Lect. 8 ***Pavement Structural Design***

Flexible Pavement Design-Part3
(AASHTOO Method, Design Equations)

Main Sources

- *"AASHTO Guide for Design of Pavement Structures 1993", AASHTO, American Association of State Highway and Transportation Officials, U.S.A., 1993.*
- *Yaug H. Huang, "Pavement Analysis and Design", Prentic Hall Inc., U.S.A., 2004.*
- *Nicholas J. Garber and Lester A. Hoel."Traffic and Highway Engineering", Fourth Edition.*
- *Yoder; E. J. and M. W. Witczak, "Principles of Pavement Design", A Wiley- Interscience Publication, John Wiley & Sons Inc., U.S.A., 1975.*
- *A.T. Papagiannakis and E. A. Masad "Pavement Design and Materials", 2008, Published by john Wiley & Sons, Inc.*

AASHTO Method,

Design Equations

The original equations were based purely on the results of the AASHO Road Test *but were modified* later by theory and experience to take care of sub-grade and climatic conditions other than those encountered in the Road Test.

Original Equations The following are the basic equations developed from the AASHO Road Test for flexible pavements (HRB, 1962) :

$$G_t = \beta(\log W_t - \log \rho) \tag{11.29}$$

$$\beta = 0.40 + \frac{0.081\,(L_1 + L_2)^{3.23}}{(\mathrm{SN} + 1)^{5.19} L_2^{3.23}} \tag{11.30}$$

$$\log \rho = 5.93 + 9.36 \log(\mathrm{SN} + 1) - 4.79 \log(L_1 + L_2) + 4.33 \log L_2 \tag{11.31}$$

Here,

G_t = logarithm of the ratio of loss in serviceability at time t to the potential loss taken at a point where $p_t = 1.5$, or $G_t = \log[(4.2 - p_t)/(4.2 - 1.5)]$, noting that 4.2 is the initial serviceability for flexible pavements;

β = a function of design and load variables, as shown by Eq. 11.30, that influences the shape of ρ versus W_t curve;

ρ = a function of design and load variables, as shown by Eq. 11.31, that denotes the expected number of load applications to a p_t of 1.5, as can be seen from Eq. 11.29, where $\rho = W_t$ when $p_t = 1.5$;

W_t = axle load application at end of time t;

p_t = serviceability at end of time t;

L_1 = load on one single axle or a set of tandem axles, in kip;

L_2 = axle code—1 for single axle, 2 for tandem axle;

SN = structural number of pavement, which was computed as

$$\mathrm{SN} = a_1D_1 + a_2D_2 + a_3D_3 \tag{11.32}$$

in which a_1, a_2, and a_3 are layer coefficients for the surface, base, and subbase, respectively, and D_1, D_2, and D_3 are the thicknesses of the surface, base, and subbase, respectively.

The procedure is greatly simplified if an equivalent 18-kip (80-kN) single axle load is used. By combining Eqs. 11.29, 11.30, and 11.31 and setting $L_1 = 18$ and $L_2 = 1$, we obtain the equation

$$\log W_{t18} = 9.36\log(\mathrm{SN} + 1) - 0.20 + \frac{\log[(4.2 - p_t)/(4.2 - 1.5)]}{0.4 + 1094/(\mathrm{SN} + 1)^{5.19}} \tag{11.33}$$

in which W_{t18} is the number of 18-kip (80-kN) single-axle load applications to time t and p_t is the terminal serviceability index. Equation 11.33 is applicable only to the flexible pavements in the AASHO Road Test with an effective subgrade resilient modulus of 3000 psi (20.7 MPa).

Modified Equations For other sub-grade and environmental conditions, Eq.11.33 is modified to:

$$\log W_{t18} = 9.36\log(\mathrm{SN} + 1) - 0.20 + \frac{\log[(4.2 - p_t)/(4.2 - 1.5)]}{0.4 + 1094/(\mathrm{SN} + 1)^{5.19}} + 2.32\log M_R - 8.07 \tag{11.34}$$

in which M_R is the effective roadbed soil resilient modulus. Note that when M_R = 3000 psi (20.7 MPa), Eq. 11.34 is identical to Eq. 11.33

To take local precipitation and drainage conditions into account, Eq.11.32 was modified to:

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \tag{11.35}$$

in which m_2 is the drainage coefficient of base course and m_3 is the drainage coefficient of subbase course.

Equation 11.34 is the performance equation that gives the allowable number of 18-kip (80-kN) single-axle load applications W_{t18} to cause the reduction of PSI to p_t.

If the predicted number of applications $W18 = W_{t18}$ the reliability of the design is only 50%, because all variables in Eq.11.34 are based on mean values.

To achieve a higher level of reliability, W_{18} must be smaller than W_{t18} by a normal deviate Z_R , as shown in Figure 11.24 :

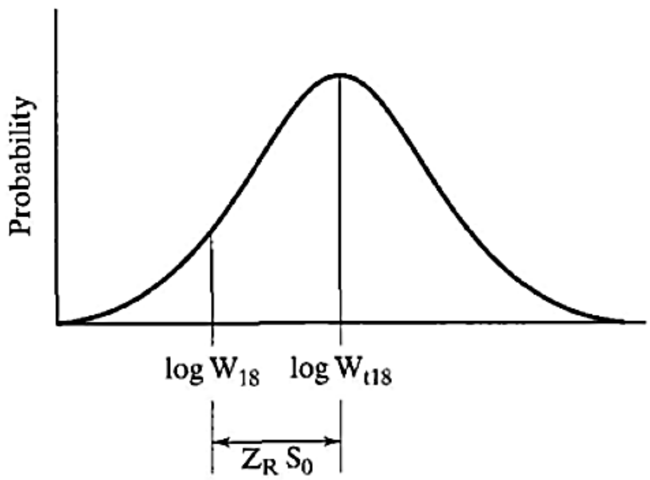


FIGURE 11.24
Reliability of design based on ESAL.

$$Z_R = \frac{\log W_{18} - \log W_{t18}}{S_0} \tag{11.36}$$

Here, ZR is the normal deviate for a given reliability R, and
So is the standard deviation

	Standard Deviation, S_o
Flexible pavements	0.40–0.50
Rigid pavements	0.30–0.40

ZR can be determined from Table 10.1 or, more conveniently, from Table 11.15.

TABLE 11.15 Standard Normal Deviates for Various Levels of Reliability

Reliability (%)	Standard normal deviate (Z_R)	Reliability (%)	Standard normal deviate (Z_R)
50	0.000	93	−1.476
60	−0.253	94	−1.555
70	−0.524	95	−1.645
75	−0.674	96	−1.751
80	−0.841	97	−1.881
85	−1.037	98	−2.054
90	−1.282	99	−2.327
91	−1.340	99.9	−3.090
92	−1.405	99.99	−3.750

Combining Eqs . 11.34 and 1.36 and replacing (4.2 – p_t) by ΔPSI yields.

$$\log W_{18} = Z_R S_0 + 9.36 \log(\text{SN} + 1) - 0.20 + \frac{\log[\Delta\text{PSI}/(4.2 - 1.5)]}{0.4 + 1094/(\text{SN} + 1)^{5.19}} + 2.32 \log M_R - 8.07 \qquad (11.37)$$

Equation 11.37 is the final design equation for flexible pavements.

Figure 11.25 is a monograph for solving Eq . 11.37.

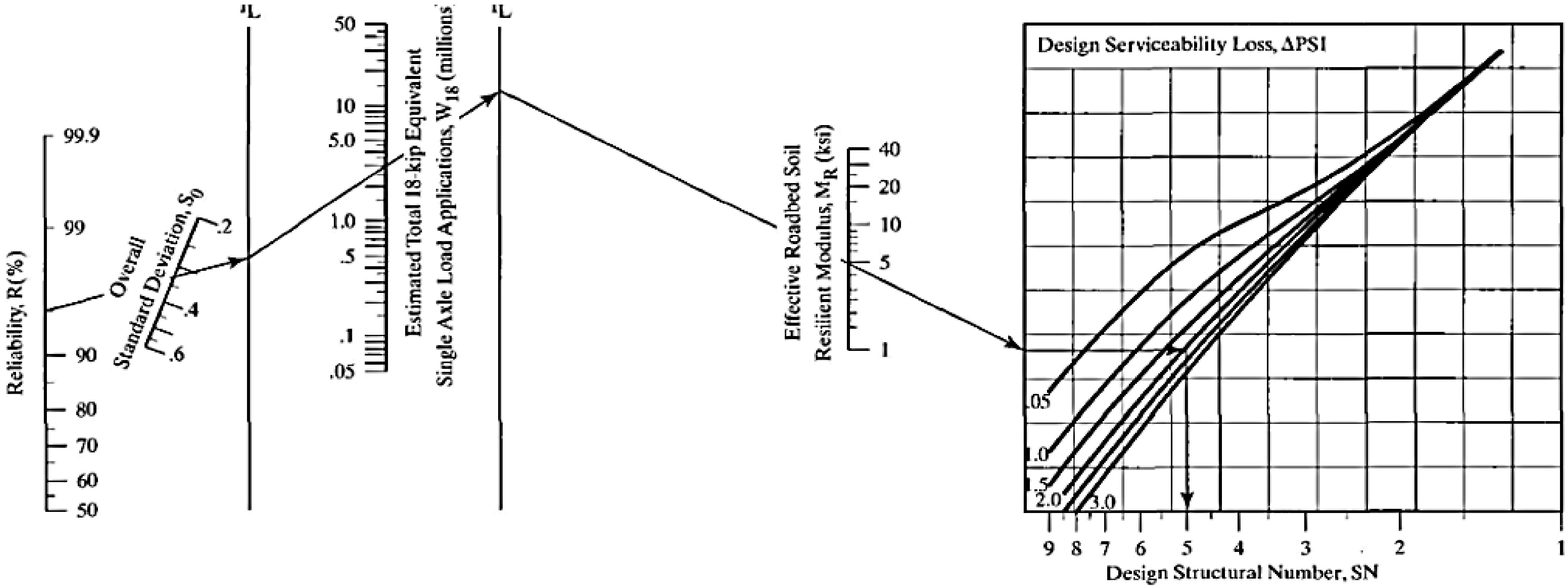


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

Steps to use 11.25 is a monograph for solving Eq. 11.37.

