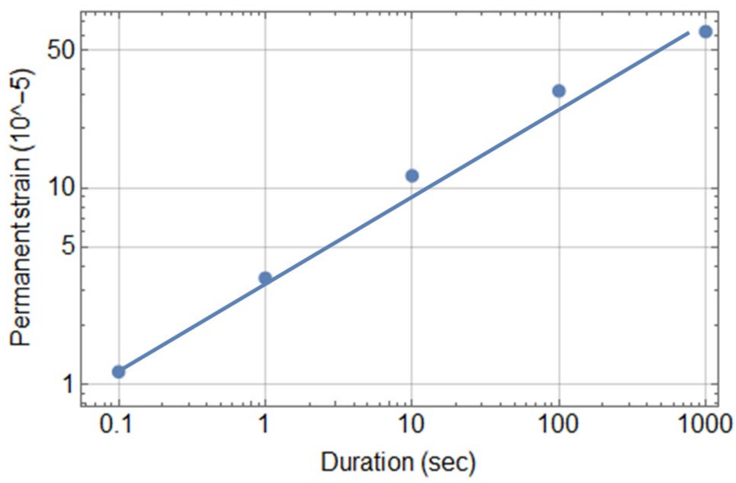
$$C = 10^{0.347} = 2.22$$

and, noting that $|E^*|$ = 379,000 psi was determined in Problem 7-6,

$$N_f = 0.00432 \times 2.22 \times 0.00015^{-3.291} \times 379{,}000^{-0.854} = \boxed{634{,}000}$$

P.7.9 ■ Solution

Per the discussion in Section 7.4.1, a bilogarithmic plot of permanent strain versus the number of load repetitions should yield a straight line, as shown.



To find the coefficients that fit the linear curve above, one way to go is to apply Mathematica's *FindFit* command:

```
data = {{0.1, 1.158}, {1, 3.474}, {10, 11.533}, {100, 31.172}, {1000, 62.483}}
{{0.1, 1.158}, {1, 3.474}, {10, 11.533}, {100, 31.172}, {1000, 62.483}}

logData = Log10[data]
{{-1., 0.0637086}, {0, 0.54083}, {1, 1.06194}, {2, 1.49376}, {3, 1.79576}}

line = SetPrecision[FindFit[logData, {a*x + b}, {a, b}, x], 3]
{a → 0.442, b → 0.549}
```

As the output of the last code indicates, we may write

$$\log(\text{Strain}) = 0.442 \log(\text{Duration}) + 0.549$$

It follows that, substituting the slope S = 0.442 into equation (7.43),

$$\alpha = 1 - S = 1 - 0.442 = \boxed{0.558}$$

The intercept I, in turn, equals

$$I = 10^{0.442 \log(0.1) + 0.549} \times 10^{-5} = 1.28 \times 10^{-5}$$

so that, using the reference strain $\varepsilon = 3.045 \times 10^{-5}$ and substituting into equation (7.44),

$$\mu = \frac{IS}{\varepsilon} = \frac{\left(1.28 \times 10^{-5}\right) \times 0.442}{3.045 \times 10^{-5}} = \boxed{0.186}$$

P.11.3 ■ Solution

Substituting the given tensile strain ε_t = 0.0005 into the fatigue equation provided, we get

$$N_f = 5\times10^{-6}\varepsilon_t^{-3} = 5\times10^{-6}\times0.0005^{-3} = 40{,}000$$

With a coefficient of variation $C[N_f]$ = 0.8, the variance of N_f is

$$V\left[N_f\right] = \left(0.8\times40{,}000\right)^2 = 1.02\times10^9$$

The cracking index c is

$$c = \frac{n}{N_f} = \frac{5000}{40{,}000} = 0.125$$

The variance of the cracking index is

$$V\left[c\right] = \left(-\frac{n}{N_f^2}\right)^2 V\left[N_f\right] = \left(-\frac{5000}{40{,}000^2}\right)^2 \times\left(1.02\times10^9\right) = 0.00996$$

Using equation (10.58), the variance of *log c* can be determined from the variance of *c*,

$$V\left[\log c\right] = \frac{0.1886}{c^2}V\left[c\right] = \frac{0.1886}{0.125^2}\times0.00996 = 0.120$$

Taking the square root of this result gives the standard deviation of *log c*,

$$S_{\log c} = \sqrt{V\left[\log c\right]} = \sqrt{0.120} = 0.346$$

The logarithm of *c* itself is *log c* = *log 0.125* = −0.903, and the *Z* score follows as

$$Z = \frac{0-\left(-0.903\right)}{0.346} = 2.61$$

Referring to Table 10.1, we see that this *Z*-score corresponds to an area ≈ 0.495473. The reliability is then 0.5 + 0.495473 ≈ 0.995, and the percent area cracked that is attributable to thermal fatigue cracking is 0.5%.

