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## Analytical Study & Design of Flexible Pavement

By Mousa Ayesh Hussein Al-Asakereh

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Flexible pavement is the pavement that remains adjacent to the surface soil road, even if the surface is rutting.

Provides sufficient thickness for load distribution through a multilayer structure so that the stresses and strains in the Subgrade soil layers are within required limits.

The strength of subgrade soil would have a direct bearing on the total thickness of the flexible pavement.

**Keywords:** flexible design, pavement, asphalt design.

**GJRE-E Classification:** DDC Code: 738.52095694 LCC Code: NA3760



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# Analytical Study & Design of Flexible Pavement

Mousa Ayesh Hussein Al-Asakereh

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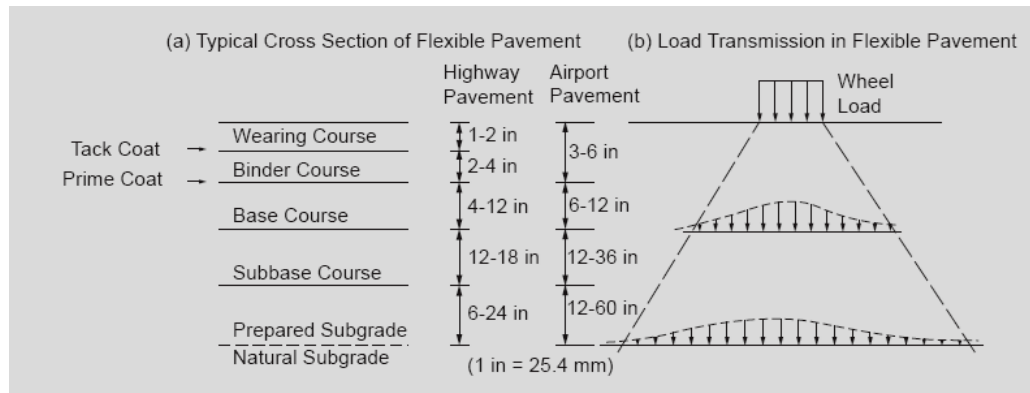
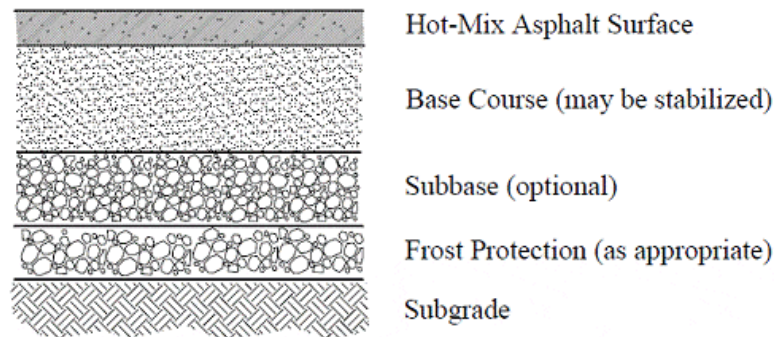
Provides sufficient thickness for load distribution through a multilayer structure so that the stresses and strains in the Subgrade soil layers are within required limits.

The strength of subgrade soil would have a direct bearing on the total thickness of the flexible pavement.

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Enter:

Structural Components of a Flexible Pavement



## 1. Subgrade (Road Bed)

The subgrade is usually the natural material located along the horizontal alignment of the road and serves as the foundation of the pavement structure.

## 2. Subbase Course

Located immediately above the subgrade, the subbase component consists of material of a superior quality to that which is generally used for subgrade construction.

## 3. Base Course

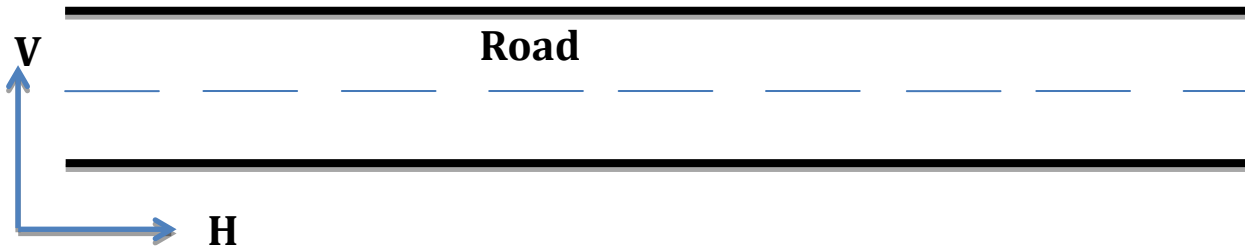
Located immediately above the subbase, if a subbase course is not used. This course usually consists of granular materials such as crushed stone, crushed or uncrushed slag, crushed or uncrushed gravel, and sand.

#### 4. Surface Course

Constructed immediately above the base course, usually consists a mixture of aggregates and asphalt. It should be capable of withstanding high tire pressures, resisting abrasive forces due to traffic, providing a skid-resistant driving surface, and preventing the penetration of surface water into the underlying layers.

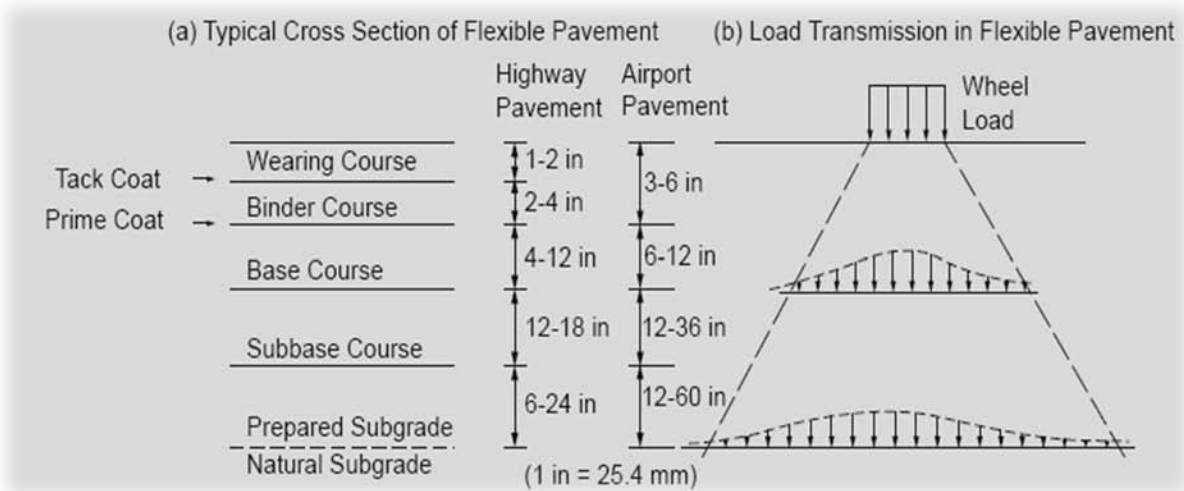
### I. GENERAL PRINCIPLES OF FLEXIBLE PAVEMENT DESIGN

Assumed initially that the subgrade layer is infinite in both the horizontal and vertical directions, whereas the other layers are finite in the vertical direction and infinite in the horizontal direction.