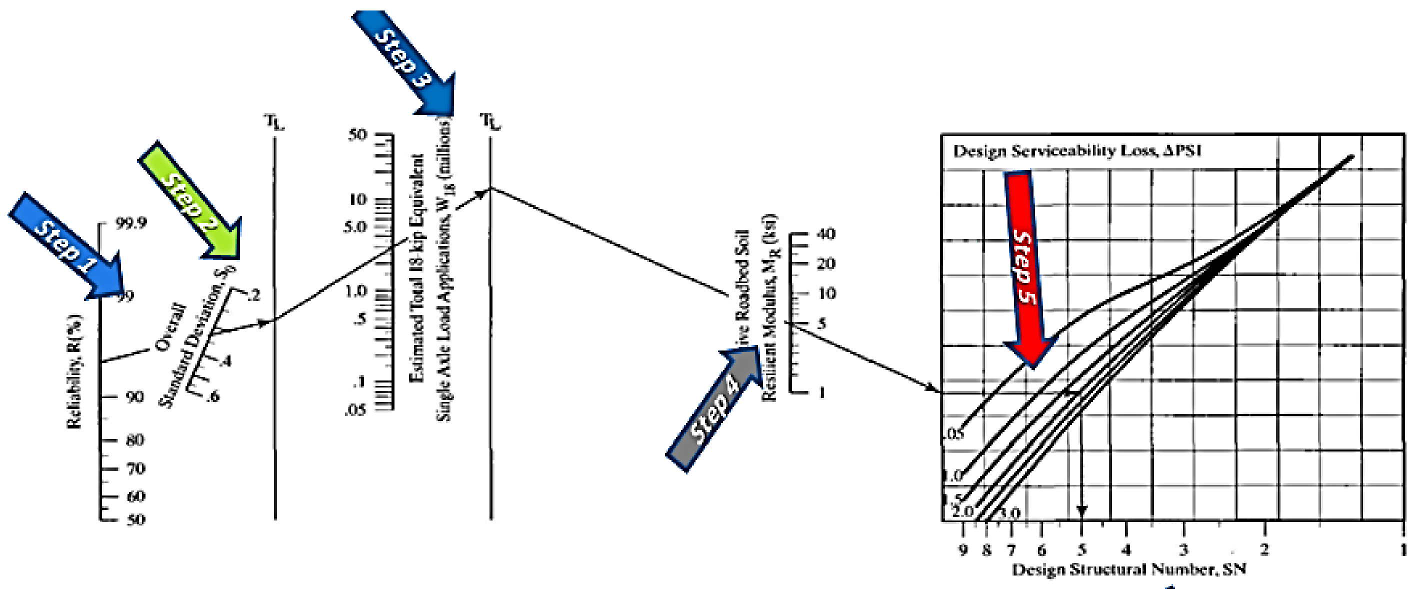


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

Example: (11.10)

Given $W_{18} = 5 \times 10^6$, $R = 95\%$, $S_0 = 0.35$, $M_R = 5000$ psi (34.5 MPa), and $\Delta PSI = 1.9$, determine SN from Figure 11.25.

Solution:

As shown by the arrows in Figure 11.25,

Step 1: starting from R = 95%, series of lines are drawn through;

Step 2: S_0=0.35;

Step 3: $W_{18}=5*10^6$;

Step 4: M_R = 5000 Psi

Step 5: ΔPSI=1.9

And finally intersect SN at 5.0, so SN = 5.0.

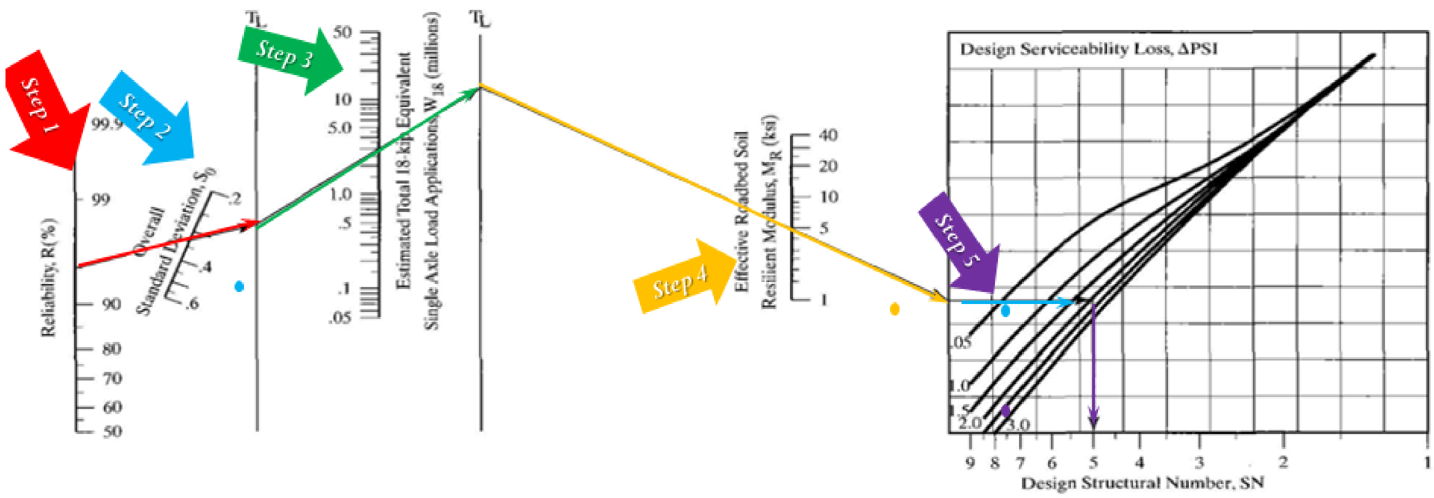


FIGURE 11.25

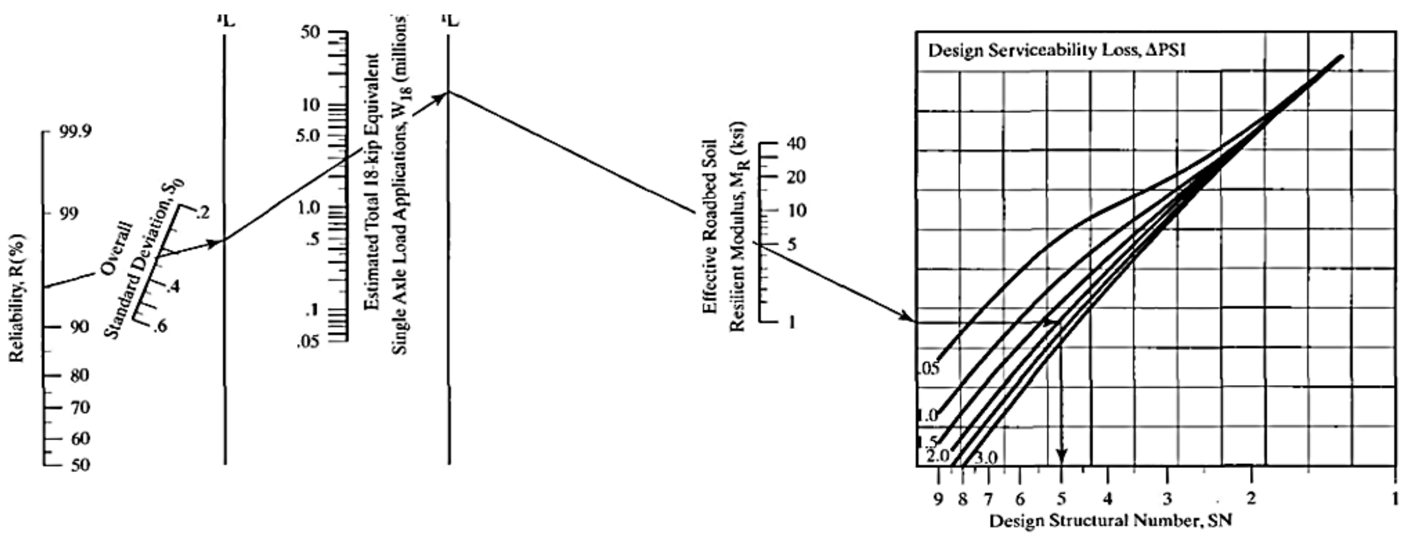


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

The chart is most convenient for determining SN, because the solution of SN by Eq.11.37 is cumbersome and requires a trial and error process. If W_{18} is the unknown to be determined, the use of Eq. 11.37 is more accurate.

Example: (11.11)

Given $R = 95\%$, SN = 5, $S_0 = 0.35$, $M_R = 5000$ psi (34.5 MPa), $\Delta PSI = 1.9$, determine W_{18} by Eq. 11.37.

Solution

Given R = 95%, from Table 11.15, $Z_R = -1.645$.

TABLE 11.15 Standard Normal Deviates for Various Levels of Reliability

Reliability (%)	Standard normal deviate (Z_R)	Reliability (%)	Standard normal deviate (Z_R)
50	0.000	93	−1.476
60	−0.253	94	−1.555
70	−0.524	95	−1.645
75	−0.674	96	−1.751
80	−0.841	97	−1.881
85	−1.037	98	−2.054
90	−1.282	99	−2.327
91	−1.340	99.9	−3.090
92	−1.405	99.99	−3.750

From Eq. 11 .37,

$$\log W_{18} = Z_R S_0 + 9.36 \log(SN+1) - 0.2 + \frac{\log[\frac{\Delta PSI}{4.2-1.5}]}{0.4 + 1094/(SN+1)^{5.19}} + 2.32 \log M_R - 8.07 \quad (11.37)$$

$$\log W_{18} = -1.645 * 0.35 + 9.36 \log(5+1) - 0.2 + \frac{\log[\frac{1.9}{2.7}]}{0.4 + 1094/(5+1)^{5.19}} + 2.32 \log(5000) - 8.07$$

$$\log W_{18} = 6.714$$

$$W_{18} = 5.18 * 10^6$$

Effective Roadbed Soil Resilient Modulus

The effective roadbed soil resilient modulus M_R is an equivalent modulus that would result in the same damage if seasonal modulus values were actually used.

