Flexible Pavement Design “AASHTO 1993”

Postgraduate Studies
Highways Engineering

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Syllabus of:
Advanced Pavement Design

4. Flexible Pavement Design Method (AASHTO 1993 Method) …….. (2.5 weeks)

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4. Flexible Pavement Design Method (AASHTO 1993 Method)

- AADHTO = The **American Association of State Highway and Transportation Officials**
- AASHTO 1993 METHOD Based on empirical models drawn from field performance data measured at the AASHO road test in the late 1950’s. Figure 4.1. shows the AASHO test.

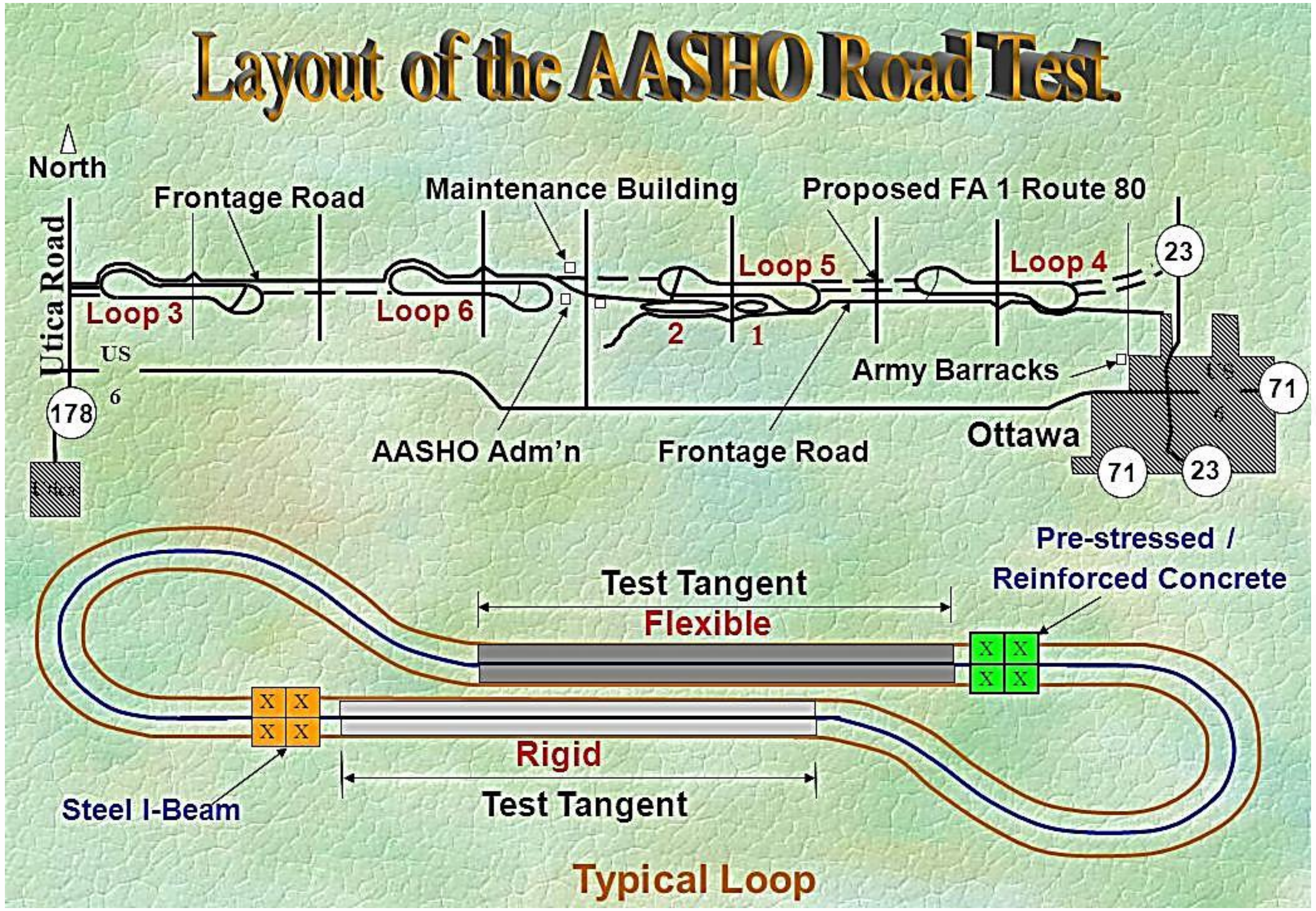
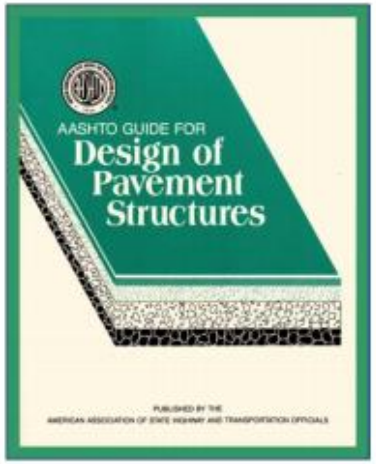


Figure 23. Test vehicles, showing typical axle arrangements and loadings.



Loop No.	Binder thickness (in.)	Surface course (in.)
1	0	1
2	0	2
3	1.5	1.5
4	1.25 1.5	1.5
5	2.0 1.5	1.5
6	1.5 1.5 1.5	1.5

Flexible Pavement

Loop No.	PCC Slab Thickness (in.)	Subbase Thickness (in.)	Transverse Dowel Bars (Diameter x Length)
1	2.5 5.0 9.5 12.5	0, 6.0 0, 6.0 0, 6.0 0, 6.0	3/8" x 12" 5/8" x 12" 1 1/4" x 18" 1 5/8" x 18"
2	2.5 3.5 5.0	0, 3.0, 6.0 0, 3.0, 6.0 0, 3.0, 6.0	3/8" x 12" 1/2" x 12" 5/8" x 12"
3	3.5 5.0 6.5 8.0	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	1/2" x 12" 5/8" x 12" 7/8" x 18" 1" x 18"
4	5.0 6.5 8.0 9.5	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	5/8" x 12" 7/8" x 18" 1" x 18" 1 1/4" x 18"
5	6.5 8.0 9.5 11.0	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	7/8" x 18" 1" x 18" 1 1/4" x 18" 1 3/8" x 18"
6	8.0 9.5 11.0 12.5	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	1" x 18" 1 1/4" x 18" 1 3/8" x 18" 1 5/8" x 18"

Rigid Pavement

❖ An empirical equations are drawn from the AASHO road test to relate observed or measurable phenomena (pavement characteristics) with outcomes (pavement performance). This empirical equation has been widely used in the design of flexible pavement. Equation 4.1 represents the final version of 1993 after several modifications

$$\log_{10}(W_{18}) = Z_R S_0 + 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log_{10}(M_R) - 8.07 \quad \ldots\ldots \quad 4.1$$

Statistically   Structurally   Environmentally   Material

W_{18}= predicted number of 18-kip equivalent single axle load applications
Z_R= standard normal deviate
S_o = combined standard error of the traffic prediction and performance prediction
ΔPSI = difference between the initial design serviceability index, p_o, and the design terminal serviceability index, p_t
M_R = resilient modulus (psi)
SN= structural Number
a_i = i^{th} layer coefficient
D_i = i^{th} layer thickness (in.)

$$\log_{10}(W_{18}) = Z_R S_0 + 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log_{10}(M_R) - 8.07$$

$$SN = \sum_{i=1}^{n} a_i D_i$$

4.1. Design Considerations

This method Incorporates various design inputs including:

- Pavement Performance (Loss of serviceability) ***(P_i and P_t)***
- Traffic ***(W_{18})***
- Subgrade soil properties **(M_R)**
- Materials of construction ***(a_1, a_2, a_3)***
- Environmental effects ***(Swelling, frost and heave)***
- Drainage ***(m_1, m_2)***
- Reliability **(Z_R and S_o)**

4.1.1. Pavement Performance (Loss of Serviceability in form of P_i *and* P_t)

The concept of serviceability is supported by five fundamental assumptions:

(1) Highways are for the comfort of the traveling user;

(2) The user's opinion as to how a highway should perform is highly subjective;

(3) There are characteristics that can be measured and related to user's perception of performance;

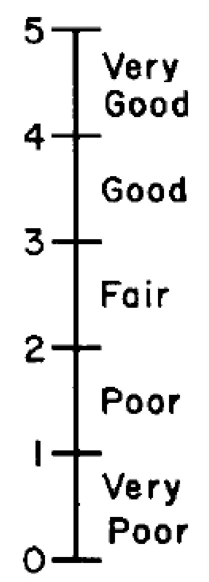
(4) Performance may be expressed by the mean opinion of all users; and

(5) Performance is assumed to be a reflection of serviceability with increasing load applications.

Based on these assumptions the definition of Present Serviceability Index(PSI) is: The ability of a specific section of pavement to serve high speed, high volume, and mixed traffic in its existing condition or PSI is defined as "Ability of a pavement to serve the traffic for which it is designed". Normally the PSI value is taken as 4.

. **The Present Serviceability Rating (PSR)** is the average of all users' ratings of a specific pavement section on a **scale from 5 to 0 (being 5 very good and 0 very poor).**

In the field, a panel of experts drove around in standard vehicles and gave their assessments or a ratings for the pavement conditions so the if $0 < PSR < 5$; $PSR < 2.5$ Unacceptable



The mathematical correlation of pavement distresses observed during visual surveys and profile measurements (roughness) with PSR is termed the **Present Serviceability Index (PSI);** PSI is the measure of performance in the AASHTO design equation.