P.11.4 ■ Solution

The mean monthly air temperature is 68ºF. Noting that the temperature at the upper third point of each layer is to be used, we substitute z = 2/3 = 0.667 for the surface course into equation (3.27), giving

$$M_p = M_a\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6 = 68\times\left(1+\frac{1}{0.667+4}\right)-\frac{34}{0.667+4}+6 = \boxed{81.3^\circ\,\mathrm{F}}$$

In turn, the depth used to compute the surface temperature of the binder course is z = 2 + 6/3 = 4 in., so that

$$M_p = 68\times\left(1+\frac{1}{4.0+4}\right)-\frac{34}{4.0+4}+6 = \boxed{78.3^\circ\,\mathrm{F}}$$

To compute the dynamic modulus of the surface course, we substitute the pertaining data serially into equations (7.27*f*) through (7.27*a*) (see Problem 7.6),

$$\beta_5 = 1.3+0.49825\log f = 1.3+0.49825\times\log 8 = 1.75$$
$$\beta_4 = 0.483V_b = 0.483\times11 = 5.31$$
$$\beta_3 = 0.553833+0.028829\left(P_{200}f^{-0.1703}\right)-0.03476V_v$$
$$+0.070377\lambda+0.931757f^{-0.02774}$$

$$\beta_3 = 0.553833 + 0.028829 \times 5 \times 8^{-0.1703} - 0.03476 \times 4$$
$$+0.070377 \times 2.5 + 0.931757 \times 8^{-0.02774} = 1.57$$

$$\beta_2 = \beta_4{}^{0.5} T^{\beta_5} = 5.31^{0.5} \times 81.3^{1.75} = 5070$$

$$\beta_1 = \beta_3 + 5\times 10^{-6}\beta_2 - 0.00189\beta_2 f^{-1.1} = 1.57 + 5\times 10^{-6} \times 5070 - 0.00189 \times 5070 \times 8^{-1.1} = 0.622$$

$$|E^*| = 100,000 \times 10^{\beta_1} = 100,000 \times 10^{0.622} = \boxed{419,000\,\text{psi}}$$

Considering the binder, calculations are identical for β_5 and β_4; in calculating β_3, substitute V_a = 7% instead of 4% to obtain β_3 = 1.47. In calculating β_2, use T = 78.3°F instead of 81.3°F to obtain β_2 = 4750. The value of β_1 should be close to 0.582. Finally,

$$|E^*| = 100,000 \times 10^{\beta_1} = 100,000 \times 10^{0.582} = \boxed{382,000\,\text{psi}}$$

Before using equation (3.28), we substitute the dynamic moduli obtained above into (3.29) to obtain the equivalent modulus

$$E_1 = \left[\frac{h_{1a}\left(E_{1a}\right)^{1/3} + h_{1b}\left(E_{1b}\right)^{1/3}}{h_{1a} + h_{1b}}\right]^3 = \left(\frac{2\times 4.19^{1/3} + 6 \times 3.82^{1/3}}{2+6}\right)^3 = 3.91 \times 10^5 \text{ psi}$$

Lastly, the modulus of the untreated base is

$$E_2 = 10.447 h_1^{-0.471} h_2^{-0.041} E_1^{-0.139} E_3^{0.287} K_1^{0.868}$$

$$E_2 = 10.447 \times 8^{-0.471} \times 8^{-0.041} \times \left(3.91 \times 10^5\right)^{-0.139} \times \left(10,000\right)^{0.287} \times 8000^{0.868} = \boxed{20,700\,\text{psi}}$$

P.11.5 ■ Solution

The *ESAL* is to be determined with equation (6.30),

$$ESAL = (ADT)_0 (T)(T_f)(G)(D)(L)(365)(Y)$$

From the problem statement, $(ADT)_0(T)$ = 1885. This is an interstate highway with two-axle, four-tire panel and pickup trucks, so a truck factor T_f = 0.52 can be read from Table 6.10. Further, this is a six-lane highway, so a percentage of trucks (D)(L) = 40% can be read from Table 6.15. For a growth rate r = 0.04 and a reference period Y = 20 years, equation (6.33) gives

$$(G)(Y) = \frac{(1+r)^Y - 1}{r} = \frac{(1+0.04)^{20} - 1}{0.04} = 29.8$$

so that

$$ESAL = 1885 \times 29.8 \times 0.4 \times 0.52 \times 365 = \boxed{4.27 \times 10^6}$$

Entering the *ESAL* value computed just now and the subgrade resilient modulus M_R = 10,000 psi into Figure 11.17, the appropriate HMA thickness is found to equal 10 in.