In the design of flexible pavements, the pavement structure usually is considered as a multilayered elastic system, with the material that may include the modulus of elasticity ( $E$ ), the resilient modulus ( $R$ ), and the Poisson ratio ( $\nu$ ).

Applying of a wheel load causes a stress distribution; the maximum vertical stresses are compressive and occur directly under the wheel load. These decrease with an increase in depth from the surface.



### II. AASHTO DESIGN METHOD CONSIDERATIONS

#### a) Pavement Performance

- Structural performance is related to the physical condition of the pavement with respect to factors that hurt the capability of the pavement to carry the traffic load.
- These factors include cracking, faulting, unraveling, and so forth.

Functional performance is an indication of how effectively the pavement serves the user.

- The main factor considered under functional performance is riding comfort.
- To quantify pavement functional performance, a concept known as the serviceability performance was developed.

And Under this concept, a procedure was developed to determine the present serviceability index (PSI) of the pavement, based on its roughness and distress, which were measured in terms of the extent of cracking, patching, and rut depth for flexible pavements.

- Two serviceability indices are used in the design procedure:

1. The initial serviceability index ( $p_i$ ) is the serviceability index immediately after the Construction of the pavement.
2. The terminal serviceability index ( $p_t$ ) is the minimum acceptable value before reconstruction is necessary.

b) *Traffic Load*

In the AASHTO design method, the traffic load is determined in Terms of the number of repetitions of an 18,000-lb (80 KN) the Single-axle load applied to the pavement.

This is usually referred to as: *The Equivalent Single-Axle Load (ESAL)*.

➤ A general equation for the accumulated ESAL for each category of axle load is

$$ESAL = AADT \times N \times F_{Ei} \times G_{rn} \times 365 \times f_d$$

Where:

ESAL = Equivalent Accumulated 18,000-lb (80 KN) single-axle load.

AADT = First year annual average daily traffic.

N = Number of axles on each vehicle.

$F_{Ei}$  = load equivalency factor for Single and Tandem axle.

$G_{rn}$  = Growth factor for a given growth rate r and design period n.

365 = Convert from day to year.

$f_d$  = Design lane factor.

Name	Equation
ESAL Design lane	$AADT \times N \times F_{Ei} \times G_{rn} \times 365 \times f_d$
Total ESAL	$AADT \times N \times F_{Ei} \times G_{rn} \times 365$
First Year ESAL Design lane	$AADT \times N \times F_{Ei} \times 365 \times f_d$
Total ESAL First Year	$AADT \times N \times F_{Ei} \times 365$
Daily ESAL Design Lane	$AADT \times N \times F_{Ei} \times f_d$
Total Daily ESAL	$AADT \times N \times F_{Ei}$

Table 19.4: Growth Factors

Design Period, Years (n)	Annual Growth Rate, Percent (r)							
	No Growth	2	4	5	6	7	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.02	2.04	2.05	2.06	2.07	2.08	2.10
3	3.0	3.06	3.12	3.15	3.18	3.21	3.25	3.31
4	4.0	4.12	4.25	4.31	4.37	4.44	4.51	4.64
5	5.0	5.20	5.42	5.53	5.64	5.75	5.87	6.11
6	6.0	6.31	6.63	6.80	6.98	7.15	7.34	7.72
7	7.0	7.43	7.90	8.14	8.39	8.65	8.92	9.49
8	8.0	8.58	9.21	9.55	9.90	10.26	10.64	11.44
9	9.0	9.75	10.58	11.03	11.49	11.98	12.49	13.58
10	10.0	10.95	12.01	12.58	13.18	13.82	14.49	15.94
11	11.0	12.17	13.49	14.21	14.97	15.78	16.65	18.53
12	12.0	13.41	15.03	15.92	16.87	17.89	18.98	21.38
13	13.0	14.68	16.63	17.71	18.88	20.14	21.50	24.52
14	14.0	15.97	18.29	19.16	21.01	22.55	24.21	27.97
15	15.0	17.29	20.02	21.58	23.28	25.13	27.15	31.77
16	16.0	18.64	21.82	23.66	25.67	27.89	30.32	35.95
17	17.0	20.01	23.70	25.84	28.21	30.84	33.75	40.55
18	18.0	21.41	25.65	28.13	30.91	34.00	37.45	45.60
19	19.0	22.84	27.67	30.54	33.76	37.38	41.45	51.16
20	20.0	24.30	29.78	33.06	36.79	41.00	45.76	57.28
25	25.0	32.03	41.65	47.73	54.86	63.25	73.11	98.35
30	30.0	40.57	56.08	66.44	79.06	94.46	113.28	164.49
35	35.0	49.99	73.65	90.32	111.43	138.24	172.32	271.02

**EX:** If the value of design period years  $n = 9$ , and annual growth rate  $r = 5\%$ , Find  $G_{rn}$  ?

\* From above table  $\rightarrow G_{rn} = 11.03$

\* From Equation  $\rightarrow G_{rn} = \frac{(1+r)^n - 1}{r} = \frac{(1+0.05)^9 - 1}{0.05} = 11.03$