The correlation between **PSI** and typical flexible pavement distresses observed during the AASHO Road Test is represented by the following equation

$$PSI = 5.03 - 1.91\log(1+SV) - 1.38\,(RD)^2 - 0.01(C+P)^{1/2} \quad \text{-------- (4.2)}$$

Where ***SV*** = slope variance (measure of longitudinal surface irregularities (roughness)

RD = average rut depth (inches / 4 feet straight edge)

C = area of cracking in **ft^2 per 1000 ft^2**

P = area of patching in **ft^2 per 1000 ft^2**

Note= take average for all above values *SV* , *RD,C, and P* and enter it in equation 4.2

PSR ≈ PSI

$\Delta PSI = PSI_o - PSI_t$

- **PSI_o = P_i = Initial serviceability index is a performance of a pavement** immediately after the construction **for Flexible pavement = 4.2 for Rigid pavement = 4.5**
- **PSI_t = P_t = Terminal serviceability index is the lowest acceptable level before it the resurfacing or reconstruction of the pavement becomes necessary**.

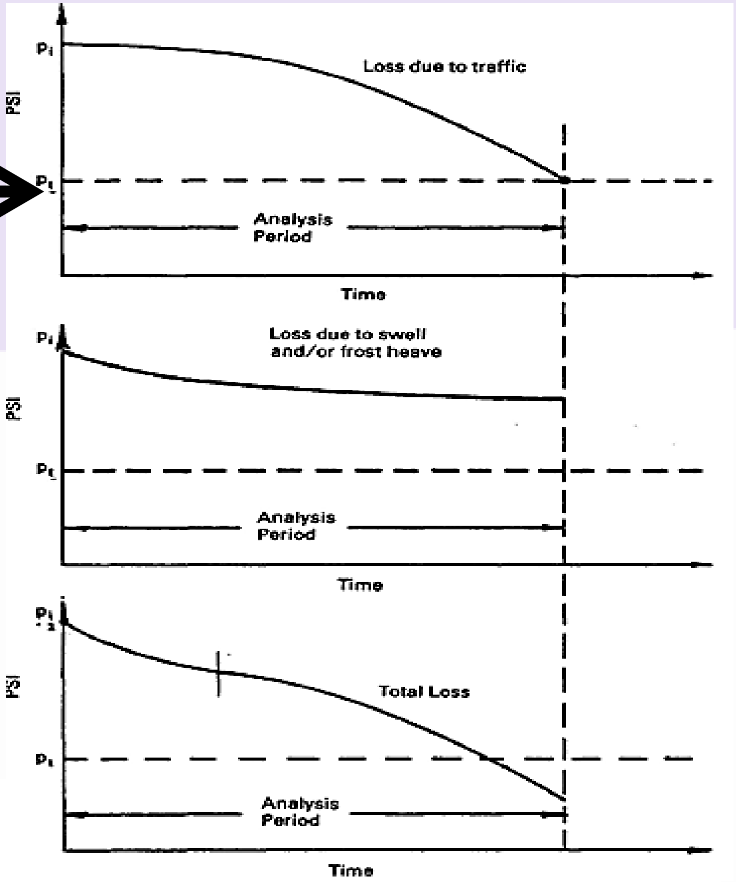
P_t value is based on class of highway for Major highways ≥ 2.5 and for Lower traffic volume = 2.0

$\Delta PSI = \Delta PSI_{Traffic} + \Delta PSI_{Environment}$ *as shown in Figure 4.3.*

ΔPSI = Total loss of serviceability during a specific period of time in years.

$\Delta PSI_{Traffic}$ = Serviceability loss due to traffic (ESAL's)

$\Delta PSI_{Environment}$ = Serviceability loss due to effect of swelling and /or frost heave of roadbed soil



$$\boldsymbol{\sigma^2 = \frac{\sum_{i=1}^{i=N}(y_i-\bar{y})^2}{n-1}} \quad \textit{where} \quad \boldsymbol{\sigma^2} \textit{ is Variance}$$

$$\sqrt{\sigma^2} = \sigma = \textit{standard deveiation}$$

<u>Slope Variance:</u>

Elevations of the surface for the pavement with respect to distance as shown in Figure 4.2.

The mean, $\bar{y}$, of f(y) from A to B is estimated by

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$

$$\boxed{SV = \frac{\sum_{i=1}^{i=N}(y_i-\bar{y})^2}{n-1}}$$

Where ***SV*** = mean of the slope variance in the two wheel paths

y = different in elevation between two points, 30cm a part

N = number of reading points = *n*

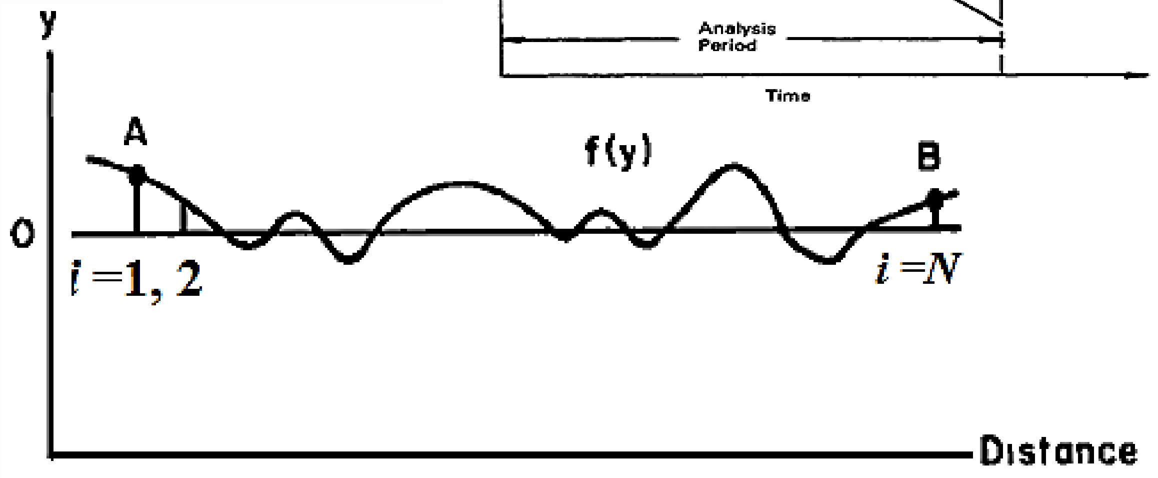


Figure 4.2. highway surface elevations with distance

Time Constraints

- ***Performance Period***
  - Period of time that the initial pavement structure will last before it requires rehabilitation.
  - The period of time which the pavement deteriorates from the initial serviceability to the terminal serviceability.
  - It is also the time between rehabilitation operations. ***as shown in Figure 4.3.***
- ***Analysis Period***
  - **Length of time that the design strategy should cover.**
  - **The analysis period is analogous to the "*design life*" used by designers in the past.**
  - The following is a list of recommended analysis periods for certain highway conditions, **Table 4.1.**

Table 4.1. Highway conditions and analysis period.

Highway Conditions	Analysis Period(years)
High-volume urban	30-50
High-volume rural	20-50
Low-volume paved	15-25
Low-volume aggregate surface	10-20

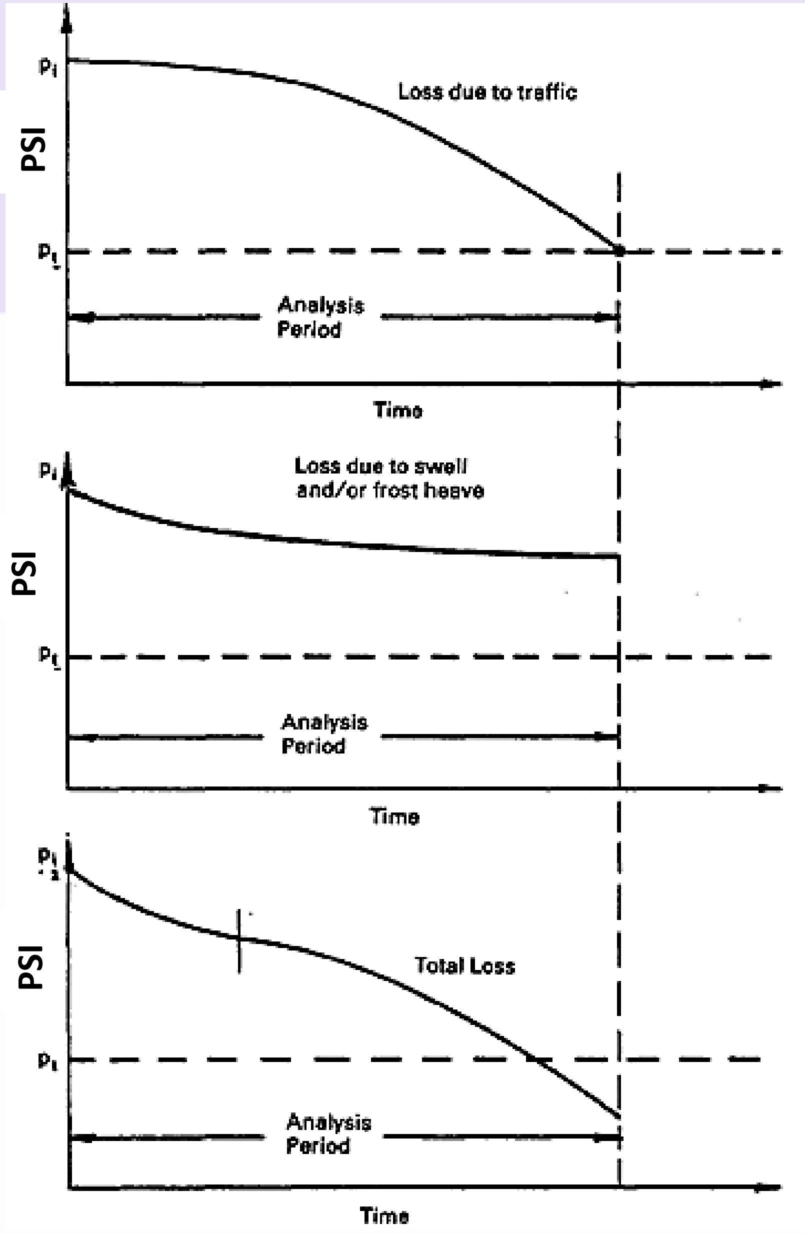


Figure 4.3. PSI vs. time (year)