Entering *ESAL* = 4.27×10^6 and M_R = 10,000 psi into Figure 11.11 gives a thickness of full-depth HMA equal to 11.5 in. Entering the same data into Figure 11.12, we read a combined thickness of HMA and emulsified asphalt mix of 12 in. Section 11.2.5 recommends assuming a 2-in. surface course, so we may compute the substitution ratio

$$\text{Substitution ratio} = \frac{12-2}{11.5-2} = 1.053$$

If we use 2 in. of HMA, the thickness of the emulsified asphalt base shall be (10 – 2) × 1.053 = 8.42 in. If we use 3.5 in. of HMA, the thickness of the emulsified asphalt base shall be (10 – 3.5) × 1.053 = 6.85 in.

P.11.9 ■ Solution

For a layer coefficient a_1 = 0.44 for the HMA, the structural number *SN* is found as $SN = a_1D_1 = 0.44 \times 12 = 5.28$. To compute the reliability of the design, we need the normal deviate Z_R as given by equation (11.36),

$$Z_R = \frac{\log W_{18} - \log W_{t18}}{S_0} \quad \text{(I)}$$

We were given $W_{18} = 3\times10^7$ and $S_0 = 0.5$; W_{t18} can be determined from equation (11.34),

$$\log W_{t18} = 9.36\log(SN+1) - 0.20 + \frac{\log\left[(4.2-p_t)/2.7\right]}{0.4+1094/(SN+1)^{5.19}} + 2.32\log M_R - 8.07$$

$$\therefore \log W_{t18} = 9.36\log(5.28+1) - 0.20 + \frac{\log\left[(4.2-2.5)/2.7\right]}{0.4+1094/(5.28+1)^{5.19}} + 2.32\log 10{,}000 - 8.07 = 8.059$$

$$\therefore W_{t18} = 10^{8.059} = 1.15\times10^8$$

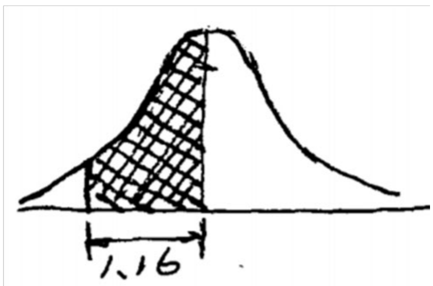
so that, substituting in (I),

$$Z_R = \frac{\log\left(3\times10^7\right) - \log\left(1.15\times10^8\right)}{0.5} = -1.167$$

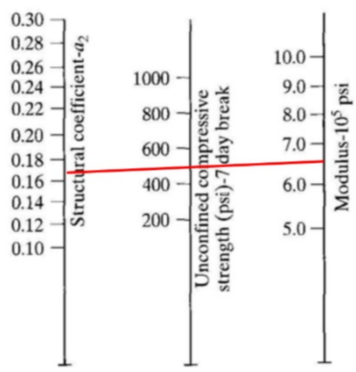
Entering this normal deviate into Table 11.15 shows that the reliability must be between 85 and 90%, as shown to the left. Referring to Table 10.1, we find that the shaded area in the Gaussian curve drawn to the right equals 0.377, so the reliability must be 0.5 + 0.377 = 0.877 ≈ 88%.

TABLE 11.15 Standard Normal D
Reliability

Reliability (%)	Standard normal deviate (Z_R)
50	0.000
60	−0.253
70	−0.524
75	−0.674
80	−0.841
85	−1.037
90	−1.282
91	−1.340
92	−1.405



P.11.10 ■ Solution



Entering a HMA resilient modulus of 4.3×10^5 psi into Figure 11.27, we read a structural coefficient $a_1 \approx 0.44$. Taking a resilient modulus of 6.5×10^5 psi for cement-treated base along with the given 7-day UCS of 500 psi, we refer to the nomograph in Figure 7.15*c* and read a structural coefficient a_2 = 0.17 (see illustration to the side). For the granular subbase course, note that layer coefficient a_3 is related to resilient modulus E_3 = 15,000 psi by equation (11.46),

$$a_3 = 0.227\left(\log E_3\right) - 0.839 = 0.227\left(\log 15{,}000\right) - 0.839 = 0.109$$

Since the resilient modulus of the HMA is well above the maximum assumed in the AASHTO method, we size the HMA layer with the minimum thickness suggested in Table 11.21. For *ESAL* = 1,200,000, which is between 500,000 and 2,000,000, we read a minimum thickness of 3.0 in.