Relative Damage From Eq. 11.37, the effect of M_R on W_{18} can be expressed as

$$\log W_{18} = Z_R S_0 + 9.36 \log(SN+1) - 0.2 + \frac{\log[\frac{\Delta PSI}{4.2-1.5}]}{0.4 + 1094/(SN+1)^{5.19}} + 2.32 \log M_R - 8.07 \quad (11.37)$$

$$\log W_{18} = \log C - \log(1.18 \times 10^8 M_R^{-2.32}) \quad (11.38)$$

in which log C is the sum of all but the last two terms in Eq. 11.37.

Equation 11.38 can be written as:

$$W_{18} = \frac{C}{1.18 \times 10^8 M_R^{-2.32}} \quad (11.39)$$

If W_T is the predicted total traffic, the damage ratio, which is a ratio between predicted and allowable number of load repetitions, can be expressed as

$$D_r = \frac{W_T}{C/(1.18 \times 10^8 M_R^{-2.32})} = \frac{W_T}{C}(1.18 \times 10^8 M_R^{-2.32}) \quad (11.40)$$

If W_T is uniformly distributed over n periods, the cumulative damage ratio is:

$$D_r = \sum_{i=1}^{n} \frac{W_T/n}{C/(1.18 \times 10^8 M_{Ri}^{-2.32})} = \frac{W_T}{C}\frac{1}{n}\sum_{i=1}^{n}(1.18 \times 10^8 M_{Ri}^{-2.32}) \quad (11.41)$$

Equating Eq. 11.40 to Eq. 11.41 gives:

$$1.18 \times 10^8 M_R^{-2.32} = \frac{1}{n}\sum_{i=1}^{n}(1.18 \times 10^8 M_{Ri}^{-2.32}) \quad (11.42)$$

Equation 11.42 can be used to determine the effective roadbed soil resilient modulus

M_R in terms of seasonal moduli M_{Ri}. Although the coefficient 1.18×108 can be canceled out to simplify the equation, the AASHTO design guide keeps the coefficient and defines the relative damage u_f as:

$$u_f = 1.18 \times 10^8 M_R^{-2.32} \tag{11.43}$$

Computation of Effective Roadbed Soil Resilient Modulus

Figure 11.26 is a worksheet for estimating effective roadbed soil resilient modulus, in which Eq. 11.43, together with a vertical scale for graphical solution of u_f, is also shown.

Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.	15,900	0.02
Feb.	27,300	0.01
Mar.	38,700	0.00
Apr.	50,000	0.00
May	900	16.52
June	1,620	4.22
July	2,340	1.80
Aug.	3,060	0.97
Sept.	3,780	0.59
Oct.	4,500	0.39
Nov.	4,500	0.39
Dec.	4,500	0.39
Summation: Σu_f =		25.30

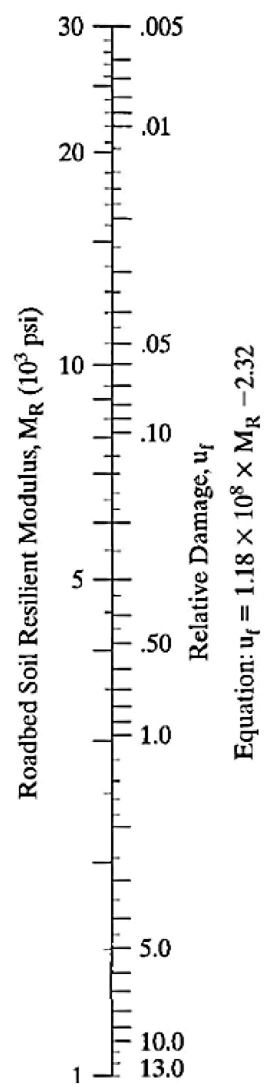


FIGURE 11.2 6
Worksheet for estimating effective roadbed soil resilient modulus (1 psi = 6 .9 kPa)

A year is divided into a number of periods during which different roadbed soil resilient moduli are specified. The shortest time period is half a month. These seasonal moduli can be determined from correlations with soil moisture and temperature conditions or from nondestructive deflection testing.

In the worksheet, the 12 monthly subgrade moduli used in the DAMA program for a MAAT of 45°F (7.2°C) and a normal modulus of 4500 psi (31 MPa), as shown in Table 11.10, are used as an example .

TABLE 11.10 Subgrade Modulus Used in the DAMA Program

MAAT	modulus Normal (psi)	Subgrade modulus by month (10^3 psi)											
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
45°F	4500	4.5	15.9	27.3	38.7	50.0	0.9	1.62	2.34	3.06	3.78	4.5	4.5
	12,000	12.0	21.5	31.0	40.5	50.0	6.0	7.20	8.40	9.60	10.8	12.0	12.0
(7°C)	22,500	22.5	29.4	36.3	43.1	50.0	15.8	17.1	18.5	19.8	21.2	22.5	22.5
60°F	4500	4.5	4.5	27.3	50.0	1.35	2.14	2.93	3.71	4.5	4.5	4.5	4.5
	12,000	12.0	12.0	31.0	50.0	7.2	8.4	9.6	10.8	12.0	12.0	12.0	12.0
(15.5°C)	22,500	22.5	22.5	38.3	50.0	18.0	19.1	20.3	21.4	22.5	22.5	22.5	22.5

Note. 1 psi = 6.9 kPa.
Source. After AI (1982).

The relative damage during *each* month can be obtained from the vertical scale or computed from Eq. 11.43; the sum, 25.30, is shown at the bottom.

The average relative damage = 25.30/12 =2.11, which corresponds to an effective roadbed resilient modulus of 2200 psi (15.2 MPa) .

$$\text{Average: } \bar{u}_f = \frac{\Sigma u_f}{n} = \underline{2.11}$$

In the preceding example, there is a large variation in the monthly resilient modulus. The maximum and minimum values are outside the range of the vertical scale and must be computed from Eq . 11.43. About 65% of the damage is done in May alone.

This is the reason that a very low effective modulus, 2200 psi (15.2 MPa), is obtained, one much lower than the normal modulus, 4500 psi (31.1 MPa).

11.8 For a mean annual air temperature of 45°F and a normal modulus of 22,500 psi, determine the effective roadbed soil resilient modulus for the monthly moduli shown in Table 11.10 [Answer: 22,200 psi]

Solution

From Table 11-10, at 45°F and Modulus Normal=22500 psi, the marked subgrade modulus by month are used to compute the uf

TABLE 11.10 Subgrade Modulus Used in the DAMA Program

MAAT	modulus Normal (psi)	Subgrade modulus by month (10^3 psi)											
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
45°F	4500	4.5	15.9	27.3	38.7	50.0	0.9	1.62	2.34	3.06	3.78	4.5	4.5
	12,000	12.0	21.5	31.0	40.5	50.0	6.0	7.20	8.40	9.60	10.8	12.0	12.0
(7°C)	22,500	22.5	29.4	36.3	43.1	50.0	15.8	17.1	18.5	19.8	21.2	22.5	22.5
60°F	4500	4.5	4.5	27.3	50.0	1.35	2.14	2.93	3.71	4.5	4.5	4.5	4.5
	12,000	12.0	12.0	31.0	50.0	7.2	8.4	9.6	10.8	12.0	12.0	12.0	12.0
(15.5°C)	22,500	22.5	22.5	38.3	50.0	18.0	19.1	20.3	21.4	22.5	22.5	22.5	22.5

Note. 1 psi = 6.9 kPa.
Source. After AI (1982).

Month	Subgrade modulus by month (10^3psi)	Uf $u_{f}=1.18*10^{8}M_R^{-2.32}$
Dec	22.5	0.009437
Jan	29.4	0.005074
Feb	36.3	0.003111
Mar	43.1	0.002089
Apr	50.0	0.00148
May	15.8	0.021429
Jun	17.1	0.017837
Jul	18.5	0.014861
Aug	19.8	0.012695
Sep	21.2	0.010834
Oct	22.5	0.009437
Nov	22.5	0.009437
Total		**0.117719**
Average uf		**0.00981**

$M_R = ((0.00981/(1.18*10^8))^{(-1/2.32)} = 22127$ psi

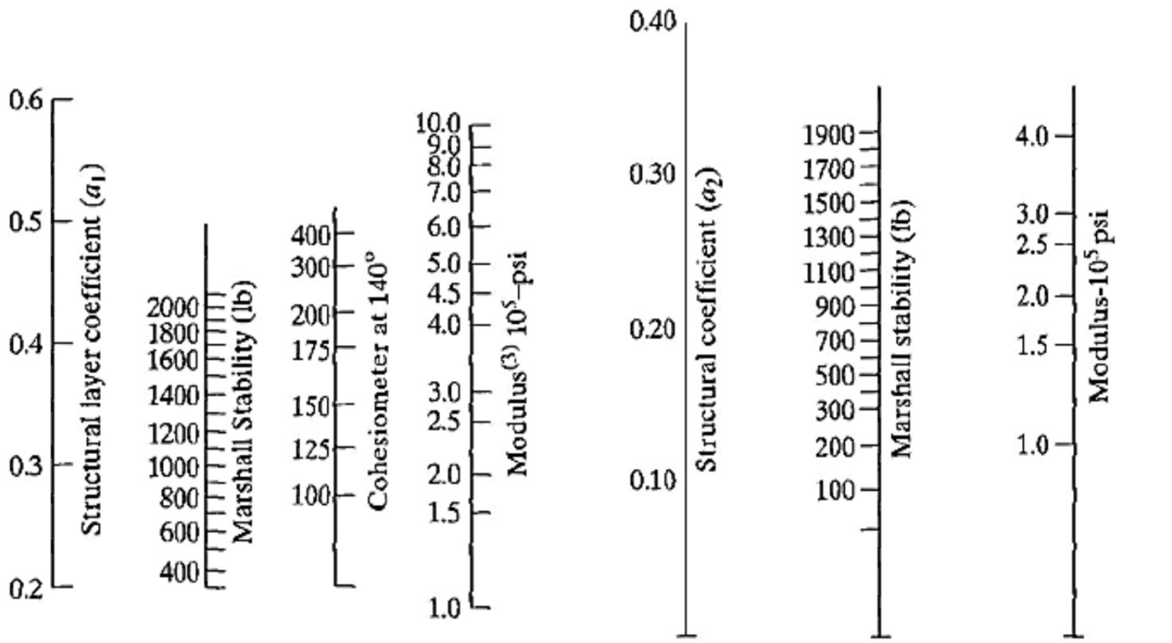
Structural Number

Structural number is a function of **layer thicknesses**, **layer coefficients**, and **drainage coefficients** and can be computed from Eq. 11.35.

$$\mathrm{SN} = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \tag{11.35}$$

Layer Coefficient:

The layer coefficient a, is a measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement. Layer coefficients can be determined from test roads or satellite sections, as was done in the AASHO Road Test, or from correlations with material properties, as was shown in Figures 7.13, 7.15, and 7.16.