4.1.2. Traffic

Equivalent Single Axle Load ($\mathbf{W_{18}}$ or ESAL on design lane): Converts wheel loads of various magnitudes and repetitions (all types of vehicles which may moved along the designed highway or used all mixed traffic) must be convert to an equivalent number of "standard" or "equivalent" loads which is based on the amount of damage they do to the pavement. The conversion is commonly used to standard load 18,000 lb. (80 kN) equivalent single axle load. Figure (4.4)

Load Equivalency can be used by ***Generalized fourth power approximation.***

Load Equivalency Factor (LEF) which cause relative damage to one pass of standard axle load Equ. (4.3)

$$\left(\frac{\text{load}}{18{,}000\,\text{lb.}}\right)^4 = \text{relative damage factor (LEF)} \qquad \text{-----------} \quad \mathbf{4.3}$$

$$W_{18\,performance}\,(W_t) = W_{18\,Predicted}\,(w_T) \times \textit{Reliability Factor}\,(F_R) \qquad \ldots\ldots\ldots\ldots\ldots\; 4.4$$

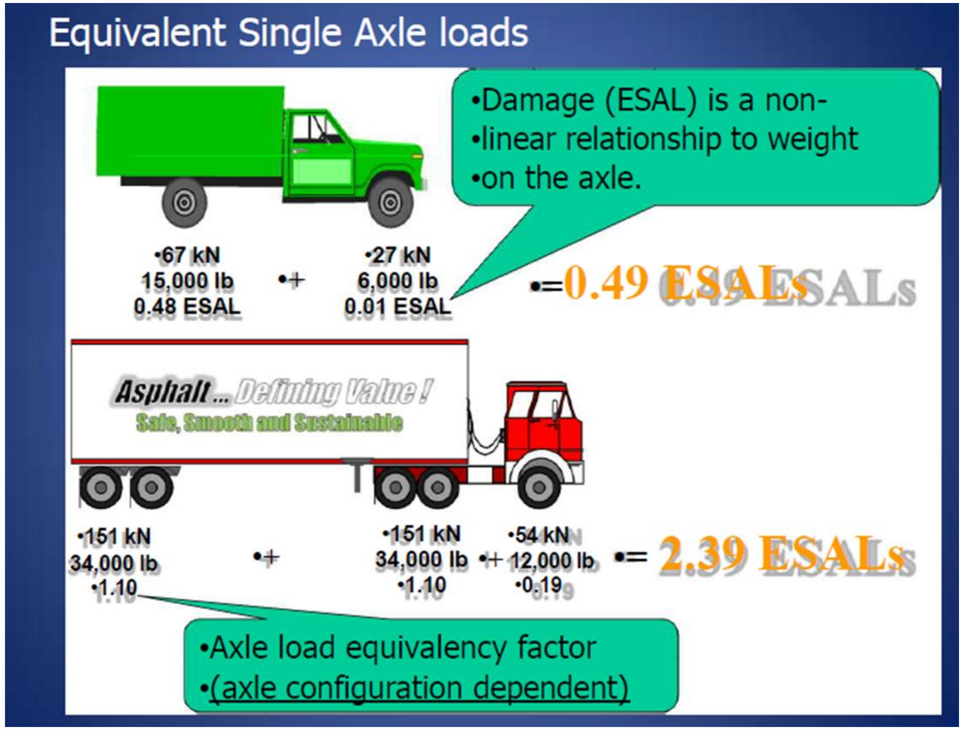
$F_R = \dfrac{W_t}{w_T}$ Where F_R is Reliability factor similar to factor of safety.

$$W_{18\,Predicted} = w_T = \left(\sum 365 \times AADT_{for\ each\ type\ of\ vehicale} \times G \times LEF_{for\ each\ type\ of\ vehicale}\right) \times D_D \times D_L \qquad \text{---}\ 4.5$$

Where D_D = Directional distribution factor , expressed as a ratio, that account for distribution of loads by direction.
Generally taken as 0.5 (50%) for most roadways

D_L = Lane distribution factor as shown in Table 4.2.

G = *growth factor* = $\dfrac{(1+r)^t - 1}{r}$, where t analysis period in years , and r = annual traffic growth rate in percent (1%-10%) 0.01 - 0.1



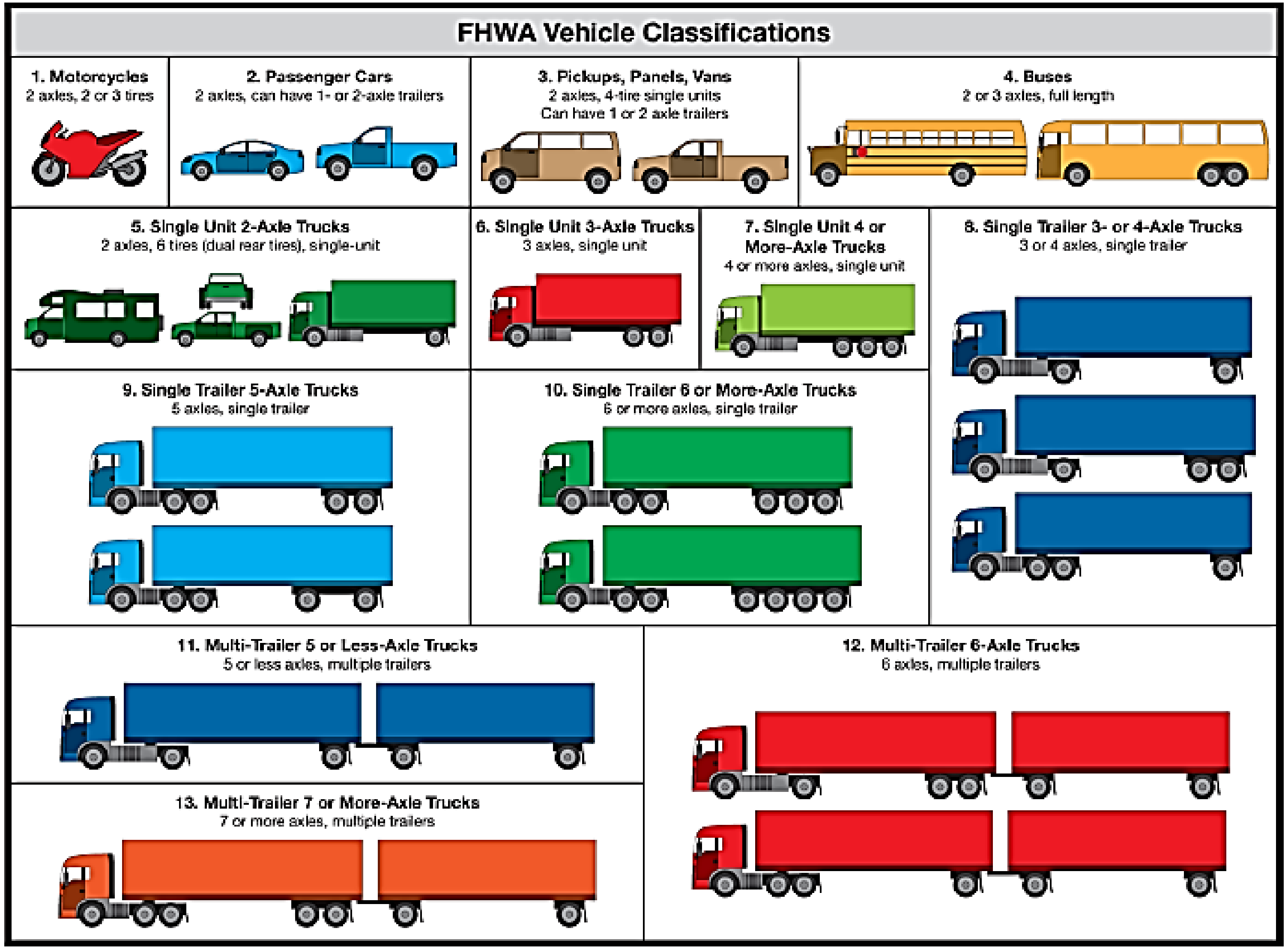


Figure 4.4. FHWA vehicles classification.