We then proceed to size the CTB course. Entering an $ESAL = 1.2\times10^6$, a resilient modulus M_R = 15,000 psi, and a ΔPSI = 2 into Figure 11.25, we read a structural number SN_2 = 2.3. Now, SN_2 is related to the thicknesses of the two uppermost layers by an expression of the form (equation 11.48)

$$SN_2 = a_1D_1 + a_2D_2m_2$$

If the CTB is unsusceptible to moisture change, m_2 = 1. Substituting and solving for D_2,

$$2.3 = 3\times 0.44 + 0.17\times D_2\times 1$$
$$\therefore D_2 = 5.76\,\text{in.}$$

For convenience, take D_2 = 6 in. Next, we turn to the subbase. Entering an $ESAL$ = 1.2×10^6, a resilient modulus M_R = 5500 psi, and a ΔPSI = 2 into Figure 11.25 gives SN_3 = 3.1. For fair drainage quality and 25% percent of time for moisture approaching saturation, we read m_3 = 0.80 from Table 11.20. The depth of the subbase can be established from equation (11.49),

$$D_3 \geq \frac{SN_3 - a_1D_1 - a_2D_2m_2}{a_3m_3} = \frac{3.1 - 0.44\times 3 - 0.17\times 6\times 1}{0.109\times 0.8} = 8.72\,\text{in.}$$

For convenience, take D_3 = 9 in.

P.12.1 ■ Solution

The allowable number N of load repetitions is given by $N = C_2n$, where C_2 = 0.06 for pavements with concrete shoulders, giving

$$N = C_2n = 0.06\times\left(2\times 10^6\right) = 1.2\times 10^5$$

We then appeal to equation (12.7),

$$\log N = 14.524 - 6.777\left(C_1P - 9.0\right)^{0.103}$$
$$\therefore \log\left(1.2\times 10^5\right) = 14.524 - 6.777\left(1.0\times P - 9.0\right)^{0.103}$$
$$\therefore P = 34.1$$

The rate of work P is defined by equation (12.8),

$$P = 268.7\frac{p^2}{hk^{0.73}}$$

We have P, the thickness h = 10 in., and k = 150 pci. Solving for pressure and substituting,

$$P = 268.7\frac{p^2}{hk^{0.73}} \rightarrow p = \sqrt{\frac{Phk^{0.73}}{268.7}}$$
$$\therefore p = \sqrt{\frac{34.1\times 10\times 150^{0.73}}{268.7}} = 7.02\,\text{psi}$$

Finally, we divide this pressure value by k to obtain the allowable corner deflection w,

$$w = \frac{p}{k} = \frac{7.02}{150} = \boxed{0.0468\,\text{in.}}$$

P.12.2 ■ Solution

For a pavement with concrete shoulders, C_2 changes from 0.06 to 0.94, giving N = 0.94 × (2×10^6) = 1.88×10^6. Substituting into (12.7) and solving for P,

$$\log\left(1.88\times 10^6\right) = 14.524 - 6.777\left(1.0\times P - 9.0\right)^{0..103}$$
$$\therefore \log\left(1.88\times 10^6\right) = 14.524 - 6.777\left(1.0\times P - 9.0\right)^{0..103}$$
$$\therefore P = 15.8$$

Substituting into (12.8),

$$p = \sqrt{\frac{Phk^{0.73}}{268.7}} = \sqrt{\frac{15.8\times 10\times 150^{0.73}}{268.7}} = 4.77\,\text{psi}$$

Lastly,

$$w = \frac{p}{k} = \frac{4.77}{150} = \boxed{0.0318\,\text{in.}}$$

P.12.3 ■ Solution

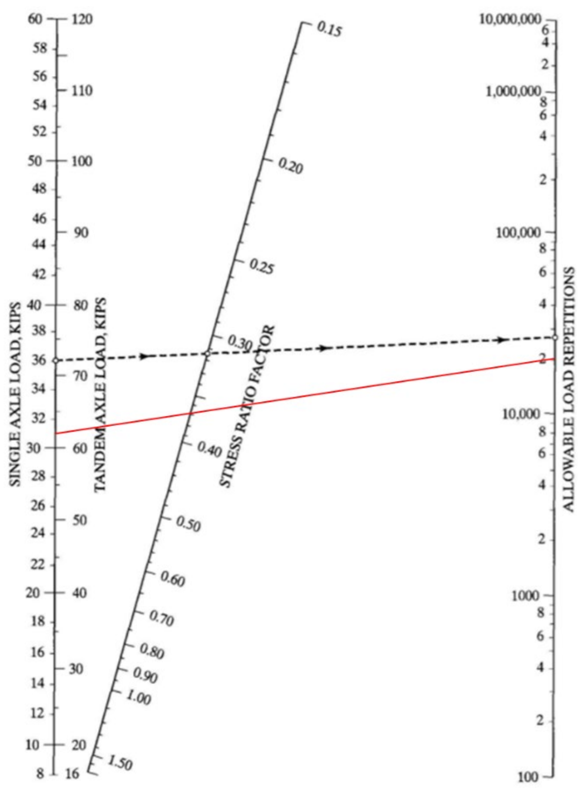
The total number of trucks during the design period in the design lane is given by the product

$$\text{Total No. of trucks} = 2500 \times 365 \times 20 \times 0.35 \times 0.5 = 3.19 \times 10^6$$