(a) Surface Course (b) Base Course

FIGURE 7.13

Correlation charts for estimating resilient modulus of HMA (1 lb = 4.45 N, 1 psi = 6.9 kPa). (After Van Til *et al.* (1972).)

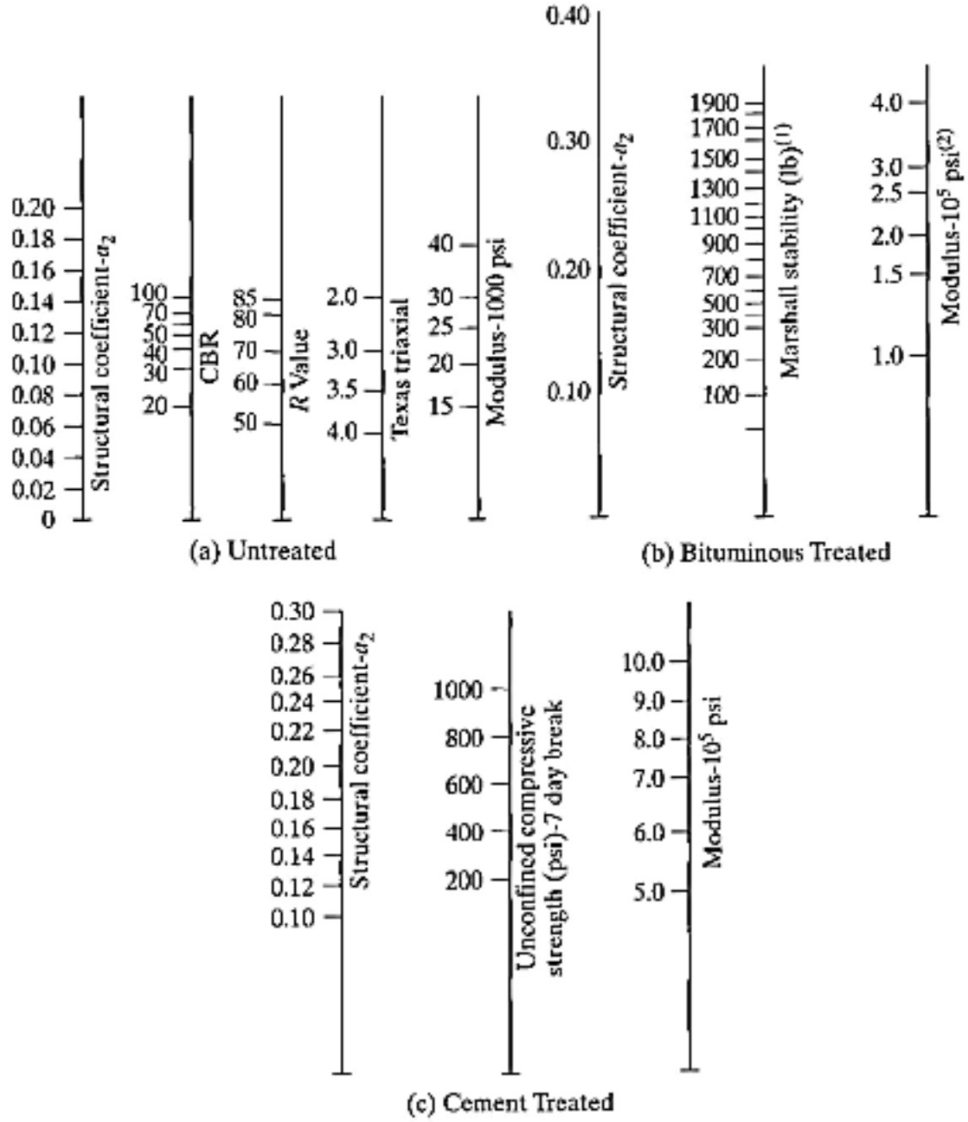


FIGURE 7.15

Correlation charts for estimating resilient modulus of bases (1 lb = 4.45 KN, 1 psi = 6.9 kPa). (After Van Til *et al.* (1972).)

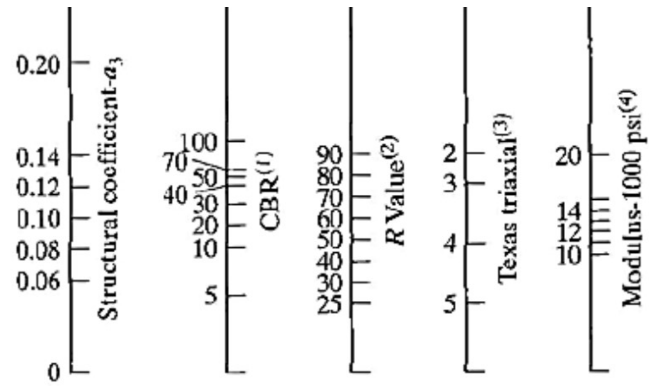


FIGURE 7.16
Correlation chart for estimating resilient modulus of subbases (1 psi = 6.9 kPa). (After Van Til *et al.* (1972).)

It is recommended that the layer coefficient be based on the resilient modulus, which is a more fundamental material property.

In following the AASHTO design guide, the notation M_R, as used herein, refers only to roadbed soils, whereas El, E2, and E3 apply to the HMA, base, and subbase, respectively.

Asphalt—Concrete Surface Course.

Figure 11.27 is a chart relating the layer coefficient of a dense-graded HMA to its resilient modulus at 70°F (21°C).

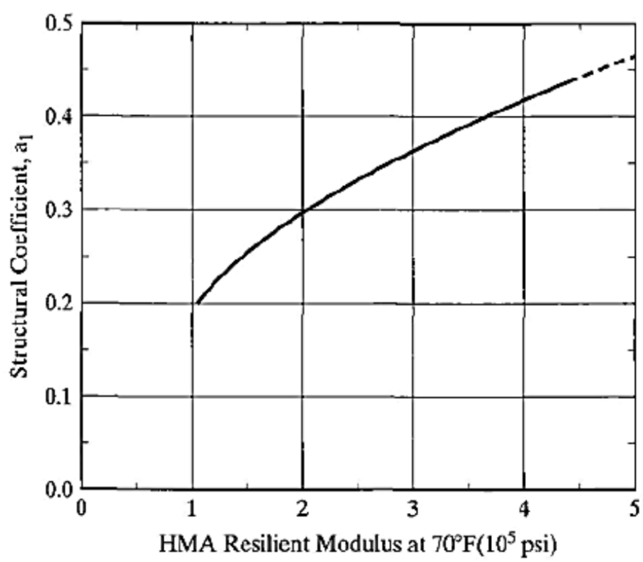


FIGURE 11.27
Chart for estimating layer coefficient of dense-graded asphalt concrete based on elastic modulus (1 psi = 6.9 kPa). (After Van Til et al. (1972).)

Caution should be used in selecting layer coefficients with modulus values greater than 450,000psi (3.1 GPa), because the use of these larger moduli is accompanied by increased susceptibility to thermal and fatigue cracking.
The layer coefficient ***a₁* for the dense-graded HMA** used in the AASHO Road Tests is **0.44,** which corresponds to **a resilient modulus of 450,000 psi** (3.1 GPa).

Untreated and Stabilized Base Courses

Figure 7.15 shows the charts that can be used to estimate the layer coefficient a_2 for untreated, bituminous-treated, and cement-treated base courses.

In lieu of Figure 7.15a, the following equation can also be used to estimate a_2 for an untreated base course from its resilient modulus E_2:

$$a_2 = 0.249(\log E_2) - 0.977 \tag{11.44}$$

The layer coefficient a_2 for the granular base material used in the AASHO Road Test **is 0.14,** which corresponds to a base **resilient modulus of 30,000 psi** (207 GPa).

The resilient modulus of untreated granular materials depends on the stress state
θ, as indicated by Eq. 3.8 and rewritten here as:

$$E_2 = K_1\,\theta^{K_2} \tag{11.45}$$

Typical values of K_1 for base materials range from 3000 to 8000; those of K_2 range from 0.5 to 0.7. Values of K_1 and K_2 for each specific base material should be determined using AASHTO Method T274.

In the absence of this information, the values shown in Table 11.16 can be used.

TABLE 11.16 Typical Values of K_1 and K_2 for Untreated Base Materials

Moisture condition	K_1	K_2
Dry	6000–10,000	0.5–0.7
Damp	4000–6000	0.5–0.7
Wet	2000–4000	0.5–0.7

Source. After AASHTO (1986).

The resilient modulus of the base course is a function not only of $K1$ and K2, but also of the stress stateθ. Values for the stress state within the base course vary with the roadbed soil resilient modulus and with the thickness of the surface layer.

Typical values of θ are shown in Table 11.17. Given K_1, K_2, andθ, E_2 can be determined from Eq. 11.45.

TABLE 11.17 Typical Values of Stress State θ for Base Course

Asphalt concrete thickness (in.)	Roadbed soil resilient modulus (psi)		
	3000	7500	15,000
Less than 2	20	25	30
2–4	10	15	20
4–6	5	10	15
Greater than 6	5	5	5

Note. Unit of θ is in psi, 1 in. = 25.4 mm, 1 psi = 6.9 kPa.
Source. After AASHTO (1986).

Granular Subbase Course

Figure 7.16 provides the chart that may be used to estimate layer coefficient a_3 of granular subbase courses. The relationship between a_3 and E_3 can be expressed as

$$a_3 = 0.227(\log E_3) - 0.839 \qquad (11.46)$$

The **layer coefficient a_3 for the granular subbase** in the AASHO Road Test is **0.11,** which corresponds to **a resilient modulus of 15,000 psi** (104 MPa).