$AADT$ = Annual Average Daily Traffic for each type of Vehicles ,

LEF = Load Equivalency factor for each type of Vehicles

Table 4.2. : Lane ditribution Factor

Number of Lanes in Each Direction	*Percent of Loads in Design Lane*
1	100
2	80 – 100
3	60 – 80
4	50 – 75

Example 1: The total AADT of a rural four lanes highway is 4600 V/day for two direction (Fig.4.5) , if the annual rate of traffic growth is 2.5%. The percent and type of vehicles are shown in Table 4.3 , base year is 2000 and target year is 2020

Table 4.3 : Data of example 1

Truck category	Load factor (ESALs per truck)	Percent of total AADT in truck category	Number of trucks per two direction
2-axles	**0.5**	**10**	**460**
3-axles	**0.85**	**9**	**414**
4-axles	**1.2**	**6**	**276**
5-axles	**1.55**	**3**	**138**
6-axles	**2.24**	**2**	**92**

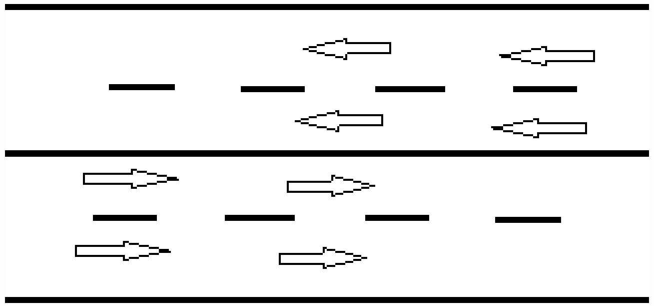


Fig.4.5: 4 lanes highway

Solution: 1- Count the number of vehicles for each type (column No.4 in table 4.3.

2- Assume D_D factor ,taken as 50%.

3- Find D_L from table 4.2 because the highway is 4 lanes ,so there are two lanes in one direction ,take D_L=85%

4- Calculate *G*, from **question t=20 years, r= 0.025 , G=25.54**

W_{18}=$D_D \times D_L \times 365 \times \mathbf{25.54} \times (460 \times 0.5 + 414 \times 0.85 + 276 \times 1.2 + 138 \times 1.55 + 92 \times 2.44)$

W_{18}= 0.5 ×0.85 ×365×25.54×1351.5= **5.35×10⁶**

4.1.3. Roadbed Soil Properties

- Roadbed soil is the foundation on which the pavement will be constructed. Soil strength must be known such that the pavement thickness is sufficient to spread the load induced by heavy vehicles on the soil without the soil deforming (rutting).
- AASHTO uses resilient modulus (M_R) as the measure of soil strength, accounting for seasonal variation in soil strength; AASHTO T 274

- Resilient modulus MR is a fundamental material property that is similar in concept to the modulus of elasticity. That is, resilient modulus is a stress-strain relationship. However, it differs from the modulus of elasticity in that it is determined from a repeated-load, triaxial-compression test and is based on only the resilient (or recoverable) portion of the strain.

- As the number of repetitions increases, the plastic strain due to each load repetition decreases . **After 100 to 200 repetitions, the strain is practically all recoverable, as indicated by ε_r as shown in Figure 4.6.**

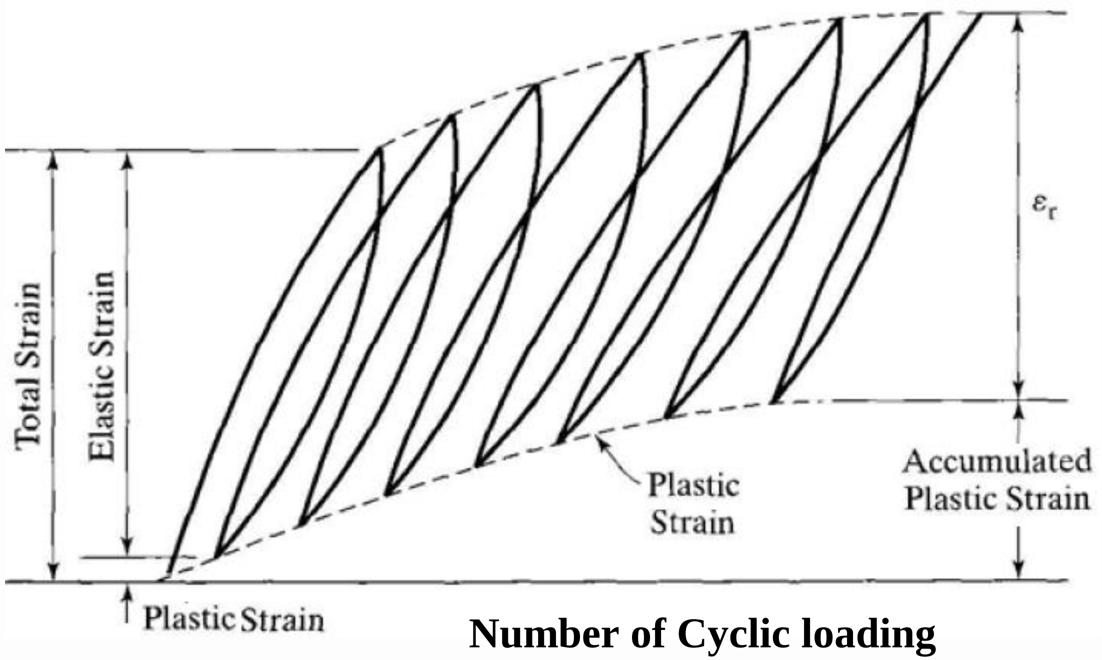


Figure 4.6. Strain vs time for resilient modulus test

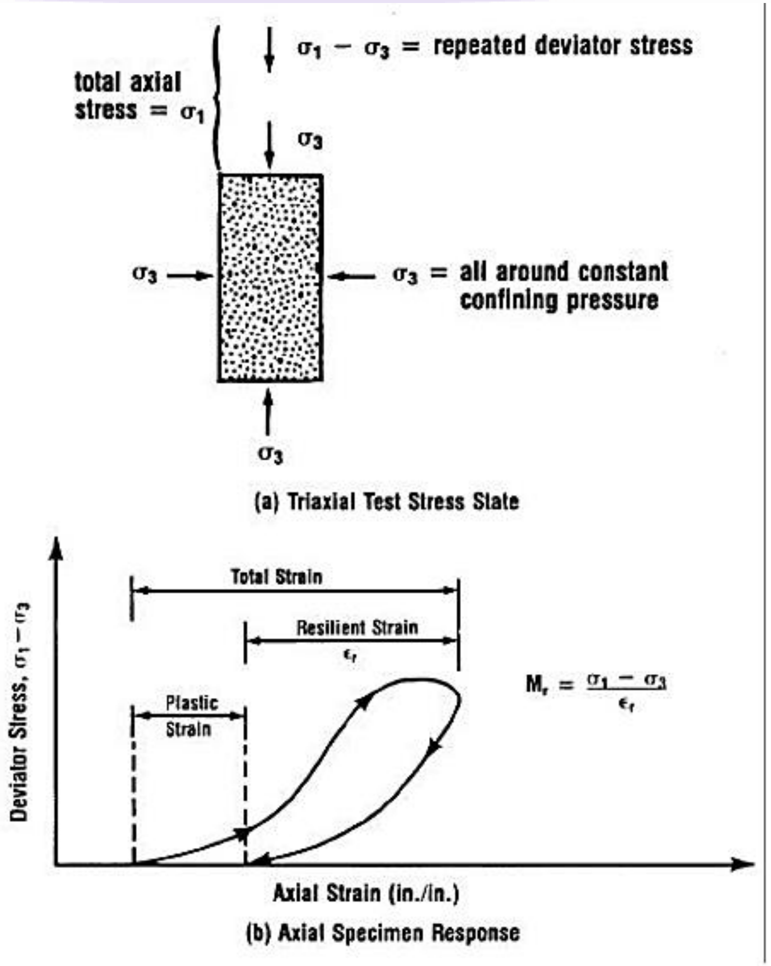
- As the load is applied, the stress increases as does the strain. When the stress is reduced, the strain also reduces **but all of the strain is not recovered after the stress is removed**. The total strain, therefore, **is composed of both a permanent (or plastic) component and a recoverable (or resilient) component.** **The plastic strain is not included in the resilient modulus.** The resilient modulus test is designed to simulate the behavior of soils and granular materials when subjected to traffic loading within a pavement system. The standard method of test is prescribed by AASHTO T-274. M_R can be calculated using Equation 4.7.

$$\mathbf{M_R = \sigma_d / \varepsilon_r \quad \dots\dots\dots\dots\dots \; 4.7}$$

$(\sigma_1 - \sigma_3) = \sigma_d$ = deviator stress, ε_r = recoverable strain

- M_R is generally estimated directly in the laboratory using repeated load triaxial testing, indirectly through correlation with other standard tests such as CBR value.

$M_r = 17.6 \times CBR^{0.64}$	(MPa)	for materials with CBR>10%
$M_r = 2555(CBR)^{0.64}$	(psi)	
$M_r = 10.3 \times CBR$	(MPa)	for materials with (2%<CBR≤10%)
$M_r = 1500 \times CBR$	(psi)	Note: 1 psi = 0.006895 MPa.