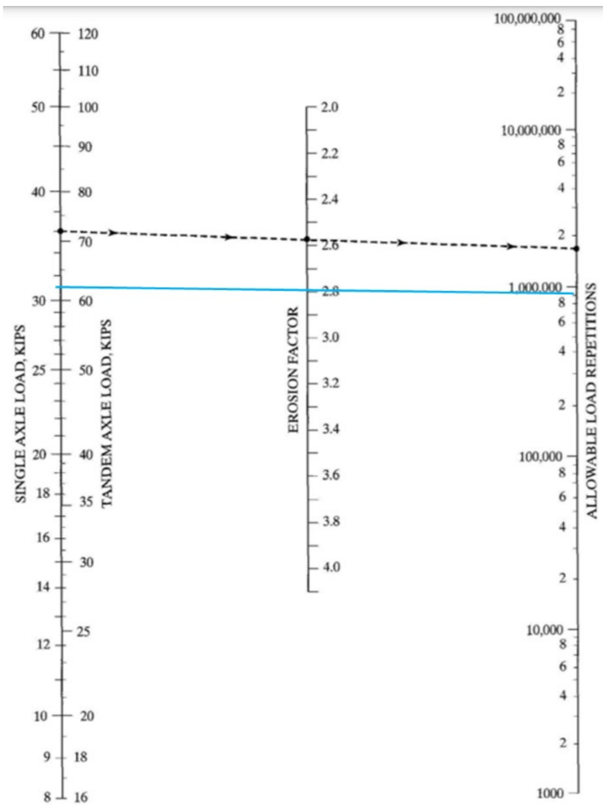
To compute the expected repetitions for a given weight category, multiply the No. of axles per 1000 trucks given in Table P12.3 by the total No. of trucks; for an axle-load value of 28 kip, for example,

$$\text{Expected repetitions of 16-kip axle loads} = \frac{0.9}{1000} \times \left(3.19 \times 10^6\right) = 2870$$

Entering an assumed thickness of 8 in. and a modulus of subgrade reaction of 200 pci into Table 12.6, we read an equivalent stress of 242 psi. Dividing this quantity by the concrete modulus of rupture gives the stress ratio factor 242/650 = 0.372. Equipped with the stress ratio factor, we can enter its value and the axle loads multiplied by *LSF* into Figure 12.12 to read the corresponding allowable repetitions. For example, entering into the nomograph an axle load of 28 kips, or 1.1 × 28 = 30.8 kips, and *SRF* = 0.372, we read an allowable number of repetitions of about 20,000, as indicated by the red line to the side. Dividing the expected number of 28-kip repetitions, which is 2870, by the allowable No. of repetitions, which is 20,000, we obtain a fatigue damage of 14.4%.



To determine the erosion factor, enter a slab thickness of 8 in. and a modulus of subgrade-subbase of 200 pci into Table 12.8 (doweled joints, no concrete shoulders); the EF is found to be 2.80. Equipped with the erosion factor, we can enter its value and the axle loads multiplied by LSF into Figure 12.13 to read the pertaining allowable repetitions. For instance, entering into the nomograph an axle load of 28 kips, or 1.1 × 28 = 30.8 kips, and *EF* = 2.80, we read an allowable number of repetitions of about 900,000, as indicated by the blue line to the side.



Proceed similarly with the tandem-axle portion of the data. In this case, use 208 psi as the equivalent stress (Table 12.6), 208/650 = 0.32 as the stress ratio factor, and 2.93 as the erosion factor (Table 12.8). Maximum allowable repetitions for fatigue and erosion are read from Figs. 12.12 and 13, respectively, as before. The calculations are tabulated below.

Single Axle			Fatigue analysis		Erosion analysis	
ES = 242 psi, *SRF* = 0.372, *EF* = 2.80						
Load (kips)	Multiplied by LSF	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
28	30.8	2870	20000	14.4	900000	0.3
26	28.6	6070	45000	13.5	1400000	0.4
24	26.4	7400	160000	4.6	2100000	0.4
22	24.2	50000	800000	6.3	3500000	1.4
20	22	200000	-	-	7200000	2.8
18	19.8	360000	-	-	16000000	2.3
16	17.6	420000	-	-	40000000	1.1
Tandem Axles			Fatigue analysis		Erosion analysis	
ES = 208 psi, *SRF* = 0.320, *EF* = 2.93						
Load (kips)	Multiplied by LSF	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
48	52.8	30700	10000000	0.31	950000	3.2
44	48.4	33500	-	-	1600000	2.1
40	44	53700	-	-	2600000	2.1
36	39.6	55000	-	-	5600000	1.0
32	35.2	76700	-	-	12000000	0.6
28	30.8	110000	-	-	40000000	0.3
24	26.4	256000	-	-	-	-
			Total =	39.0	Total =	17.9

Note that with the thickness at hand the cumulative damage and erosion criteria are well below 100%. Accordingly, we design the pavement with a thickness of 8.0 in.