**$F_{Ei}$  From table 19.3a & 19.3b**

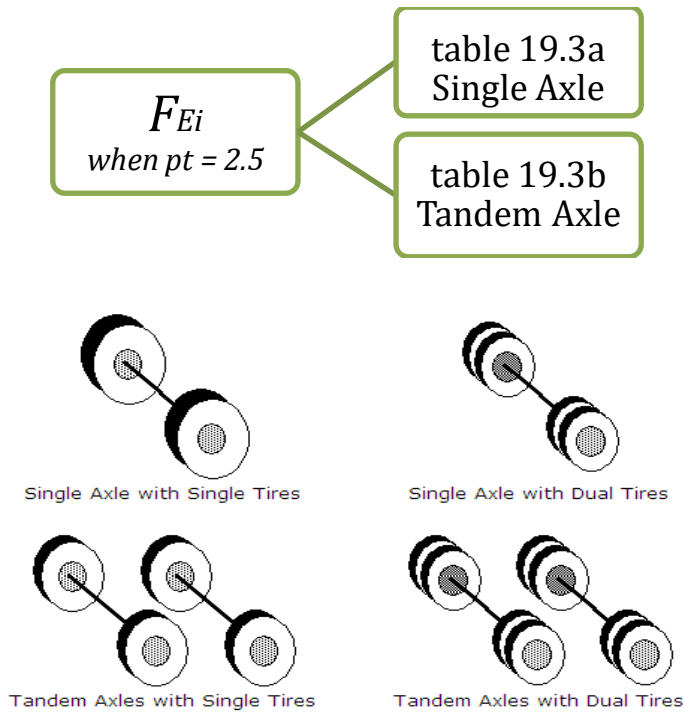


Table 19.3a: Axle Load Equivalency Factors for Flexible Pavements, Single Axles, and  $p_t$  of 2.5

Axle Load (kips)	Pavement Structural Number (SN)					
	1	2	3	4	5	6
2	.0004	.0004	.0003	.0002	.0002	.0002
4	.003	.004	.004	.003	.002	.002
6	.011	.017	.017	.013	.010	.009
8	.032	.047	.051	.041	.034	.031
10	.078	.102	.118	.102	.088	.080
12	.168	.198	.229	.213	.189	.176
14	.328	.358	.399	.388	.360	.342
16	.591	.613	.646	.645	.623	.606
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.3	9.5	7.9	6.8	7.0	7.8
32	13.9	12.8	10.5	8.8	8.9	10.0
34	18.4	16.9	13.7	11.3	11.2	12.5
36	24.0	22.0	17.7	14.4	13.9	15.5
38	30.9	28.3	22.6	18.1	17.2	19.0
40	39.3	35.9	28.5	22.5	21.1	23.0
42	49.3	45.0	35.6	27.8	25.6	27.7
44	61.3	55.9	44.0	34.0	31.0	33.1
46	75.5	68.8	54.0	41.4	37.2	39.3
48	92.2	83.9	65.7	50.1	44.5	46.5
50	112.0	102.0	79.0	60.0	53.0	55.0

**Ex 1 :**

Traffic (AADT) in both directions on the Highway during the first year of operation will be 12,000 with the following vehicle mix and axle loads.

- **2-axle single-unit trucks** (2000 lb/axle) = 50%
- **2-axle single-unit trucks** (6000 lb/axle) = 33%
- **3-axle single-unit trucks** (10,000 lb/axle) = 17%

And the traffic growth rate is 4% for all vehicles, design period of **20 years**, assume **SN = 5**, and the percent of the traffic on the design lane is 45%; **determine the design & Total ESAL?**

**Single unit trucks**

Find  $F_{Ei}$  from table 19.3a

- 1- 2000 lb/axle = 2 kips/axle →  $F_{Ei1} = 0.0002$
- 6000 lb/axle = 6 kips/axle →  $F_{Ei2} = 0.01$
- 10000 lb/axle = 10 kips/axle →  $F_{Ei3} = 0.088$

- 2- AADT 1 = 50% \* 12000 = 6000
- AADT 2 = 33% \* 12000 = 3960
- AADT 3 = 17% \* 12000 = 2040

- 3- n = 20 years
- r = 4% → from table 19.4,  $G_{rn} = 29.78$

$$\text{Design ESAL} = \left[ \frac{\text{AADT1 } N1 \ F_{Ei1}}{\quad} + \frac{\text{AADT2 } N2 \ F_{Ei2}}{\quad} + \frac{\text{AADT3 } N3 \ F_{Ei3}}{\quad} \right] \times 29.78 \times 365 \times 0.45 = 3033429 = 3.03 \times 10^6$$

$$\text{Total ESAL} = \frac{3033429}{0.45} = 6740953 = 6.74 \times 10^6$$

**Ex 2:**

The present AADT (in both directions) of 6000 vehicles is expected to grow at 5% per annum. Assume SN =4 and the percent of the traffic on the design lane is 55%, the design life is 20 years.

If the vehicle mix is:

(3-axle tandem, 4-single axle) trucks (10000 lb/axle) = 60%

2-axle single-unit trucks (5000 lb/axle) = 30%

(3-axle single-unit, 2-axle tandem) trucks (7000 lb/axle) = 10%

Determine :

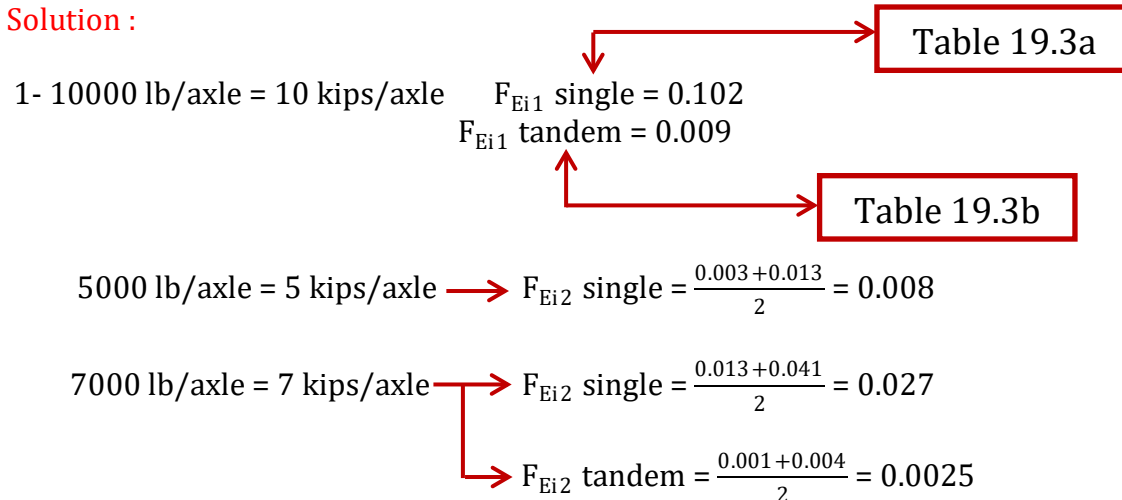
a- Daily Design ESAL

b- Total ESAL for the First year

c- Total ESAL

d- Design ESAL for (10000 lb/axle)

e- Daily Total ESAL for (7000 lb/axle)