As with granular base courses, values of K_1 and K_2 for granular subbase courses can be determined from the resilient modulus test (AASHTO T274) or estimated from Table 11.18.

TABLE 11.18 Typical Values of K_1 and K_2 for Granular Subbase Materials

Moisture condition	K_1	K_2
Dry	6000–8000	0.4–0.6
Damp	4000–6000	0.4–0.6
Wet	1500–4000	0.4–0.6

Source. After AASHTO (1986).

Values of $K1$, $K2$, θ, and E_3 for the subbase in the AASHO Road Test are shown in Table 11.19 .

TABLE 11.19 Values of Resilient Modulus for AASHO Road Test Subbas Materials

			Stress state θ (psi)		
Moisture condition	K_1	K_2	5	7.5	10
Damp	5400	0.6	14,183	18,090	21,497
Wet	4600	0.6	12,082	15,410	18,312

Note. Resilient modulus is in psi; 1 psi = 6.9 kPa.
Source. After Finn *et al.* (1986).

Drainage Coefficient

Depending on the quality of drainage and the availability of moisture, drainage coefficients ***m_2* and *m_3* should be applied to granular bases and subbases** to modify the layer coefficients, as shown in Eq. 11.35.

At the AASHTO Road Test site, **these drainage coefficients are all equal to 1,** as indicated by Eq. 11.32.

Table 11.20 shows the recommended drainage coefficients for untreated base and subbase materials in flexible pavements. The quality of drainage is measured by the length of time for water to be removed from bases and subbases and depends primarily on their permeability. The percentage of time during which the pavement structure is exposed to moisture levels approaching saturation depends on the average yearly rainfall and the prevailing drainage conditions.

TABLE 11.20 Recommended Drainage Coefficients for Untreated Bases and Subbases in Flexible Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	2 hours	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1 day	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1 week	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1 month	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	Never drain	1.05–0.95	0.95–0.75	0.75–0.40	0.40

Source. After AASHTO (1986).

Selection of Layer Thicknesses

Once the design structural number SN for an initial pavement structure is determined, it is necessary to select a set of thicknesses so that the provided SN, as computed by
Eq. 11.35 will be greater than the required SN.

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \tag{11.35}$$

Note that Eq. 11.35 does not have a single unique solution. Many combinations of layer thicknesses are acceptable, so their cost effectiveness along with the construction and maintenance constraints must be considered to avoid the possibility of producing an impractical design.
From a cost-effective view point, if the ratio of costs for HMA and granular base is less than the corresponding ratio of layer coefficients times the drainage coefficient, then the optimum economical design is to use a minimum base thickness by increasing the HMA thickness.

Minimum Thickness

It is generally impractical and uneconomical to use layers of material that are less than some minimum thickness. Furthermore, traffic considerations may dictate the use of a certain minimum thickness for stability.
Table 11.21 shows the minimum thicknesses of asphalt surface and aggregate base. Because such minimums depend somewhat on local practices and conditions, they may be changed if needed.

TABLE 11.21 Minimum Thickness for Asphalt Surface and Aggregate Base

Traffic (ESAL)	Asphalt concrete	Aggregate base
Less than 50,000	1.0	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Note. Minimum thickness is in in.; 1 in. = 25.4 mm.
Source. After AASHTO (1986).

General Procedure The procedure for thickness design is usually started from the top, as shown in Figure 11.28 and described as follows :

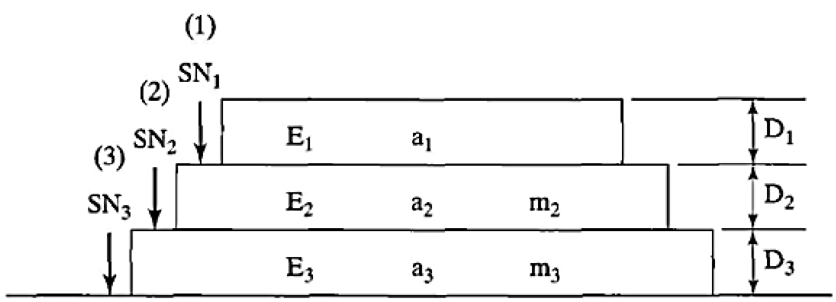


FIGURE 11.28
Selection of thicknesses.

1. Using E_2 as M_R, determine from Figure 11.25 the structural number SN_1 required to protect the base, and compute the thickness of layer 1 from

$$D_1 \geq \frac{SN_1}{a_1} \tag{11.47}$$

2. Using E_3 as M_R, determine from Figure 11.25 the structural number SN_2 required to protect the subbase, and compute the thickness of layer 2 from

$$D_2 \geq \frac{SN_2 - a_1 D_1}{a_2 m_2} \tag{11.48}$$

3. Based on the roadbed soil resilient modulus M_R, determine from Figure 11.25 the total structural number SN_3 required, and compute the thickness of layer 3 from

$$D_3 \geq \frac{SN_3 - a_1 D_1 - a_2 D_2 m_2}{a_3 m_3} \tag{11.49}$$

Example 11.12:

Figure 11.29 is a pavement system with the resilient moduli, layer coefficients, and drainage coefficients as shown. If predicted ESAL=18.6 x 10^6, R=95%, S_o=0.35, and ΔPSI=2.1, select thicknesses D_l, D_2, and D_3.

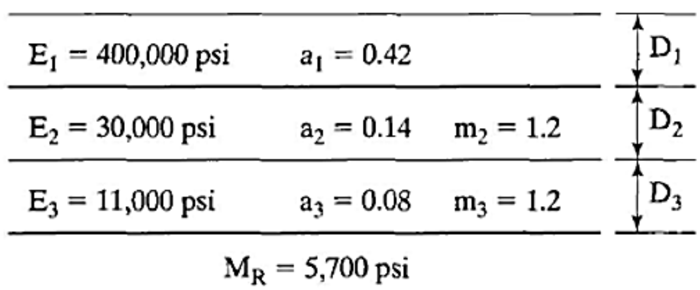


FIGURE 11.29
Example 11.12 (1 psi = 6.9 kPa).

Solution:

To select D_1 (thickness of the first layer),

With MR = E_2 = 30,000 psi (207 MPa),

from Figure 11.25, SN_1 = 3.2 ;….. الخط الاحمر

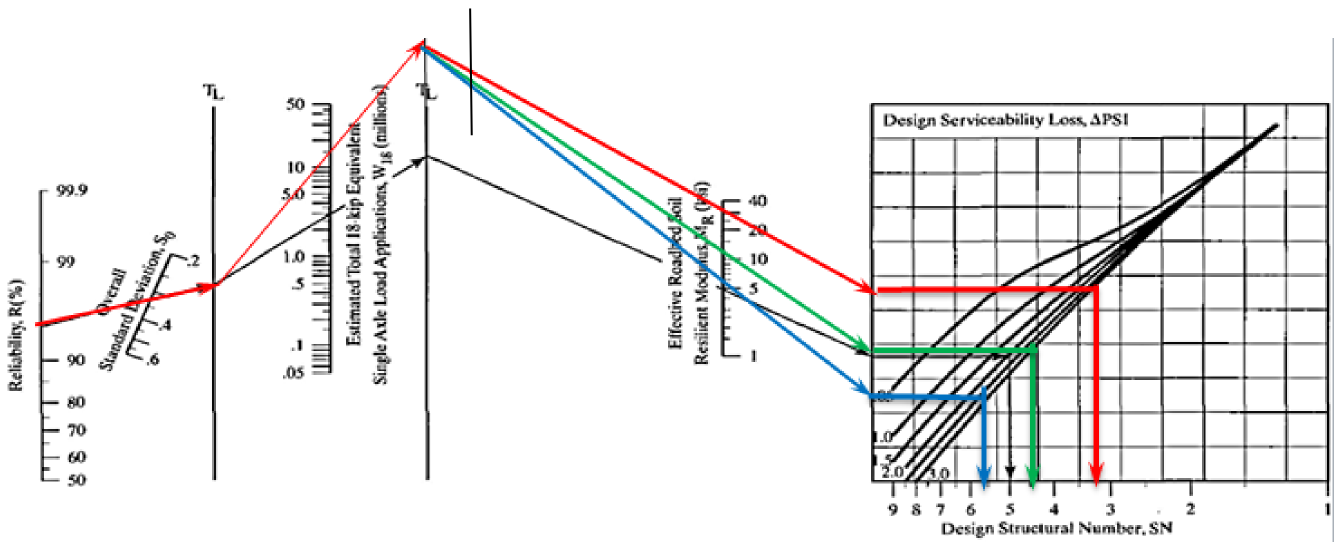


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

from Eq. 11.47 ,

$$D_1 \geq \frac{SN_1}{a_1} \qquad (11.47)$$

$D_1 \geq 3.2/0.42 = 7.6$ in. (193 mm); use $D_1 = 8$ in. (203 mm).

$D_1 = 8$ in $\geq$ minimum D_1 =(4 in) from table 11.21……. **OK**

TABLE 11.21 Minimum Thickness for Asphalt Surface and Aggregate Base

Traffic (ESAL)	Asphalt concrete	Aggregate base
Less than 50,000	1.0	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Note. Minimum thickness is in in.; 1 in. = 25.4 mm.
Source. After AASHTO (1986).

To select D_2 (thickness of the second layer),

With $MR = E_3$ = 11,000 psi (76 MPa),

from Figure 11.25, $SN_2 = 4.5$; ……الخط الاخضر

from Eq. 11.48,

$$D_2 \geq \frac{SN_2 - a_1 D_1}{a_2 m_2} \tag{11.48}$$

$D_2 \geq (4.5 - 0.42 \times 8) / (0.14 \times 1.2) = 6.8$ in. (173 mm);

use $D_2 = 7$ in. (178 mm). ≥ minimum D_2 =(6 in) from table 11.21…… **OK**

To select D_3 (thickness of the third layer),

With MR = 5700 psi (39.3 MPa),

from Figure 11.25, $SN_3 = 5.6$; ……الخط الازرق

from Eq . 11.49,

$$D_3 \geq \frac{SN_3 - a_1 D_1 - a_2 D_2 m_2}{a_3 m_3} \tag{11.49}$$

$D_3 \geq (5.6 - 0.42 \times 8 - 0.14 \times 7 \times 1.20) / (0.08 \times 1.2) = 11.1$ in. (282 mm);

use $D_3 = 11.5$ in. (292 mm) .