P.12.4 ■ Solution

The total No. of trucks on the design lane during the design period is 3460 × 365 × 20 = 2.53×10^7. Initially, a trial thickness of 8.5 in. is selected. For a modulus of subgrade reaction of 150 pci and the given trial thickness of 8.5 in., we read equivalent stresses of 191 and 166 from Table 12.7. The corresponding stress ratio factors are 191/650 = 0.294 and 166/650 = 0.255. For a pavement with doweled joints and concrete shoulders, the erosion factor can be read from Table 12.10; since there is no entry for a *k* value of 150 pci, we interpolate using the data points for *k* = 100 and *k* = 200 pci, yielding 2.32/2.45. The pertaining data are processed below.

Single Axle				Fatigue analysis		Erosion analysis	
ES = 191 psi, *SRF* = 0.294, *EF* = 2.32							
Load (kips)	Multiplied by LSF	Category 3 axle load dist. (Table 12.13)	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
30	36	0.45	11385	110000	10.4	680000	1.7
28	33.6	0.85	21505	300000	7.2	1200000	1.8
26	31.2	1.78	45034	1750000	2.6	2000000	2.3
24	28.8	5.21	131813	-	-	5000000	2.6
22	26.4	7.85	198605	-	-	15000000	1.3
20	24	16.33	413149	-	-	-	-
18	21.6	25.15	636295	-	-	-	-
16	19.2	31.82	805046	-	-	-	-
14	16.8	47.73	1207569	-	-	-	-
12	14.4	182.02	4605106	-	-	-	-
Tandem Axles				Fatigue analysis		Erosion analysis	
ES = 166 psi, *SRF* = 0.255, *EF* = 2.45							
Load (kips)	Multiplied by LSF	Category 3 axle load dist. (Table 12.13)	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
52	62.4	1.19	30107	10000000	0.30	680000	4.4
48	57.6	2.91	73623	-	-	1300000	5.7
44	52.8	8.01	202653	-	-	3000000	6.8
40	48	21.31	539143	-	-	8000000	6.7
36	43.2	56.25	1423125	-	-	-	-
32	38.4	103.63	2621839	-	-	-	-
28	33.6	121.22	3066866	-	-	-	-
24	28.8	72.54	1835262	-	-	-	-
20	24	85.94	2174282	-	-	-	-
16	19.2	99.34	2513302	-	-	-	-
				Total =	20.4	Total =	33.3

As can be seen, a pavement with a trial thickness of 8.5 in. exceeds neither the fatigue damage nor the erosion damage criterion; accordingly, the design is sound. Try performing the calculations for a trial thickness of 8 in. and you'll find that the ensuing fatigue damage will be greater than 100%; it follows that a thickness of 8.5 in. is close to the minimum we can propose for the situation at hand.

In the simplified approach, we can enter the given *MR* of 650 psi, a concrete-shoulder endowed road, and a subgrade-subbase support assumed to be *medium* in nature into Table 12.15; for a slab thickness of 8 in., the allowable ADTT is found to be 5700, which is less than the given ADTT of 3460. Thus, a 8-in. thickness is taken as a sound design per the simplified method.

Slab thickness (in.)	Concrete shoulder or curb			
	Subgrade-subbase support			
	Low	Medium	High	Very high
6.5			83	320
7	52	220	550	1900
7.5	320	1200	2900	9800
8	1600	$\boxed{5700}$	13,800	
8.5	6900	23,700[b]		

P.12.5 ■ Solution

Use a trial thickness of 9.5 in. For a modulus of subgrade reaction of 150 pci and the given trial thickness of 8.5 in., we read equivalent stresses of 200 and 183 from Table 12.6 (*not* Table 12.7, as the road has no concrete shoulders). The corresponding stress ratio factors are 200/650 = 0.308 and 183/650 = 0.282. For a pavement with doweled joints and *no* concrete shoulders, the erosion factor can be read from Table 12.8; since there is no entry for a *k* value of 150 pci, we interpolate using the data points for *k* = 100 and *k* = 200 pci, yielding 2.59/2.78. The pertaining data are processed below.