**Solution :**

2- AADT1 = 60% × 6000 = 3600

AADT2 = 30% × 6000 = 1800

AADT3 = 10% × 6000 = 600

3- n = 20 years

r = 5%  $\rightarrow G_{rn} = 33.06$

**a- Daily Design ESAL**

Daily Design ESAL = AADT × N ×  $F_{Ei}$  ×  $f_d$

$$DDESAL = [ 3600(3 \times 0.009 + 4 \times 0.102) + 1800(2 \times 0.008) + 600(3 \times 0.027 + 2 \times 0.0025) ] \times 0.45 = 741$$

**b- Total ESAL for First year**

Total ESAL the First Year = AADT × N ×  $F_{Ei}$  × 365

$$= [ 3600(3 \times 0.009 + 4 \times 0.102) + 1800(2 \times 0.008) + 600(3 \times 0.027 + 2 \times 0.0025) ] \times 365 = 600936$$

**c- Total ESAL**

Total ESAL = AADT × N ×  $F_{Ei}$  ×  $G_{rn}$  × 365

$$= [ 3600(3 \times 0.009 + 4 \times 0.102) + 1800(2 \times 0.008) + 600(3 \times 0.027 + 2 \times 0.0025) ] \times 365 \times 33.06 = 19866944 = 19.9 \times 10^6$$



**d- Design ESAL for (10000 lb/axle)**

10000 lb/axle = 10 kips/axle  $\rightarrow F_{Ei1}$  single = 0.102  
 $\rightarrow F_{Ei1}$  tandem = 0.009

$$DESAL = AADT_{10} \times N \times F_{Ei} \times G_{rn} \times 365 \times f_d$$

$$= 3600(3 \times 0.009 + 4 \times 0.102) \times 33.06 \times 365 \times 0.45$$

$$= 8503544 = 8.5 \times 10^6$$

**e- Daily Total ESAL for (7000 lb/axle)**

$$\text{Total ESAL} = AADT_7 \times N \times F_{Ei} \times G_{rn} \times 365$$

$$= 600(3 \times 0.027 + 2 \times 0.0025) \times 33.06 \times 365$$

$$= 622652 = 0.62 \times 10^6$$

c) *Roadbed Soils (Subgrade Material)*

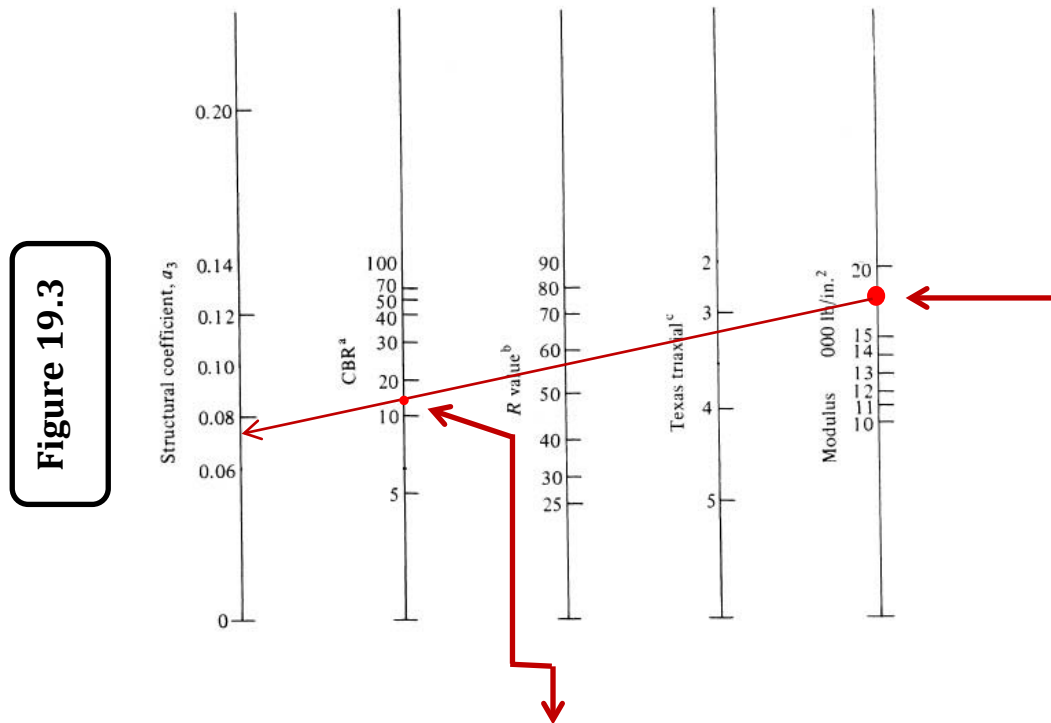
AASHTO Code uses the *Resilient Modulus (Mr)* of the soil to define its property and convert the CBR value of the soil to an equivalent Mr value using the following conversion factor  $Mr \text{ (lb/in}^2\text{)} = 1500 \text{ CBR}$  (for CBR of 10 or less).

d) *Materials of Construction*

The materials used for the construction of pavement can be classified under three general groups:

i. *Subbase Construction Materials*

The quality of the material used is determined in terms of the layer coefficient ( $a_3$ ), which is used to convert the actual thickness of the subbase to an equivalent Structure Number (SN).