(a) Triaxial Test Stress State

(b) Axial Specimen Response

Note: Text book yang page 284 articles 7.1.3 & 7.1.4

❑ During seasonal changes, rainfall and groundwater may infiltrate the subgrade, changing the moisture content and, therefore, changing the resilient modulus. Temperature fluctuations (freezing and thawing) in the subgrade, depending on the depth, may also affect the performance of the subgrade resilient modulus. Thus AASHTO 1993 procedure suggested to use effective resilient modulus.

❑ Steps how to find effective roadbed Resilient Modulus

1. Find (Mr) for subgrade for each season or each month during the whole year.
2. Compute Relative damage for each season or each month during the whole year using Equation 7.8.

$$\mu_f = 1.18\times 10^{8} \times M_R^{\ -2.32} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 4.8.$$

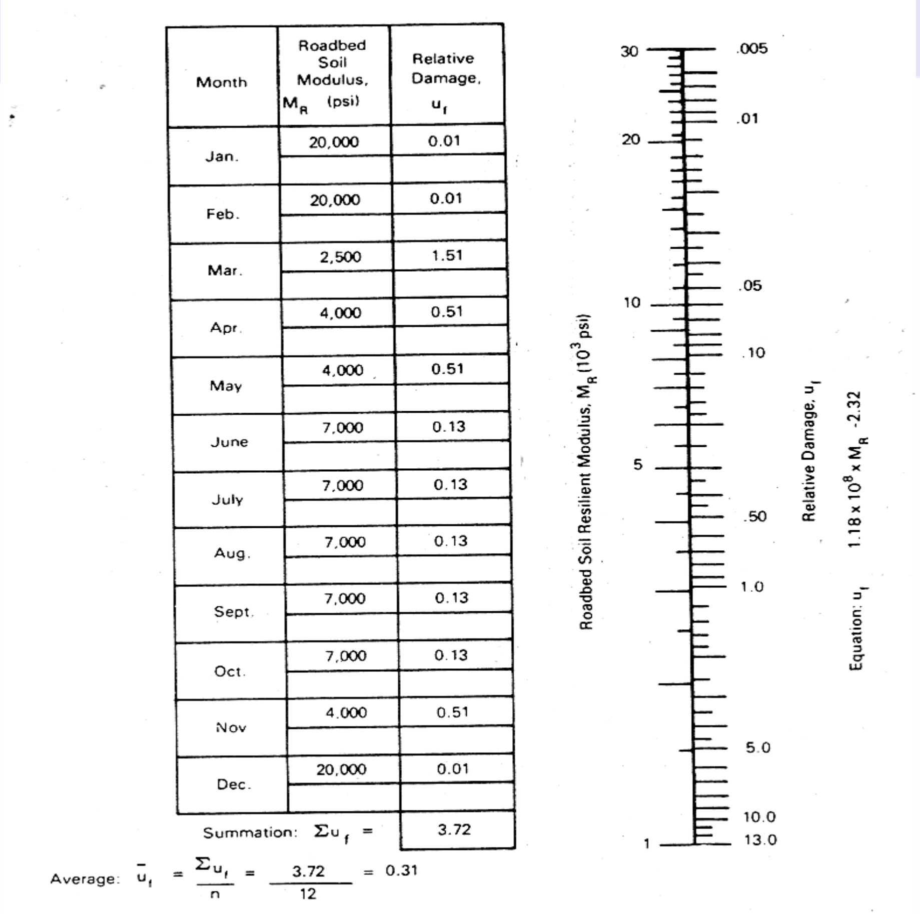
Where μ_f is relative damage in , MR resilient modulus in psi.

3. Compute the average relative damage value.

$$\bar{\mu}_f = \frac{\sum \mu_f}{n} \quad \ldots\ldots \ \ldots\ldots\ldots \ 4.9$$

4. Use the average relative damage ($\bar{\mu}_f$) value to determine the effective roadbed (Mr).

5. The scale (Figure 4.8) can be used for finding effective resilient modulus.



Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.	20,000	0.01
Feb.	20,000	0.01
Mar.	2,500	1.51
Apr.	4,000	0.51
May	4,000	0.51
June	7,000	0.13
July	7,000	0.13
Aug.	7,000	0.13
Sept.	7,000	0.13
Oct.	7,000	0.13
Nov	4,000	0.51
Dec.	20,000	0.01
Summation: Σu_f =		3.72

Average: $\bar{u}_f = \frac{\Sigma u_f}{n} = \frac{3.72}{12} = 0.31$

Effective Roadbed Soil Resilient Modulus, M_R (psi) = 5,000 (corresponds to $\bar{u}_f$)

FIGURE 16-12 Chart for estimating effective roadbed soil resilient modulus for flexible pavements designed using the serviceability criteria. (Courtesy American Association of State Highway and Transportation Officials.)

Figure 4.8. Chart for estimating M_R effective.

Statistic Concept:

- **The mean (Arithmetic or average mean)**

The mean ($\bar{x}$)is the sum of observed values divided by the total number of the values, as shown in Equation 4.10.

Note: the symbol $\bar{x}$ is used for sample while μ is used for population.

$$\bar{x} = \frac{\sum_{i=1}^{i=n} \sum x_i}{n} = \frac{x_1+x_2+\cdots+x_n}{n} \quad \ldots\ldots\ \ldots\ldots\ldots\ 4.10$$

- **Median (MD)**

The value that lies in the middle of the data when the data set is ordered. If the data set has an odd number of entries, then the median is the middle data entry. If the data has an even number of entries, then the median is obtained by adding the two numbers in the middle and dividing result by two.

- **Mode (Mo)**

The data entry that occurs with the greatest frequency. A data set may have one mode, more than one mode, or no mode. If no entry is repeated the data set has no mode

- **Standard Deviation**

The standard deviation (**σ**) measures variability and consistency of the sample or population. σ is the root square of variance as shown in Equation 4.11.

$$\text{Standard deviation} = \sigma = \sqrt{\frac{\sum(x_i-\bar{x})^2}{n-1}} \quad \ldots\ \ldots\ \ldots\ 4.11$$

Example 2: For the data (5, 10, 15, 20) find mean , median, mode variance and standard deviation?.

Solution:

$$\bar{x} = \frac{\Sigma x}{n} = \frac{5+10+15+20}{4} = \frac{50}{4} = 12.5$$

Data	$x - \bar{x}$	$(x - \bar{x})^2$
5	$5 - (12.5) = -7.5$	$(-7.5)^2 = 56.25$
10	$10 - (12.5) = -2.5$	$(-2.5)^2 = 6.25$
15	$15 - (12.5) = 2.5$	$(2.5)^2 = 6.25$
20	$20 - (12.5) = 7.5$	$(7.5)^2 = 56.25$
		$\Sigma(x - \bar{x})^2 = 125.01$

- **Normal Distribution**

The normal distribution is a continuous, symmetric, bell shape distribution of a variable, Figure 4.9. The curve of normal distribution is a function of **x, σ, and μ.** As shown in Equation 4.12.

$$f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2} \quad \ldots\ldots\ldots \mathbf{4.12}$$

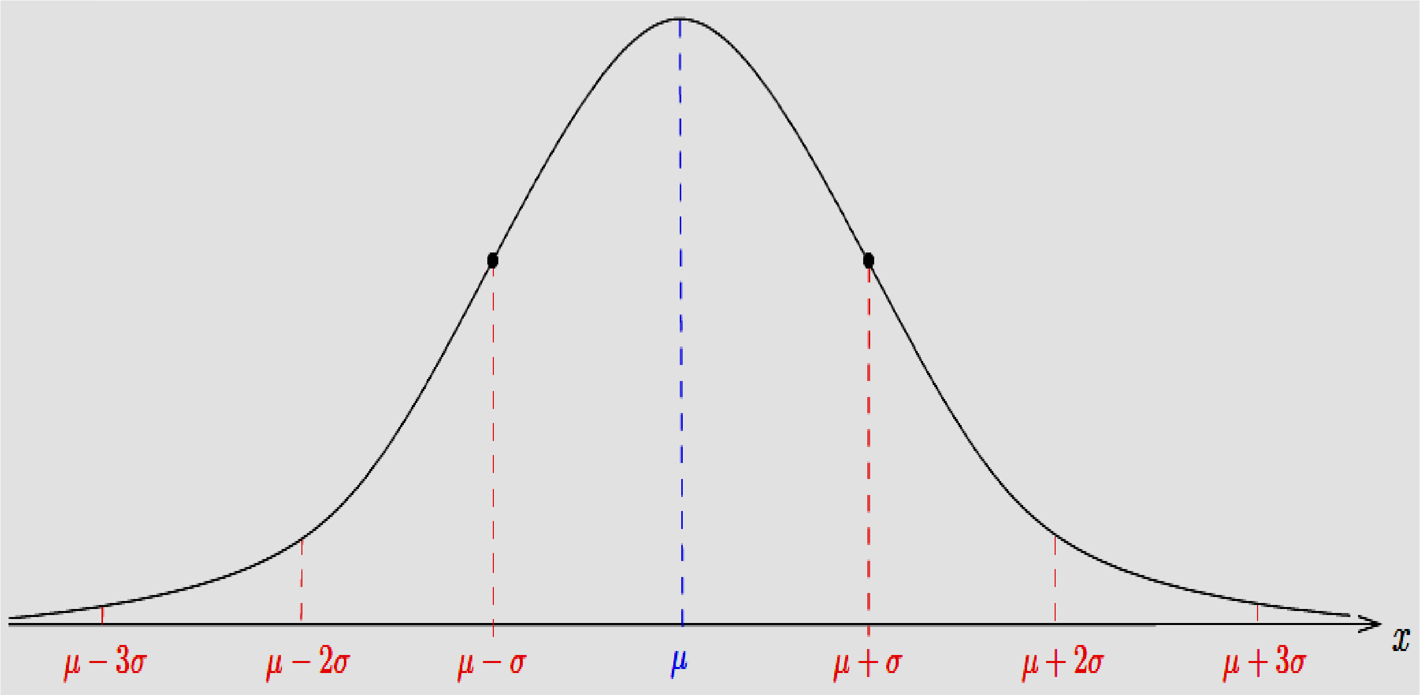


Figure 4.9. A typical normal distribution curve.