Single Axle				Fatigue analysis		Erosion analysis	
ES = 200 psi, *SRF* = 0.308, *EF* = 2.59							
Load (kips)	Multiplied by LSF	Category 3 axle load dist. (Table 12.13)	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
30	36	0.45	11385	40000	28.5	1400000	0.8
28	33.6	0.85	21505	120000	17.9	2000000	1.1
26	31.2	1.78	45034	400000	11.3	3400000	1.3
24	28.8	5.21	131813	3000000	4.4	5800000	2.3
22	26.4	7.85	198605	-	-	10000000	2.0
20	24	16.33	413149	-	-	21000000	2.0
18	21.6	25.15	636295	-	-	60000000	1.1
16	19.2	31.82	805046	-	-	-	-
14	16.8	47.73	1207569	-	-	-	-
12	14.4	182.02	4605106	-	-	-	-
Tandem Axles				Fatigue analysis		Erosion analysis	
ES = 183 psi, *SRF* = 0.282, *EF* = 2.78							
Load (kips)	Multiplied by LSF	Category 3 axle load dist. (Table 12.13)	Expected repetitions	Allowable repetitions	Fatigue damage (%)	Allowable repetitions	Erosion damage (%)
52	62.4	1.19	30107	4000000	0.75	900000	3.3
48	57.6	2.91	73623	-	-	1400000	5.3
44	52.8	8.01	202653	-	-	2100000	9.7
40	48	21.31	539143	-	-	4000000	13.5
36	43.2	56.25	1423125	-	-	8000000	17.8
32	38.4	103.63	2621839	-	-	20000000	13.1
28	33.6	121.22	3066866	-	-	80000000	3.8
24	28.8	72.54	1835262	-	-	-	-
20	24	85.94	2174282	-	-	-	-
16	19.2	99.34	2513302	-	-	-	-
				Total =	62.8	Total =	77.0

The fatigue damage and erosion damage criteria are closer to 100 than in the analysis of the design with concrete shoulders, but remain below this threshold. The design is adequate. From Table 12-15, a thickness of 9.5 in. is prescribed to withstand a ADTT of up to 10,800; a thickness of 9 in. is not adequate because the daily truck traffic of 3460 exceeds the 2700 truck traffic limit for this thickness level.

No concrete shoulder or curb				
Slab thickness (in.)	Subgrade-subbase support			
	Low	Medium	High	Very high
MR = 650 psi				
7.5				250
8		130	350	1300
8.5	160	640	1600	6200
9	700	2700	7000	11,500[b]
9.5	2700	10,800		
10	9900			

P.12.7 ■ Solution

From Table 11.20, the drainage coefficient for poor drainage with 5% of time at saturation is taken as 0.90. From Figure 12.18, we can read a composite modulus of subgrade reaction $k \approx 350$ pci. To determine W_{18}, we appeal to equation (12.21) without the reliability term, giving

$$\log W_{18} = 7.35\log(D+1) - 0.06 + \frac{\log[\Delta PSI/(4.5-1.5)]}{1+1.624\times10^{7}/(D+1)^{8.46}}$$

$$+(4.22-0.32p_t)\log\left\{\frac{S_c C_d\left(D^{0.75}-1.132\right)}{215.63J\left[D^{0.75}-18.42\big/(E_c/k)^{0.25}\right]}\right\}$$

$$\therefore \log W_{18} = 7.35\log(8.0+1) - 0.06 + \frac{\log[2.5/(4.5-1.5)]}{1+1.624\times10^{7}/(8.0+1)^{8.46}}$$

$$+(4.22-0.32\times2.0)\log\left\langle\frac{650\times0.9\times\left(8.0^{0.75}-1.132\right)}{215.63\times3.2\times\left\{8.0^{0.75}-18.42\big/\left[\left(4.0\times10^{6}\right)/100\right]^{0.25}\right\}}\right\rangle$$

$$\therefore \log W_{18} = 6.93$$

$$\therefore W_{18} = 10^{6.93} = \boxed{8.51\times10^{6}}$$

Entering our data into the AASHTO chart, we read $W_{18} \approx 8.5\times10^{6}$, which is close to our result.

P.12.8 ■ Solution

Per the discussion in section 12.3.2, if a slab is placed directly on the subgrade without a subbase the modulus of subgrade reaction can be related to the resilient modulus by the simple equation

$$k = \frac{M_R}{19.4} \quad \text{(I)}$$

with k in pci and M_R in psi. The relative damage to rigid pavements, u_r, is given by equation (12.29),

$$u_r = \left(D^{0.75} - 0.39k^{0.25}\right)^{3.42} \quad \text{(II)}$$

This equation can be used to compute the effective modulus of subgrade reaction k in terms of the seasonal moduli k_i. The data are processed below.