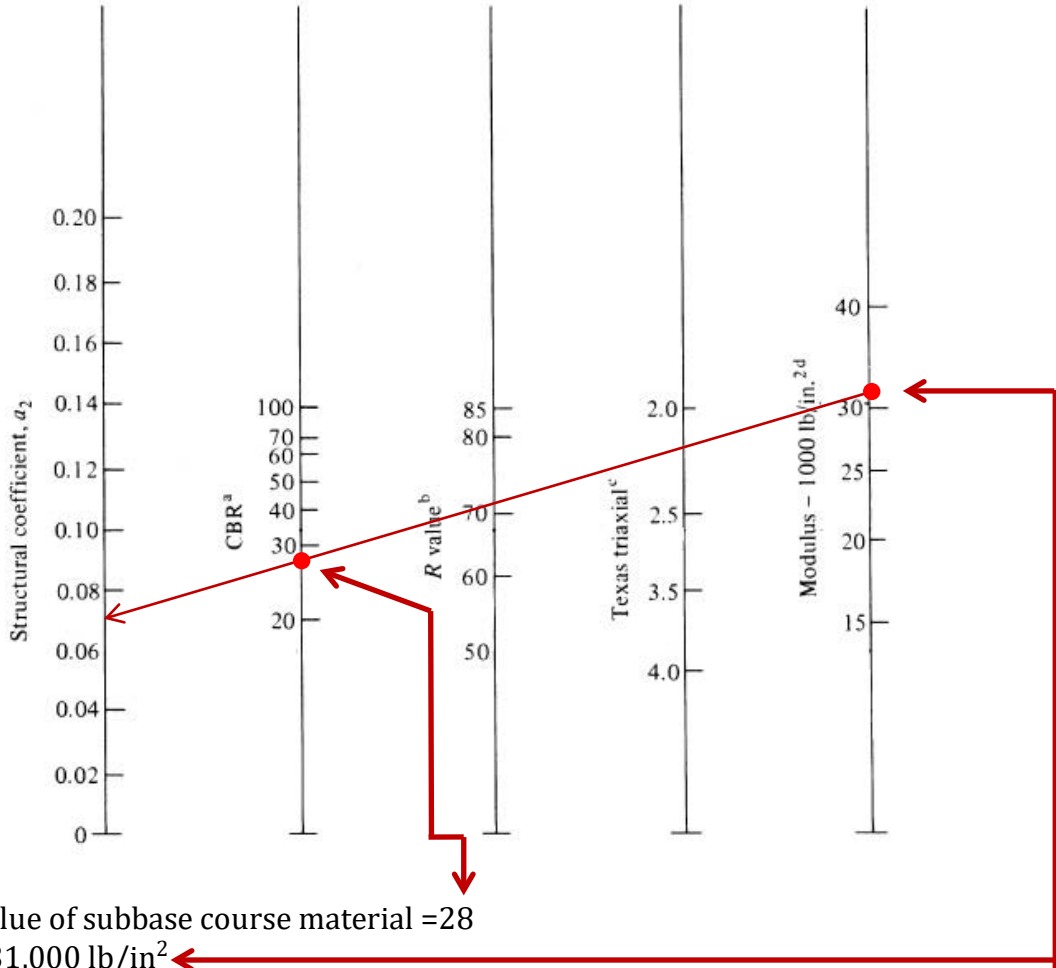
**EX:** CBR value of subbase course material = 15  
 $Mr = 17,500 \text{ lb/in}^2$   
 Find Subbase layer Coefficient  $a_3$ ?  $\rightarrow a_3 = 0.077$



ii. Base Course Construction Materials

Materials selected should satisfy the general requirements for base course materials, A structural layer coefficient,  $a_2$ , for the material used also should be determined.

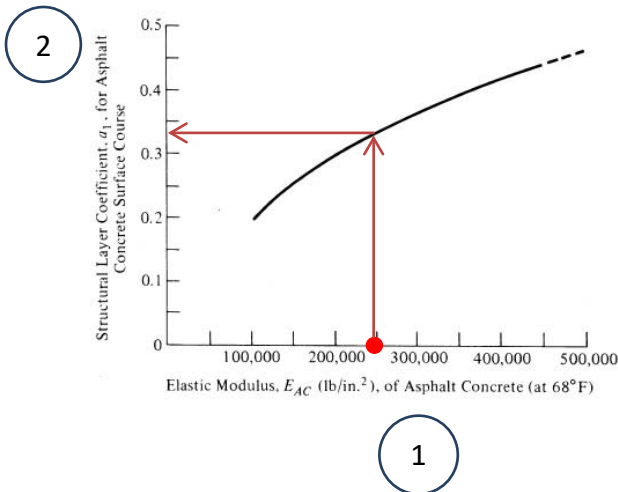
**Figure 19.4**



iii. Surface Course Construction Materials

The structural layer coefficient ( $a_1$ ) relates to a dense graded asphalt concrete surface with its resilient modulus at 68°F.

**Figure 19.5**



EX:  
 Elastic Modulus of Asphalt Concrete  $E_{AC} = 250,000 \text{ lb/in}^2$   
 Find Asphalt layer Coefficient  $a_1$  ?  
 $a_1 = 0.33$

e) *Environment*

Temperature and rainfall are the two main environmental factors used in evaluating pavement performance in the AASHTO method.

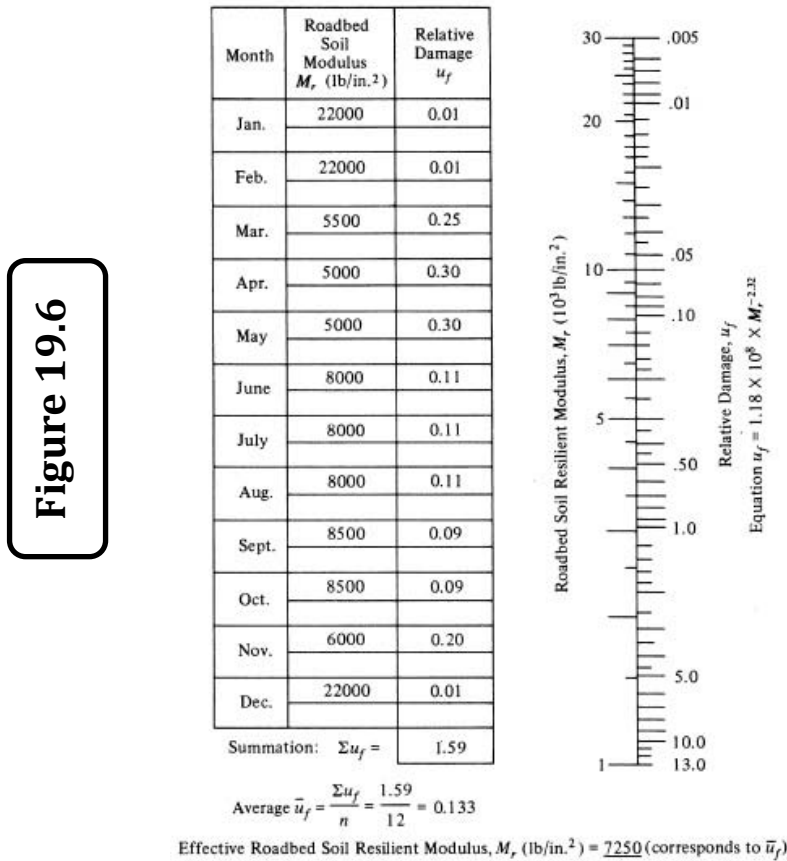
The effects of temperature on asphalt pavements include stresses induced by thermal action and the impact of freezing and thawing water in the subgrade.