Properties of a Normal Distribution Curve

A normal distribution is a continuous probability distribution for a random variable x. The graph of a normal distribution is called the normal curve, which has all of the following properties:

1. The mean, median, and mode are equal.
2. The normal curve is bell-shaped and is symmetric about the mean.
3. The total area under the curve is equal to one or 100% , it means 50% either to the right and to the left of mean.
4. The normal curve approaches, but never touches, the x-axis.
5. Area under the normal curve between **$\mu \pm 1\sigma = 0.68$, for $\mu \pm 2\sigma = 0.95$, and $\mu \pm 3\sigma = 0.997$.**

- **The Standard Normal Distribution Curve**

Since each normally distributed variable has its won mean and standard deviation, the shape and location of these curve will vary . In practical applications, then, one would have to have a table of areas under the curve for each variable. To simplify the situation statisticians used what is called the **Standard Normal Distribution which is defined as is a normal distribution with a mean of 0 and standard deviation of 1. A**ll normally distributed variables can be transformed into the standard normally distributed variable using the formula for the standard score (Z), Equation 4.13. Table 4.3. can be used for determine the area under the curve.

$$z = \frac{X-\mu}{\sigma} \quad \text{................} \quad 4.13$$

<u>Example:</u>

Find the area to the left of z = -1.16 ?

<u>Solution:</u>

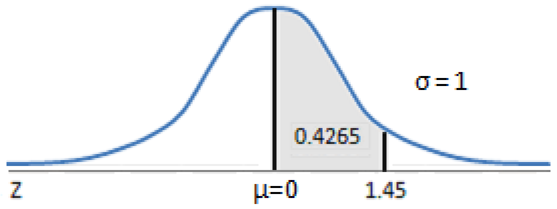
From Table 4.3, Z = -1.16, the area from the mean ($\mu = 0$) to the left (x = -1.16) is 0.377, so the total area is the sum of this area with the 0.5 from the right hand.

The total area = 0.377 + 0.5 = 0.877

Table 4.3. Area under Z curve

Areas Under the One-Tailed Standard Normal Curve

This table provides the area between the mean and some Z score.
For example, when Z score = 1.45 the area = 0.4265.



Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.0000	0.0040	0.0080	0.0120	0.0160	0.0199	0.0239	0.0279	0.0319	0.0359
0.1	0.0398	0.0438	0.0478	0.0517	0.0557	0.0596	0.0636	0.0675	0.0714	0.0753
0.2	0.0793	0.0832	0.0871	0.0910	0.0948	0.0987	0.1026	0.1064	0.1103	0.1141
0.3	0.1179	0.1217	0.1255	0.1293	0.1331	0.1368	0.1406	0.1443	0.1480	0.1517
0.4	0.1554	0.1591	0.1628	0.1664	0.1700	0.1736	0.1772	0.1808	0.1844	0.1879
0.5	0.1915	0.1950	0.1985	0.2019	0.2054	0.2088	0.2123	0.2157	0.2190	0.2224
0.6	0.2257	0.2291	0.2324	0.2357	0.2389	0.2422	0.2454	0.2486	0.2517	0.2549
0.7	0.2580	0.2611	0.2642	0.2673	0.2704	0.2734	0.2764	0.2794	0.2823	0.2852
0.8	0.2881	0.2910	0.2939	0.2967	0.2995	0.3023	0.3051	0.3078	0.3106	0.3133
0.9	0.3159	0.3186	0.3212	0.3238	0.3264	0.3289	0.3315	0.3340	0.3365	0.3389
1.0	0.3413	0.3438	0.3461	0.3485	0.3508	0.3531	0.3554	0.3577	0.3599	0.3621
1.1	0.3643	0.3665	0.3686	0.3708	0.3729	0.3749	0.3770	0.3790	0.3810	0.3830
1.2	0.3849	0.3869	0.3888	0.3907	0.3925	0.3944	0.3962	0.3980	0.3997	0.4015
1.3	0.4032	0.4049	0.4066	0.4082	0.4099	0.4115	0.4131	0.4147	0.4162	0.4177
1.4	0.4192	0.4207	0.4222	0.4236	0.4251	0.4265	0.4279	0.4292	0.4306	0.4319
1.5	0.4332	0.4345	0.4357	0.4370	0.4382	0.4394	0.4406	0.4418	0.4429	0.4441
1.6	0.4452	0.4463	0.4474	0.4484	0.4495	0.4505	0.4515	0.4525	0.4535	0.4545
1.7	0.4554	0.4564	0.4573	0.4582	0.4591	0.4599	0.4608	0.4616	0.4625	0.4633
1.8	0.4641	0.4649	0.4656	0.4664	0.4671	0.4678	0.4686	0.4693	0.4699	0.4706
1.9	0.4713	0.4719	0.4726	0.4732	0.4738	0.4744	0.4750	0.4756	0.4761	0.4767
2.0	0.4772	0.4778	0.4783	0.4788	0.4793	0.4798	0.4803	0.4808	0.4812	0.4817
2.1	0.4821	0.4826	0.4830	0.4834	0.4838	0.4842	0.4846	0.4850	0.4854	0.4857
2.2	0.4861	0.4864	0.4868	0.4871	0.4875	0.4878	0.4881	0.4884	0.4887	0.4890
2.3	0.4893	0.4896	0.4898	0.4901	0.4904	0.4906	0.4909	0.4911	0.4913	0.4916
2.4	0.4918	0.4920	0.4922	0.4925	0.4927	0.4929	0.4931	0.4932	0.4934	0.4936
2.5	0.4938	0.4940	0.4941	0.4943	0.4945	0.4946	0.4948	0.4949	0.4951	0.4952
2.6	0.4953	0.4955	0.4956	0.4957	0.4959	0.4960	0.4961	0.4962	0.4963	0.4964
2.7	0.4965	0.4966	0.4967	0.4968	0.4969	0.4970	0.4971	0.4972	0.4973	0.4974
2.8	0.4974	0.4975	0.4976	0.4977	0.4977	0.4978	0.4979	0.4979	0.4980	0.4981
2.9	0.4981	0.4982	0.4982	0.4983	0.4984	0.4984	0.4985	0.4985	0.4986	0.4986
3.0	0.4987	0.4987	0.4987	0.4988	0.4988	0.4989	0.4989	0.4989	0.4990	0.4990
3.1	0.4990	0.4991	0.4991	0.4991	0.4992	0.4992	0.4992	0.4992	0.4993	0.4993
3.2	0.4993	0.4993	0.4994	0.4994	0.4994	0.4994	0.4994	0.4995	0.4995	0.4995
3.3	0.4995	0.4995	0.4995	0.4996	0.4996	0.4996	0.4996	0.4996	0.4996	0.4997
3.4	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4998
3.5	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998
3.6	0.4998	0.4998	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
3.7	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
3.8	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
3.9	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000

STANDARD NORMAL DEVIATE (Z_R)

Table 4.4 Suggested levels of reliability for various functional classifications (AASHTO, 1993).

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 base on a survey of AASHTO Pavement Design Task Force.

Step 1 – Determine Recommended Reliability Level

Table C-3. 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

Step 2 – Determine ZR using Recommended Reliability Level

Reliability (R)

- Reliability **(R)** is a means of incorporating of some degree of certainty into the design process to insure that various design alternatives will last the analysis period. The reliability design factor account for chance variations in both traffic prediction (**w_{18}** = **w_T**) and the performance prediction (**W_{18}** = **W_t**), and therefore provides **a predetermined level of assurance (R) that pavement sections will survive the period for which they are designed. R value depends on the functional classification of highways such as rural or urban (interstate, freeways, principal arterials, collectors and local road)** as shown in Table 4.4.

$$W_{18\,performance}(W_t) = W_{18\,Predicted}(w_T) \times Reliability\ Factor\ (F_R) \quad \ldots\ldots\ldots\ldots\ldots 4.4$$

$$F_R = \frac{W_t}{w_T}$$ Where F_R is Reliability factor **similar to** factor of safety.

<u>**Note**</u>: In design, overall reliability (**$R_{overall}$**) is used which can be estimated based on the stage's reliability (**$R_{stage\ or\ individual}$**) using the formula [**R_{stage} = $(R_{overall})^{1/n}$**]. For example if **$R_{overall}$ = 0.9,** then **R_{stage} for two stages (n=2)** is (**R_{stage} = $(0.9)^{1/2}$ = 0.95**).