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. [Answer: 88%]

Solution

P_i=4.2, P_t=2.5, So=0.5, ESAL=30000000, R=?

a=0.44 12 in

10000psi

Using AASHTOO Equation

$SN_1 = D_1\, a_1 = 12*0.44 = 5.28$

$$\text{Log W18} = 9.36\log(SN+1) - 0.02 + \frac{\log\left[\frac{4.2-P_t}{4.2-1.5}\right]}{0.4+1094/(SN+1)^{5.19}} + 2.32\log M_R - 8.07$$

Log W18 = +9.36 log(5.28+1)-0.2+(Log((4.2-2.5)/(4.2-1.5))/(0.4+1094/(5.28+1)$^{5.19}$)+2.32log10000-8.07

Log W18=7.47-0.2-0.42+9.28-8.07=8.06……> Wt18=114,960,945.6

$$Z_R = \frac{\log W_{18} - \log W_{t18}}{S_O} \qquad (11.36)$$

ZR=(log $3*10^7$ – Log114,960,945.6)/0.5= 1.167

From table 11:15, R=88%

TABLE 11.15 Standard Normal Deviates for Various Levels of Reliability

Reliability (%)	Standard normal deviate (Z_R)	Reliability (%)	Standard normal deviate (Z_R)
50	0.000	93	−1.476
60	−0.253	94	−1.555
70	−0.524	95	−1.645
75	−0.674	96	−1.751
80	−0.841	97	−1.881
85	−1.037	98	−2.054
90	−1.282	99	−2.327
91	−1.340	99.9	−3.090
92	−1.405	99.99	−3.750

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 base 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 thicknesses of the surface, base, and subbase courses required. [Answer: 3 in., 6 in., and 9 in.]

Solution

Given, ESAL=$1.2*10^6$, drainage quality fair (water can be removed from the subbase within a week), 25% of the time the pavement will be exposed to moisture levels approaching saturation, D1=minimum, D2=?, D3=?

E1=430000 psi	D1
E2= ? psi	D2
E3=15000 psi	D3
MR=5500 psi	

1. D1=Minimum thickness , from table 11.21….>D1=3 in

2. $D2 \geq \frac{SN2 - a1\,D1}{a2\,m2}$

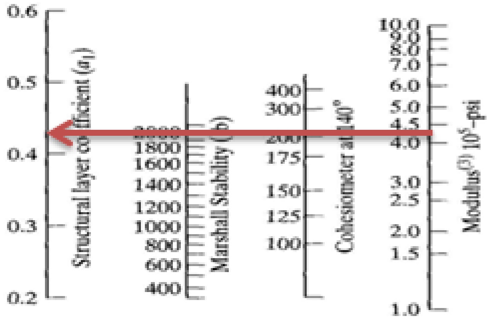
   Find SN2, a_1, a_2 and m_2

TABLE 11.21 Minimum Thickness for Asphalt Surface and Aggregate Base

Traffic (ESAL)	Asphalt concrete	Aggregate base
Less than 50,000	1.0	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

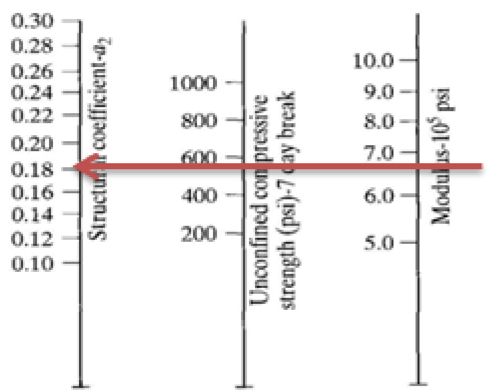
Note. Minimum thickness is in in.; 1 in. = 25.4 mm.
Source. After AASHTO (1986).

3. From Figure 7.13……> a_1=0.44



(a) Surface Course

4. from Figure 7.15 (b)……..> a_2= 0.18, E_2=650000 psi



(c) Cement Treated

5. m_2=m_3=0.8 from Table11.20

TABLE 11.20 Recommended Drainage Coefficients for Untreated Bases and Subbases in Flexible Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	2 hours	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1 day	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1 week	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1 month	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	Never drain	1.05–0.95	0.95–0.75	0.75–0.40	0.40

Source. After AASHTO (1986).

6. To find SN_2, use Figure 11.25, so we need to find R_o, S_o, and ΔPSI

7. From Table 11.14 , Find R_o=85%

TABLE 11.14 Suggested Levels of Reliability for Various Functional Classifications

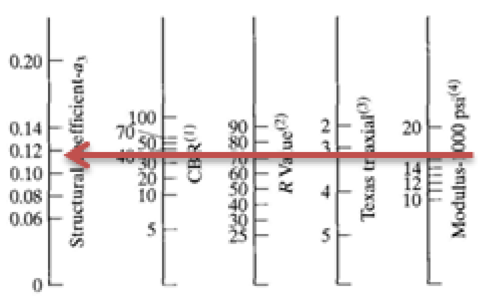
Functional classification	Recommended level of reliability	
	Urban	Rural
Interstate and other freeways	85–99.9	80–99.9
Principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Note. Results based on a survey of AASHTO Pavement Design Task Force.
Source. After AASHTO (1986).

8. So is not given, for flexible pavement assume $S_0 = 0.4$

	Standard Deviation, S_o
Flexible pavements	0.40–0.50

9. $W_{18}=1.2*10^6$
10. E_3=15000 psi (Given)
11. Assume P_i=4.2 and P_t=2.5….>ΔPSI=1.7
12. From Figure 11.25…..> SN_2=2.6
13. $D2 \geq \frac{SN2-a1\ D1}{a2\ m2} \geq \frac{2.6-0.44*3}{0.18*1} \geq 6.6\ in$….> 6.5 in
14. $D3 \geq \frac{SN3-a1\ D1-a2\ D2\ m2}{a3\ m3}$, ….>find SN_3 and a_3
15. From Figure 7.16…..> a_3=0.12



16. From Figure 11.25…..>SN_3=3.6
17. $D3 \geq \frac{3.6-0.44*3-0.18*6.5*1}{0.12*1} = 9.3\ in \ldots\ldots > D3 = 9.5\ in$

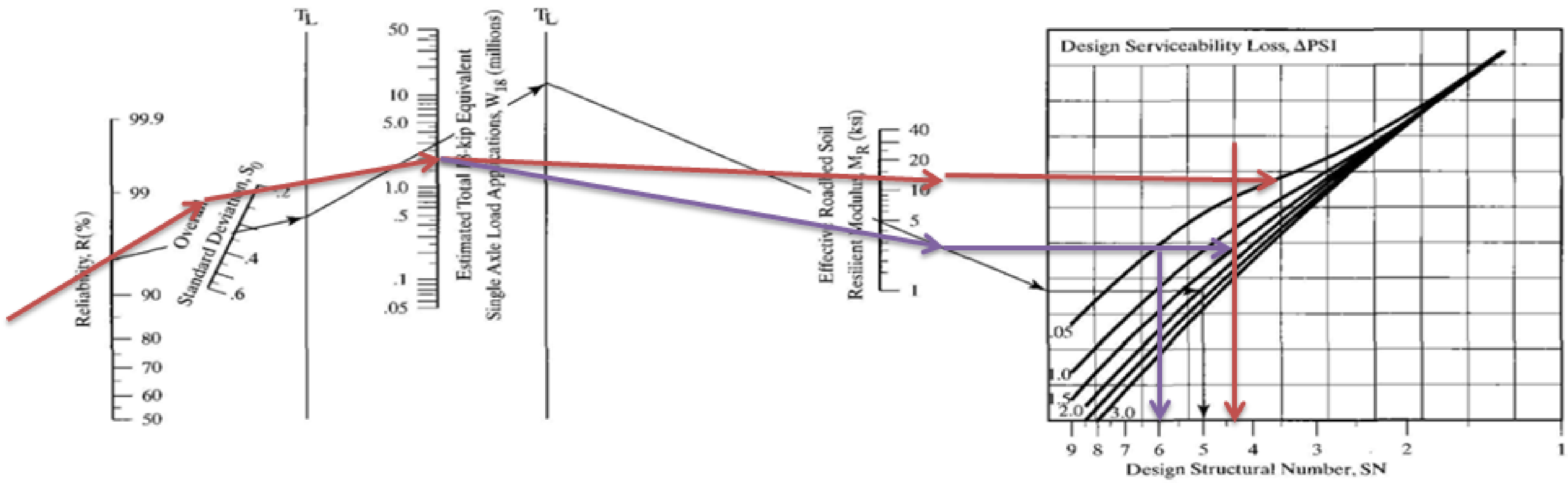


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

Question

Determine the thickness of the pavement courses layers of a principal arterial in a rural area with R=90% which its supposed layers and the properties of the used materials are shown in Figure 3. Given, ESAL=$3.0*10^6$. Assume S_0=0.35, $m_1=m_2$=1 and P_t=4.2 and p_i=2.5.

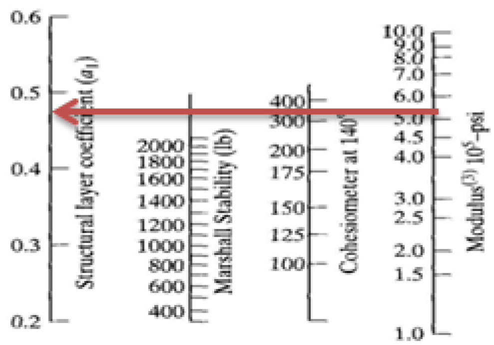
HMA surface	E1=500000 psi	D1
Untreated base course	E2= 20000 psi	D2
Sand gravel subbase	E3=15000 psi	D3
MR=5500 psi		

Solution

18. $D1 \geq \frac{SN1}{a1}$

Find SN_1 and a_1

19. From figure 7.13, a1= 0.46



(a) Surface Course

To find SN_1, use Figure 11.25, so we need to find R_o, S_o, and ΔPSI

20. From Table 11.14 , Find R_o=80%-90%......> assume R_0=90%

TABLE 11.14 Suggested Levels of Reliability for Various Functional Classifications

Functional classification	Recommended level of reliability: Urban	Rural
Interstate and other freeways	85–99.9	80–99.9
Principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Note. Results based on a survey of AASHTO Pavement Design Task Force.
Source. After AASHTO (1986).