Month	M_R (psi)	k (pci) (Eq. I)	u_r (Eq. II)
JAN	15900	819.6	37.8
FEB	27300	1407.2	25.9
MAR	38700	1994.8	19.2
APR	50000	2577.3	14.8
MAY	900	46.4	110.7
JUNE	1620	83.5	96.1
JULY	2340	120.6	86.6
AUGUST	3060	157.7	79.6
SEPTEMBER	3780	194.8	74.1
OCTOBER	4500	232.0	69.5
NOVEMBER	4500	232.0	69.5
DECEMBER	4500	232.0	69.5
		Total =	753.2

Dividing the cumulative u_r by 12 gives 62.8. Substituting into (II),

$$\bar{u}_r = \left(D^{0.75} - 0.39k_{\text{eff}}^{0.25}\right)^{3.42} = 62.8$$

$$\therefore \left(8.5^{0.75} - 0.39k_{\text{eff}}^{0.25}\right)^{3.42} = 62.8$$

The equation above can be easily solved for k_{eff} using logarithms. For convenience, we simply employ the Mathematica code

```
In[118]:= Solve[(8.5^0.75 - 0.39 * keff^0.25)^3.42 == 62.8, keff]

Solve: Inverse functions are being used by Solve, so some solu
Reduce for complete solution information.

Out[118]= {{keff → 299.854}}
```

That is, $k_{\text{eff}} \approx 300$ pci. This result is different from the 305 figure that the textbook indicates as the correct answer; my explanation for the disparity is the following. Computing the relative damage contributions given by (II) with an exponent of 3.24 instead of 3.42 yields a cumulative damage of 601.8, which in turn leads to a 12-month average of 50.15. Substituting this $\bar{u}_r$ into (II) and solving for k_{eff}, again using an exponent of 3.24, we get

```
In[120]:= Solve[(8.5^0.75 - 0.39 * keff^0.25)^3.24 == 50.15, keff]

Solve: Inverse functions are being used by Solve, so some solutions may not be found; use
Reduce for complete solution information.

Out[120]= {{keff → 305.275}}
```

that is, k_{eff} = 305 pci in this case. In short, my guess is that whoever prepared the "official" solutions used an exponent of 3.24 instead of 3.42 in equation (12.30): I stand by my reviewed solution, which gives $k_{eff} \approx 300$ pci.

P.12.9 ■ Solution

The equation in question is (5.7), namely

$$k = 0.95\left(\frac{E_f}{E}\right)^{\frac{1}{3}} \frac{E_f}{\left(1-\nu_f^2\right)h}$$

Here, $E_f = M_R$, $E = 4\times10^6$ psi, $\nu_f = 0.45$, and $h = D = 8.5$ in., giving

$$k = 0.95\left(\frac{M_R}{4\times10^6}\right)^{\frac{1}{3}} \frac{M_R}{\left(1-0.45^2\right)\times 8.5} = 8.83\times10^{-4} M_R^{4/3} \quad \text{(I)}$$

The expression for cumulative damage is no different from the one used in the previous problem,

$$u_r = \left(D^{0.75} - 0.39k^{0.25}\right)^{3.42} \quad \text{(II)}$$

The data are processed below.

Month	M_R (psi)	k (pci) (Eq. I)	u_r (Eq. II)
JAN	15900	353.0	58.6
FEB	27300	725.8	40.6
MAR	38700	1155.9	30.0
APR	50000	1626.5	23.0
MAY	900	7.7	150.1
JUNE	1620	16.8	134.1
JULY	2340	27.4	123.2
AUGUST	3060	39.2	114.8
SEPTEMBER	3780	52.0	107.9
OCTOBER	4500	65.6	102.2
NOVEMBER	4500	65.6	102.2
DECEMBER	4500	65.6	102.2
		Total =	1088.8

Dividing the cumulative u_r by 12 gives 90.7. Substituting into (II),

$$\bar{u}_r = \left(D^{0.75} - 0.39k_{\text{eff}}^{0.25}\right)^{3.42} = 90.7$$

$$\therefore \left(8.5^{0.75} - 0.39k_{\text{eff}}^{0.25}\right)^{3.42} = 90.7$$

As before, we apply the Mathematica code

```
In[128]:= Solve[(8.5^0.75 - 0.39 * keff^0.25)^3.42 == 90.7, keff]
  Solve: Inverse functions are being used by Solve, so some solutions may not be found; use
  Reduce for complete solution information.
Out[128]= {{keff → 102.911}}
```

Clearly, $k_{\text{eff}} \approx 103$ pci.

▶ REFERENCE

- HUANG, Y.H. (2004). *Pavement Analysis and Design*. 2nd edition. Upper Saddle River: Pearson.

Got any questions related to this quiz? We can help!
Send a message to contact@montogue.com and we'll
answer your question as soon as possible.