Estimation of S_o

A standard deviation (S_o) should be selected that is representative of local conditions. Values of S_o depends upon the expected error in **traffic and performance period prediction**. However the **performance prediction error** developed at the road test was 0.25 for rigid and 0.35 for flexible pavement. The <u>**combined overall standard deviation**</u> **for traffic of 0.35 and 0.45 for rigid and flexible pavements, respectively.**

$$\log F_R = -Z_R \times S_o \quad gives \quad F_R = 10^{-Z_R \times S_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.14$$

Structural Number (SN)

The structural number **(SN as detailed in Equation 4.15)** is an abstract number expressing the structural strength of a pavement required for given combinations of:

1. Soil support (**M_R**)
2. Total traffic expressed in equivalent 18-kip single axle loads (***W_{18}***)
3. Terminal serviceability (***ΔPSI***), and
4. Environment**.**

***Or SN is** an* **index number** that represents the overall pavement system structural requirements needed **to sustain the design traffic loading for the design period.**

Analytically:

The required **SN** must be converted to actual thickness of **surfacing, base and subbase** by means of appropriate layer coefficients ***(a_i)*** representing the relative strength of the construction materials. Average values of layer coefficients for materials used in the AASHO Road Test are as follows:

- Asphalt concrete surface course = 0.44
- Crushed stone base course = 0.14
- Sandy gravel subbase = 0.11

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad \ldots\ldots \mathbf{4.15}$$

Where: D_1 is the thicknesses of surface layer, (inches)

D_2 is the thicknesses of base layer, (inches)

D_3 is the thicknesses of subbase layer, (inches)

m_2 and m_3 are drainage coefficients.

Layer Coefficients (a_i)

The AASHTO design method estimates the structural layer coefficients (a_i values) which are required for standard flexible pavement structural design. A value for this coefficient is assigned to each layer material in pavement structure in order to convert actual layer thicknesses into structural number (***SN***). This layer coefficient expresses the empirical relationship between SN and thickness and is a measure of the relative ability of the material to function as a structural component of the pavement. Equation 4.16 reflects the relative impact of the layer coefficients (a_i) and thickness (D_i) on structural number (***SN***).

$$SN = \sum_{i=1}^{n} a_i D_i \quad \dots\dots\dots\dots \; \mathbf{4.16}$$

✓ Layer Coefficient (a_1) for Asphalt Concrete Surface Course

a_1 can be determine using Figure 4.10 which is estimated for a dense graded asphalt concrete surface course based on its elastic resilient modulus (E_{AC}) at 68°F (20°C). The recommended value of E_{AC} must not be exceeded than 450000 psi. Although higher modulus of asphalt concrete are stiffer and more resistant to bending, they are also more susceptible to thermal and fatigue cracking.

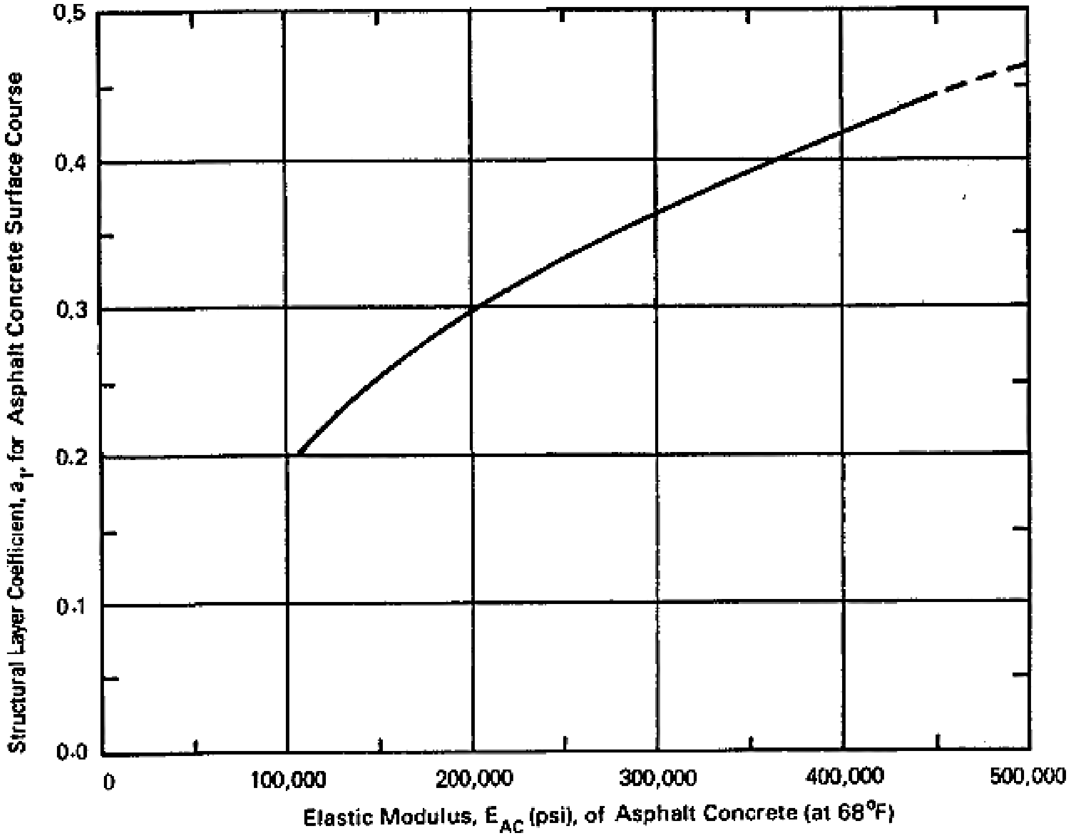


Figure 4.10 Chart for Estimating Structural Layer Coefficient of Dense-Graded Asphalt Concrete Based on the Elastic (Resilient) Modulus

Note: E_{Ac} at 20 °C (psi) =483× Marshall stability (kg)

✓ Layer Coefficient (a_2) for Granular Base Layers

- ❑ a_2 can be estimated using Figure 4.11. this figure can be used by knowing one of four different laboratory test results for granular base layer material: CBR, R-value, base resilient modulus (E_{BS}) , and Texas Tri-axial test. For example:

a_2 = 0.14 for E_{BS} = 30000 psi or CBR = 100% or R-value = 85

Equation (4.17) can be used to estimate the value of a_2 .

$$a_2 = 0.249 (\log E_{BS}) - 0.977 \ldots \ldots \ldots 4.17$$

- ❑ For cement-treated base materials, a_2 can be estimated using Figure 4.12. this figure can be used by knowing either its elastic modulus (E_{BS}) or 7-day unconfined compressive strength (psi).

- ❑ For bituminous-treated base materials, a_2 can be estimated using Figure 4.13. this figure can be used by knowing either its elastic modulus (E_{BS}) or its Marshal stability (lb)

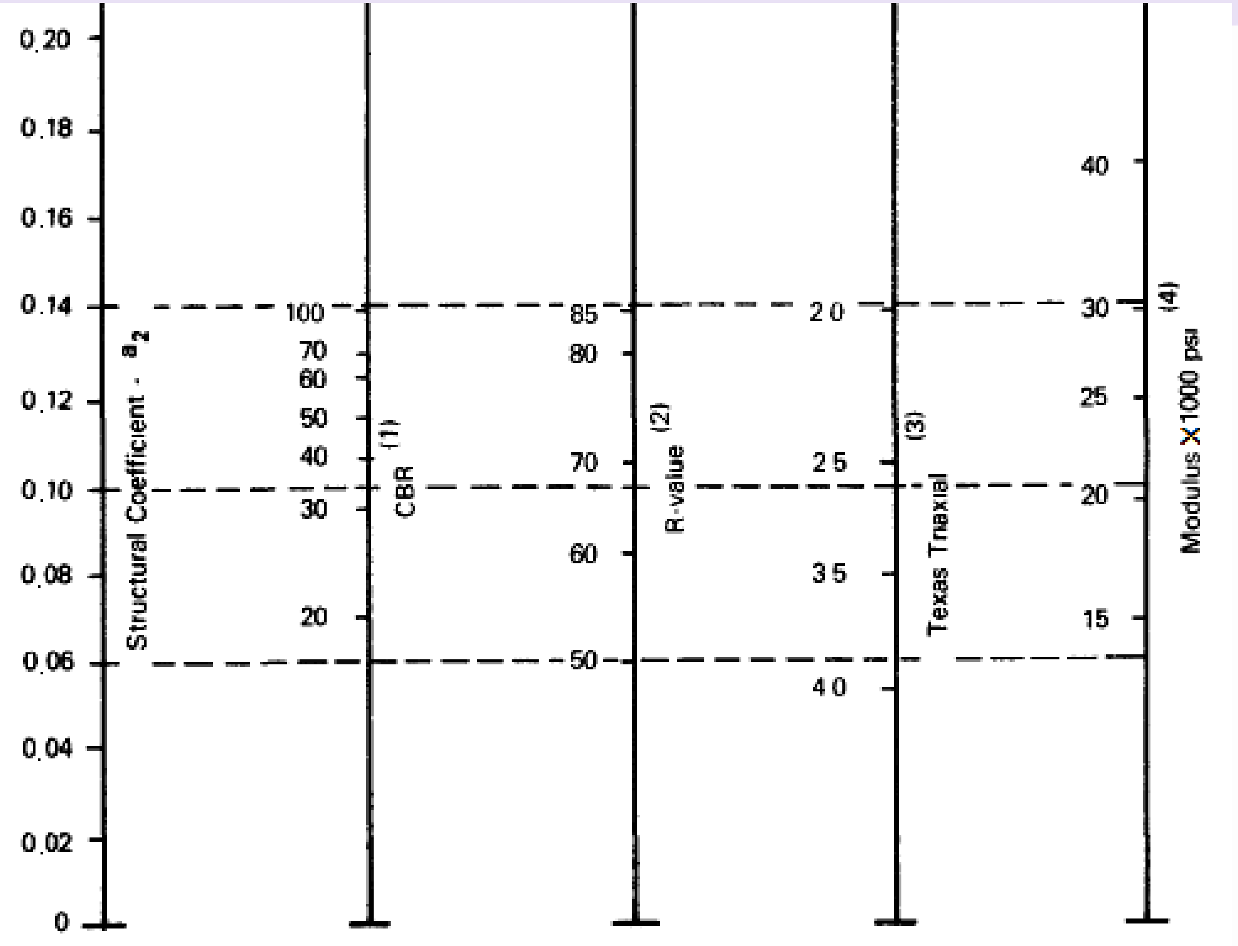


Figure 4.11 Variation in Granular Base Layer Coefficient (a_2) with Various Base Strength Parameters