21. W18=$1.0*10^6$ (Given), E_2=15000 psi (Given), ΔPSI=2.0 , S_o=0.35 (Given)

22. From Figure 11.25…..> SN1=2.4
23. D1≥$\frac{2.4}{0.46}$= 5.2 in…. take D1= 5.5 in
24. D1> min D1 (from table 11.21= 3 in)…..>OK

TABLE 11.21 Minimum Thickness for Asphalt Surface and Aggregate Base

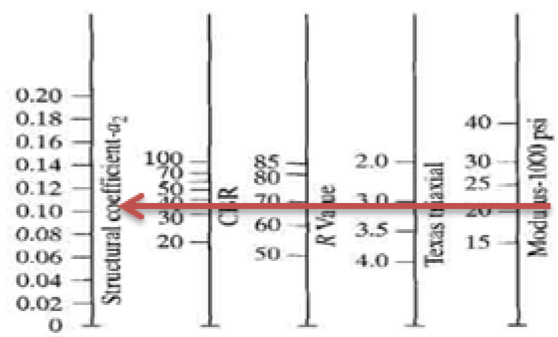
Traffic (ESAL)	Asphalt concrete	Aggregate base
Less than 50,000	1.0	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Note. Minimum thickness is in in.; 1 in. = 25.4 mm.
Source. After AASHTO (1986).

25. $D2 \geq \frac{SN2 - a1\ D1}{a2\ m2}$

Find SN2, a1, a2 and m2

26. from Figure 7.15 (a)……..> a2= 0.10



(a) Untreated

27. m_2=m_3 are equal or greater than 1 from Table11.20…..> take m_2=1.0

TABLE 11.20 Recommended Drainage Coefficients for Untreated Bases and Subbases in Flexible Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	2 hours	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1 day	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1 week	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1 month	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	Never drain	1.05–0.95	0.95–0.75	0.75–0.40	0.40

Source. After AASHTO (1986).

28. To find SN_2, use Figure 11.25,

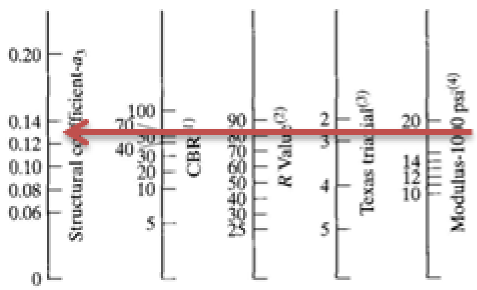
29. From Figure 11.25…..> SN2=2.9

30. $D2 \geq \frac{SN2 - a1\ D1}{a2\ m2} \geq \frac{2.9 - 0.46*5.5}{0.10*1} \geq 3.7\ in$

31. D2 is less than the minimum D2 from table 11.21…….> then take D2=minimum = 6 in.

32. $D3 \geq \frac{SN3 - a1\ D1 - a2\ D2\ m2}{a3\ m3}$, ….>find SN3 and a3

33. From Figure 7.16…..> a3=0.12



34. From Figure 11.25…..>SN3=4

35. $D3 \geq \frac{4 - 0.46*5.5 - 0.10*6*1}{0.12*1} = 7.25\ in \ldots\ldots > D3 = 7.5\ in$

Stage Construction

If the maximum performance period is less than the analysis period, any initial structure selected will require an overlay to last out the analysis period.

- The thickest recommended initial structure is that corresponding to the maximum performance period.
- Thinner initial structures, selected for the purpose of life cycle cost analyses, will result in shorter performance periods and require thicker overlays to last out the same analysis period.
- The design of the initial structure for stage construction works the same as that for new construction, except that the reliability must be compounded over all stages.
- If the loss of serviceability is caused by traffic loads alone, the length of the performance period, which is related to W_{18}, for a given serviceability loss can be determined from Figure 11.25 or directly from Eq. 11.37.
- However, if the serviceability loss is caused by both traffic loads and the environmental effects of roadbed swelling and frost heave, the performance period for a given terminal serviceability can be determined only by an iterative process, as illustrated by the following example.

Example 11.13:

Given the following design inputs, **determine the length of the performance period required.**

Structural number SN=5.0, reliability R = 95%, standard deviation S_o = 0.35, initial serviceability p_o = 4.3, terminal serviceability p_t = 2.5, effective roadbed soil resilient modulus MR = 5000 psi (35 MPa), ΔPSI due to both swelling and frost heave as shown in Figure 11.23, and traffic versus time relationship as

$$W_{18} = 10 \times 10^6 [(1.03)^Y - 1] \qquad (11.50)$$

or

$$Y = 77.9 \log\left(\frac{W_{18}}{10 \times 10^6} + 1\right) \qquad (11.51)$$

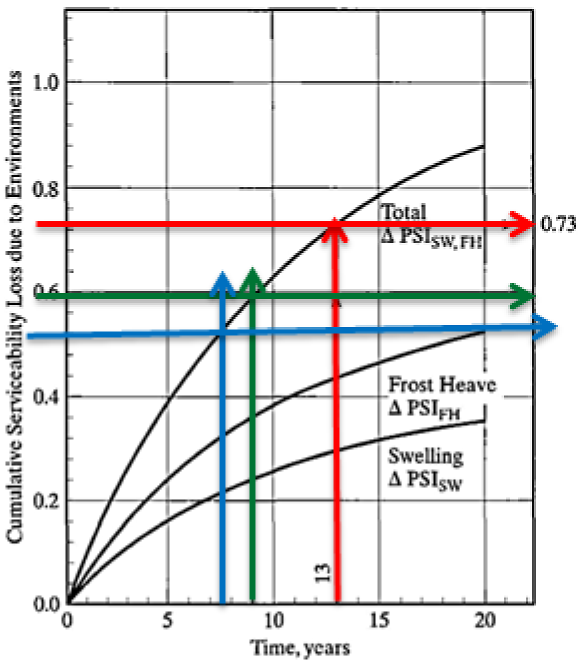


FIGURE 11.23
Environmental serviceability loss versus time for a specific location. (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Transportation Officials, Washington, DC. Used by permission.)

Solution:

First, assume Y = 13 years.

From Figure 11.23, ΔPSI due to environmental effects = 0.73; ....الخط الاحمر

ΔPSI due to traffic = 4.3 – 2.5 – 0.73 = 1.07.

From Eq. 11.37 or Figure 11.25, W18 = 1.6 X 10^6. ....الخط الاحمر

From Eq. 11.51, Y = 5.1 years< 13 years assumed.

13 - 5.1=7.9 > 1year ….Not OK

Next assume Y as the average of 13 and 5.1 years, or 9.0 years.

Y= (13+5.1)/2=9.05….> Assume Y=9.0 years.

From Figure 11.23, ΔPSI due to environmental effects = 0.59; ....الخط الاخضر

ΔPSI due to traffic = 4.3 – 2.5 – 0.59 = 1.21.

From Eq. 11.37 or Figure 11.25, $W_{18} = 2.1 \times 10^6$. ……الخط الاخضر

From Eq. 11.51, Y = 6.5 years.> 9.0 years assumed.

9 – 6.5 = 2.5 > 1 year….Not OK

Finally, assume Y= (9+ 6.5)/2 = 7.7 years.

From Figure 11.23, ΔPSI due to environmental effects =0.52; ……الخط الازرق

ΔPSI due to traffic = 4.3 – 2.5 – 0.52 = 1.28.

From Eq. 11.37 or Figure 11.25, $W_{18} = 2.4 \times 10^6$. ……الخط الازرق

From Eq. 11.51, Y =7.3< 7.7 years assumed.

7.7 – 7.3 = 0.4 < 1 year…. OK

When the difference between the assumed and calculated values is smaller than 1 year, no more iteration are needed and the average of the two values can be used as the performance period.

Therefore, the performance period = (7.7 + 7.3)/2 = 7.5 years.