The effect of temperature, particularly about to the weakening of the underlying material during the thaw period, is considered a significant factor in determining the strength of the underlying materials used in the design. The effect of rainfall is due mainly to the penetration of the surface water into the underlying material, if penetration occurs, the properties of the underlying materials may be altered significantly.

The resilient modulus of materials susceptible to frost action can reduce by 50 percent to 80 percent during the thaw period, and it is likely that the strength of the material will be affected during the periods of heavy rains.

The AASHTO guide suggests a method for determining the effective, resilient modulus. In this method, a relationship is then used to determine the resilient modulus for each season based on the estimated in situ moisture content and Relative damage during the period of time.

The relative damage  $u_f$  for each period is determined from the following chart, using the vertical scale or the equation given in the chart. The mean comparable damage  $\bar{u}_f$  then computed, and the effective subgrade resilient modulus is determined using the Chart and value of  $u_f$ .



**Ex:**

1- Find Roadbed Resilient Modulus  $M_r$  When Relative Damage  $u_f$  7.23?

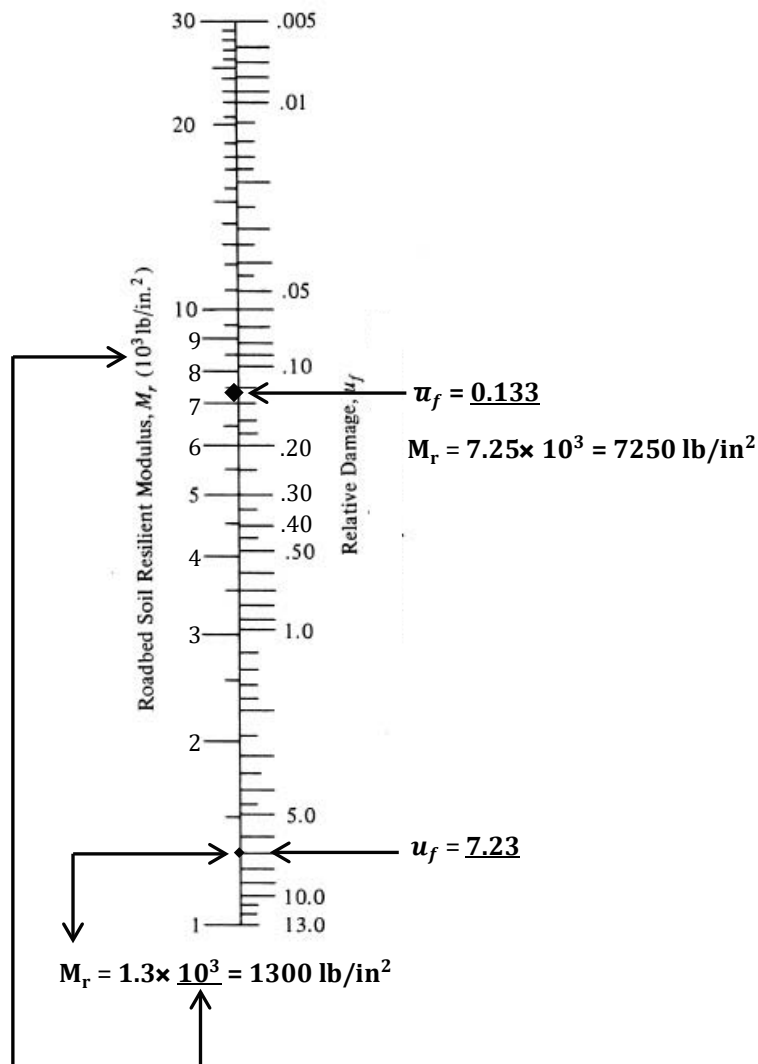
2- Find Roadbed Resilient Modulus  $M_r$  For mean Relative damage  $u_f$ ?

- Using the Equation:  $u_f = 1.18 \times 10^8 \times M_r^{-2.32}$

1-  $0.723 = 1.18 \times 10^8 \times M_r^{-2.32}$  **Solving**  $\rightarrow M_r = 1285 \text{ lb/in}^2$

2- Mean  $u_f = \underline{0.133} = 1.18 \times 10^8 \times M_r^{-2.32} \rightarrow M_r = 7193 \text{ lb/in}^2$

-Using vertical scale:



f) *Drainage. ( $m_i$ )*

The effect of drainage on the performance of flexible pavement is considered to the effect water has on the strength of the base material and roadbed soil, and The approach used is to provide for the rapid drainage of the water from the pavement structure by providing a suitable drainage layer and by modifying the structural layer coefficient.

The modification is carried out by adding a factor  $m_i$  for the base and subbase layer coefficients ( $a_2$  and  $a_3$ ). The  $m_i$  factors are based both on the percentage of time during which the pavement structure will be nearly saturated, and on the quality of drainage, which is dependent on the time it takes to drain the base layer to 50 percent of saturation.

**Ex1:**

A flexible pavement takes **one day** for water to be drained from within it and the pavement structure will be exposed to moisture levels approaching saturation for 7% of the time. Find the pavement drainage coefficient?

Table 19.5: Definition of Drainage Quality

Quality of Drainage		Water Removed Within*	
Excellent	2	2 hours	1
Good		1 day	
Fair		1 week	
Poor		1 month	
Very poor		(water will not drain)	

**Time required to drain the base layer to 7% saturation.**Table 19.6: Recommended  $m_i$  Values

Quality of Drainage	Percent of Time Pavement Structure Is Exposed to Moisture Levels Approaching Saturation			
	Less Than 1%	1 to 5%	5 to 25%	Greater Than 25%
Excellent	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	1.05–0.95	0.95–0.75	0.75–0.40	0.40

**Pavement drainage coefficient  $m = (1.15 - 1)$**

g) *Reliability, R%*

The cumulative ESAL is an essential input to any pavement design method. However, the determination of this input is usually based on assumed growth rates which may not be accurate.

AASHTO guide proposes the use of a reliability factor that considers the possible uncertainties in traffic prediction and pavement performance prediction.

For example, a 50% reliability design level implies 50% chance for successful pavement performance.

Table 19.7 shows suggested reliability levels based on the AASHTO guide.

*Table 19.7:* Suggested Levels of Reliability for Various Functional Classifications

<i>Recommended Level of Reliability</i>		
<i>Functional Classification</i>	<i>Urban</i>	<i>Rural</i>
Interstate and other freeways	85–99.9	80–99.9
Other principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80



## III. FLEXIBLE PAVEMENT STRUCTURAL DESIGN

$$SN = a_1 \times D_1 + a_2 \times D_2 \times m_2 + a_3 \times D_3 \times m_3$$

$m_{2,3}$  = drainage coefficient for the base, subbase layer

$a_{1,2,3}$  = layer coefficient of surface, base, and subbase Course

$D_{1,2,3}$  = actual thickness **in inches** of the surface, base, and subbase courses

## 1- By Equation

$$\log_{10} (W_{18}) = Z_R S_o + 9.36 \log_{10} (SN+1) - 0.2 + \frac{\log_{10} \left( \frac{\Delta PSI}{2.7} \right)}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \log_{10} (M_R) - 8.07$$

Where:

$W_{18}$  = predicted number of 18,000-lb (80 kN) single-axle load applications

$\Delta PSI = p_i - p_t$

SN = structural number indicative of the total pavement thickness

$Z_R$  = standard normal deviation for a given reliability

$S_o$  = overall standard deviation

Standard Deviation,  $S_o$

Flexible pavements	0.40–0.50
Rigid pavements	0.30–0.40

Table 19.8: Standard Normal Deviation ( $Z_R$ ) Values Corresponding to Selected Levels of Reliability

R% given	Reliability (R%)	Standard Normal Deviation, $Z_R$
1	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
	93	-1.476
2	94	-1.555
	95	-1.645
	96	-1.751
	97	-1.881
	98	-2.054
	99	-2.327
	99.9	-3.090
	99.99	-3.750

## 2- By Figure 19.8

### Ex: Designing a Flexible Pavement Using the AASHTO Method

A flexible pavement for an urban interstate highway  $R = 95\%$ , and Standard deviation  $S_o = 0.45$  is to be designed to carry a **design ESAL of  $2 \times 10^6$** . It is estimated that it takes about a **week** for the water to be drained from within the pavement, and **the pavement structure will be exposed to moisture levels approaching saturation for 30% of the time**. The following additional information is available:

Initial serviceability index  $p_i = 4.5$

Final serviceability index  $p_t = 2.5$

Resilient modulus of asphalt concrete at  $68^\circ\text{F} = 450,000 \text{ lb/in}^2$

CBR value of base course material = 100,  $M_r = 31,000 \text{ lb/in}^2$

CBR value of subbase course material = 22,  $M_r = 13,500 \text{ lb/in}^2$

CBR value of subgrade material = 5

$$M_r = 1500 * \text{CBR} = 1500 * 5 = 7500 \text{ lb/in}^2$$

### Solution:

1- Find Drainage Coefficient  $m_i$  from table 19.5, 19.6

Table 19.5: Definition of Drainage Quality

Quality of Drainage	Water Removed Within*
Excellent	2 hours
Good	1 day
Fair	1 week
Poor	1 month
Very poor	(water will not drain)

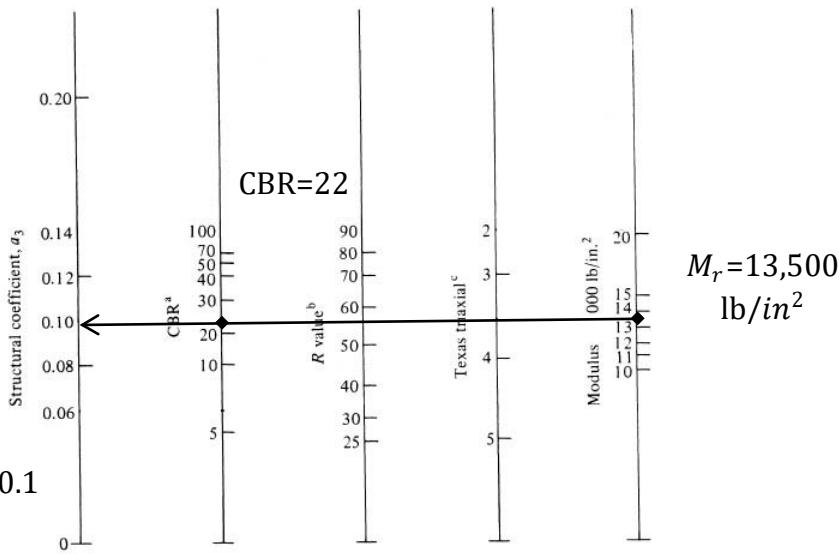
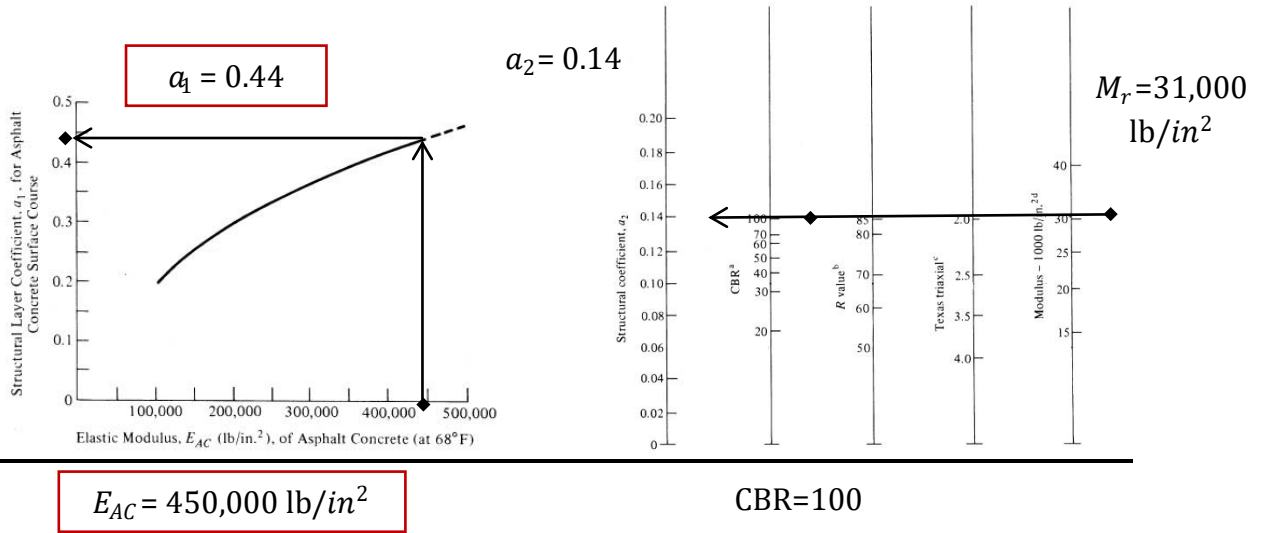
Table 19.6: Recommended  $m_i$  Values