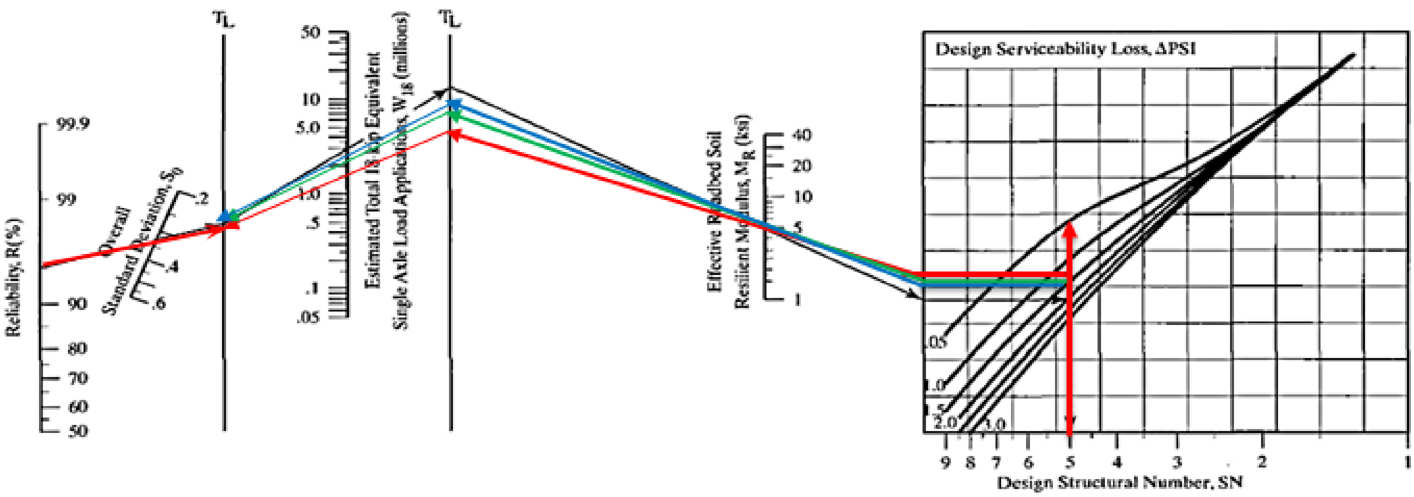


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

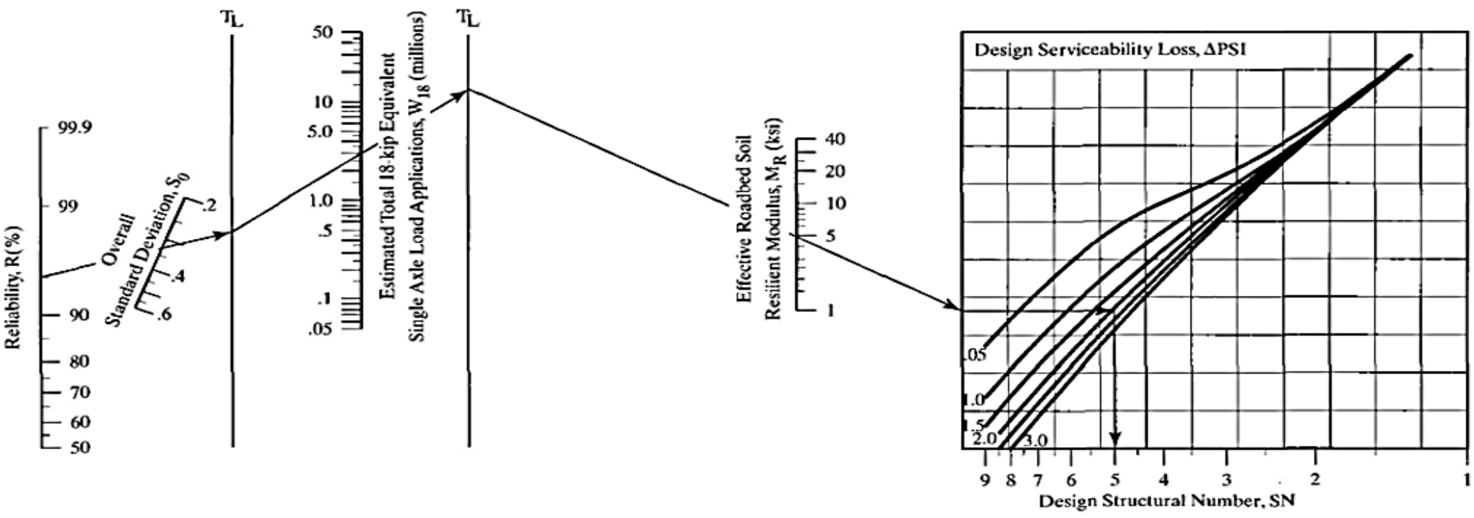


FIGURE 11.25

Design chart for flexible pavements based on mean values for each input (1 ksi = 6.9 MPa). (From the *AASHTO Guide for Design of Pavement Structures*. Copyright 1986. American Association of State Highway and Tranportation Officials, Washington, DC. Used by permission.)

Example

Flexible pavement is composed of 3 layers, asphalt course, untreated base course and sub base course.

Analysis period =20 years, 2 stages

P_0=4.6, P_t=2.5, Δpsi due to environmental effect =0.33768 (1-$e^{-0.075t}$)

Growth rate per year=3%,

Number of load repetitions per design years in the first year =2.5 *10^6

R=90%, E (Asphalt course)=400000 psi

Untreated base course with E=30000 psi

Subbase with E=11000 psi

M_R for subgrade soil = 6500 psi (season 1) and 5000 psi (season 2)

m_2=m_3=1.2

Directional distribution factor (D) =0.5

Lane distribution factor (L)= 0.8

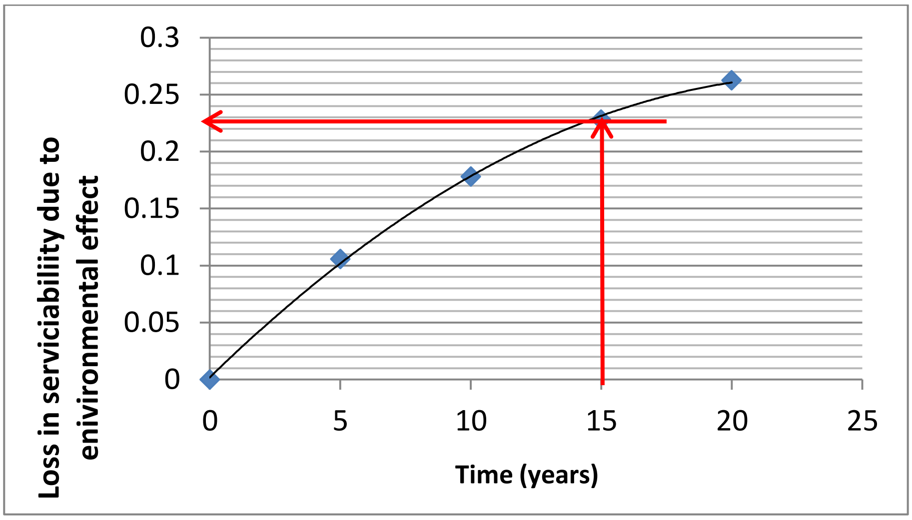
Select the thickness of the three layers.

Solution:

Loss in serviceabilityΔpsi due to traffic =4.6-2.5=2.1

Δpsi due to environmental effect $=0.33768\ (1-e^{-0.075t})$ نعوض قيم زمن كما في الجدول التالي

t	Δpsi due to environmental $0.33768\ (1-e^{-0.075t})$
0	0
5	0.105596
10	0.178171
15	0.228051
20	0.262333

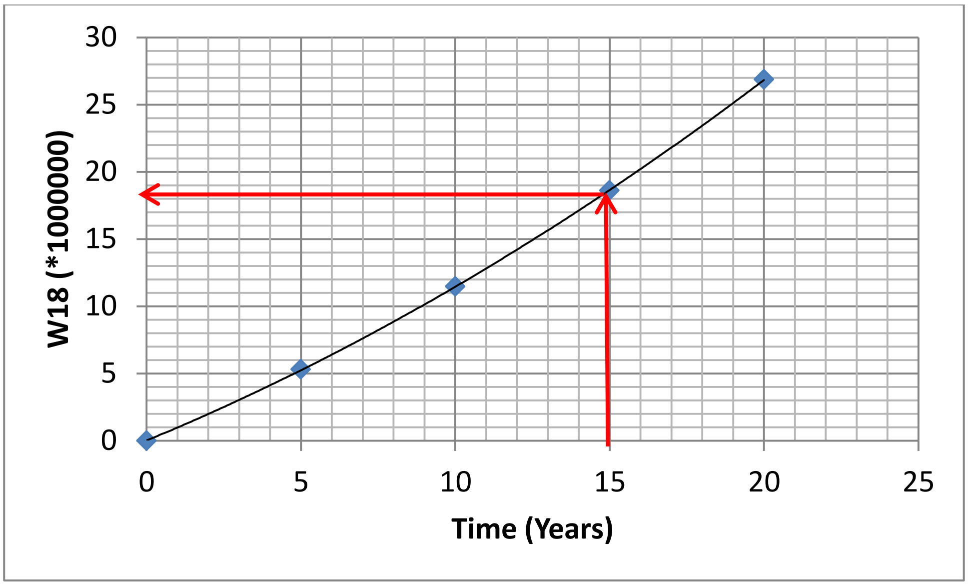


$W_{18} = \sum 360\times C\times Y\times G\times D\times L = 2.5\times 10^6\ ((1+0.03)^t-1)/0.03)\times 0.5\times 0.8$

$=33.335*10^6\ (1.03)^t-1)$

نعوض قيم مختلفة للزمن كما في الجدول التالي

t	W_{18}
0	0
5	$5.3*10^6$
10	$11.46*10^6$
15	$18.6*10^6$
20	$26.86*10^6$



$R_{stage}=(R_{overal})^{1/2}=(90)^{½}=95\%$

$S_0=0.35$ (for flexible pavement)

a_1= from equation or chart (E=400000 psi) …> $a_1=0.42$

$$a_2 = 0.249(\log_{10} M_r) - 0.977$$

$$a_3 = 0.227(\log_{10} M_r) - 0.839$$

E=30000 psi…..> $a_2= 0.14$

E=11000 psi …..> $a_3=0.08$

Effective roadbed soil M_R

M_R	$u_{f=1.18*10^8 M_R^{-2.32}}$
5000	0.168
6500	0.309
Average u_f	0.2385
Effective M_R	5590

At 15 years, $W_{18}=18.6*10^6$ and Δpsi due to traffic =4.6-2.5=2.1

M_R (for roadbed soil)=5590psi, R=95% and So=0.35

Use chart 11.25 or Eq 11.37 to find SN_3…..>SN_3=5.6

Because stage construction is applied (two stages), the performance period should be estimated.

Assume performance period=13 years

Substitute t=13 in (W18 =33.335*10^6 $(1.03)^t$-1)) and find W18

W18=16*10^6

$$Y = 77.9 \log\left(\frac{W_{18}}{10 \times 10^6} + 1\right) \qquad (11.51)$$

Y= 13.26 years which is greater than the assumed (y=3) by 0.26<1 year

So performance period=13 years

From the above results W_{18}=16*10^6 at y=13years

And Δpsi due to environmental effect =0.21

Δpsi due to traffic and environmental effect = 2.1-0.21=1.89

From figure 11.25 (or eq11.37), SN_1=3.4

$D_1 \geq 3.4/0.42 \leq 8.00$ in > minimum from table 11.21=3 in

From figure 11.25 (or eq11.37), SN_2=4.6

$D_2 \geq$ (4.6-8*0.42)/1.2*.14=7.38 in..> minimum OK

D_2=7.5 in

From figure 11.25 (or eq11.37), SN_3=5.6

$D_3 \geq$(5.6-8*0.42-7.5*0.14*1.2)/1.2*0.08=10.2 in..> minimum OK

D_3=10.5 in