Quality of Drainage	Percent of Time Pavement Structure Is Exposed to Moisture Levels Approaching Saturation			
	Less Than 1%	1 to 5%	5 to 25%	Greater Than 25%
Excellent	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	1.05–0.95	0.95–0.75	0.75–0.40	0.40

**Drainage Coefficient  $m_i$  for base and subbase layer = 0.8**



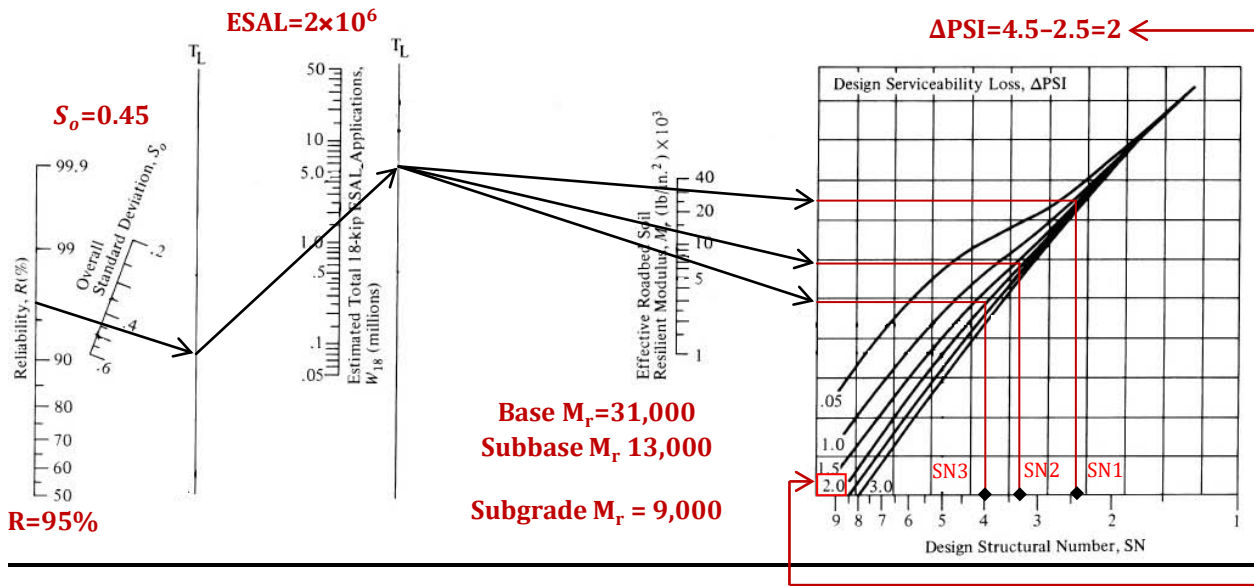
2- Find Layer Coefficient  $a_1, a_2, a_3$  from figure 19.3, 19.4, 19.5



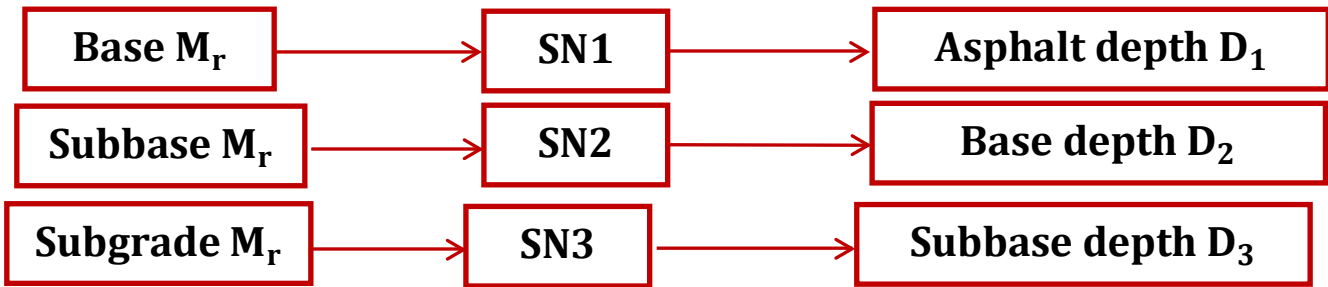
Layer Coefficient:  $a_1 = 0.44, a_2 = 0.14, a_3 = 0.1$



3- Find the Structure Number for each layer from figure 19.8



SN1=2.45      SN2=3.4      SN3=4



$$SN1 = a_1 \times D_1$$

$$2.45 = 0.44 \times D_1$$

$$D_1 = 5.57 = 6 \text{ in}$$

$$SN1 = 0.44 \times 6 = 2.64$$

$$SN2 = SN1 + a_2 \times D_2 \times m_2$$

$$3.4 = 2.64 + 0.14 \times D_2 \times 0.8$$

$$D_2 = 6.79 = 8 \text{ in}$$

$$SN2 = 2.64 + 0.14 \times 8 \times 0.8 = 3.54$$

$$SN3 = SN2 + a_3 \times D_3 \times m_3$$

$$4 = 3.54 + 0.1 \times D_3 \times 0.8$$

$$D_3 = 5.75 = 6 \text{ in}$$

$$SN3 = 3.54 + 0.1 \times 6 \times 0.8 = 4.02$$

REFERENCES RÉFÉRENCES REFERENCIAS

1. Principles of Pavement Design Yoder Ej (ch1,2,3).
2. Highway and Traffic Engineering N. Garber (ch19,20).