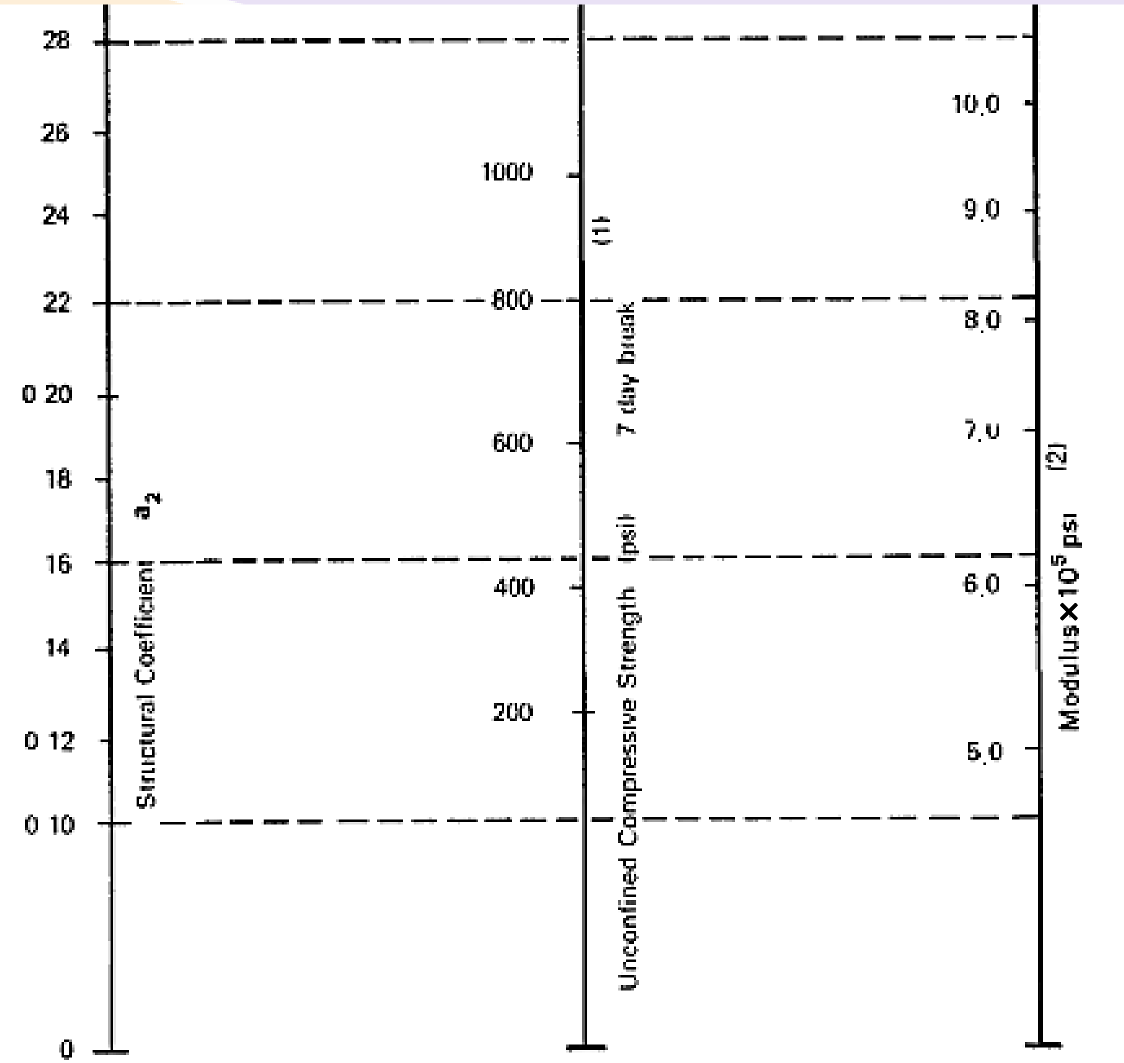


Figure 4.12. Variation in a_2 for Cement-Treated Bases with Base Strength Parameter

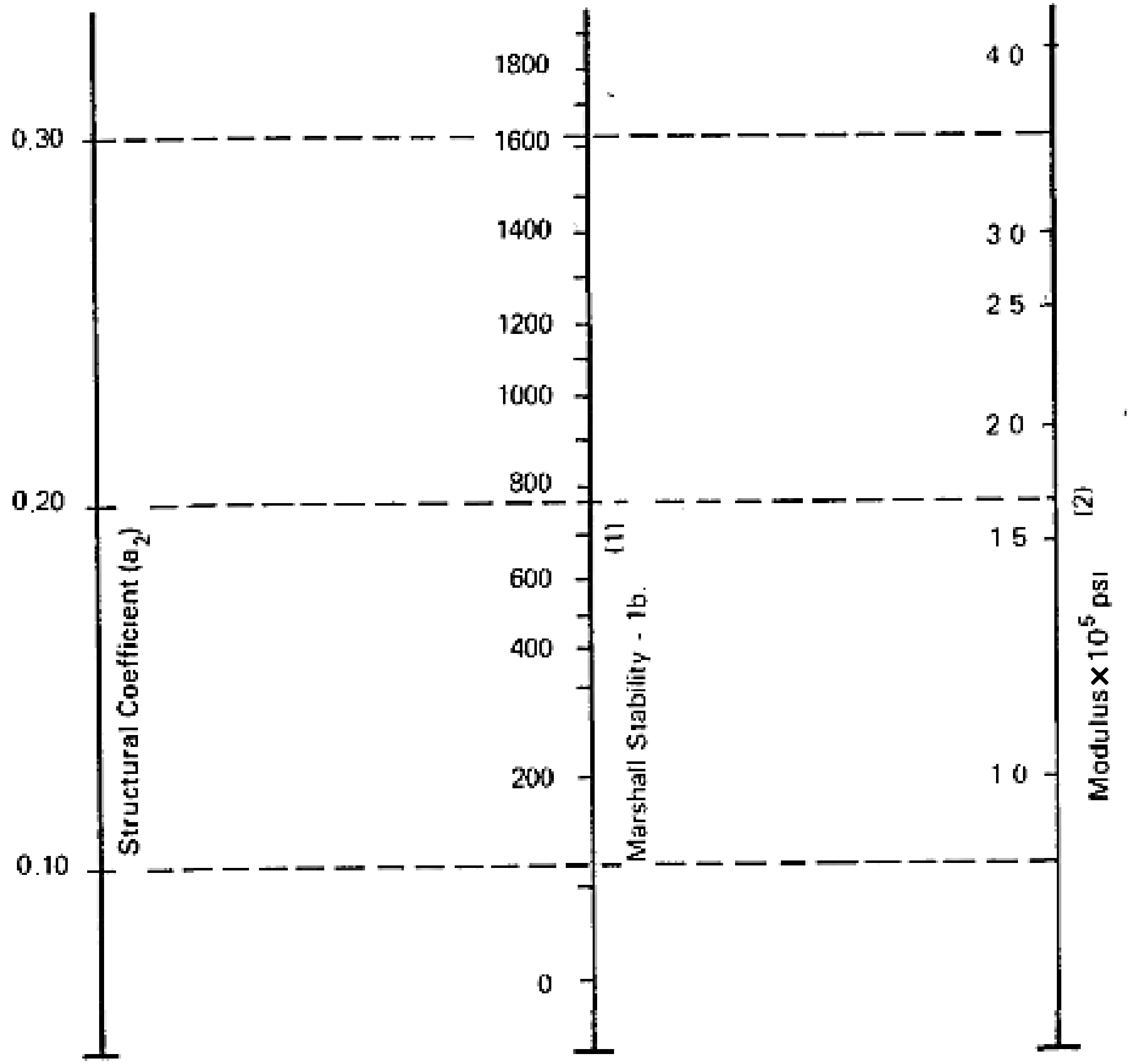


Figure 4.13. Variation in a_2 for Bituminous-Treated Bases with Base Strength Parameter

✓ Layer Coefficient (a_3) for Granular Subbase Layers

a_3 can be estimated using Figure 4.14. this figure can be used by knowing one of four different laboratory test results for granular subbase layer material: CBR, R-value, subbase resilient modulus (E_{SB}) , and Texas Tri-axial test. For example:

a_3 = 0.11 for E_{SB} = 15000 psi or CBR = 30% or R-value = 60

Equation (4.18) can be used to estimate the value of a_3 .

$$a_3 = 0.227 (\log E_{SB}) - 0.839 \quad \ldots \ldots \ldots \quad 4.18$$

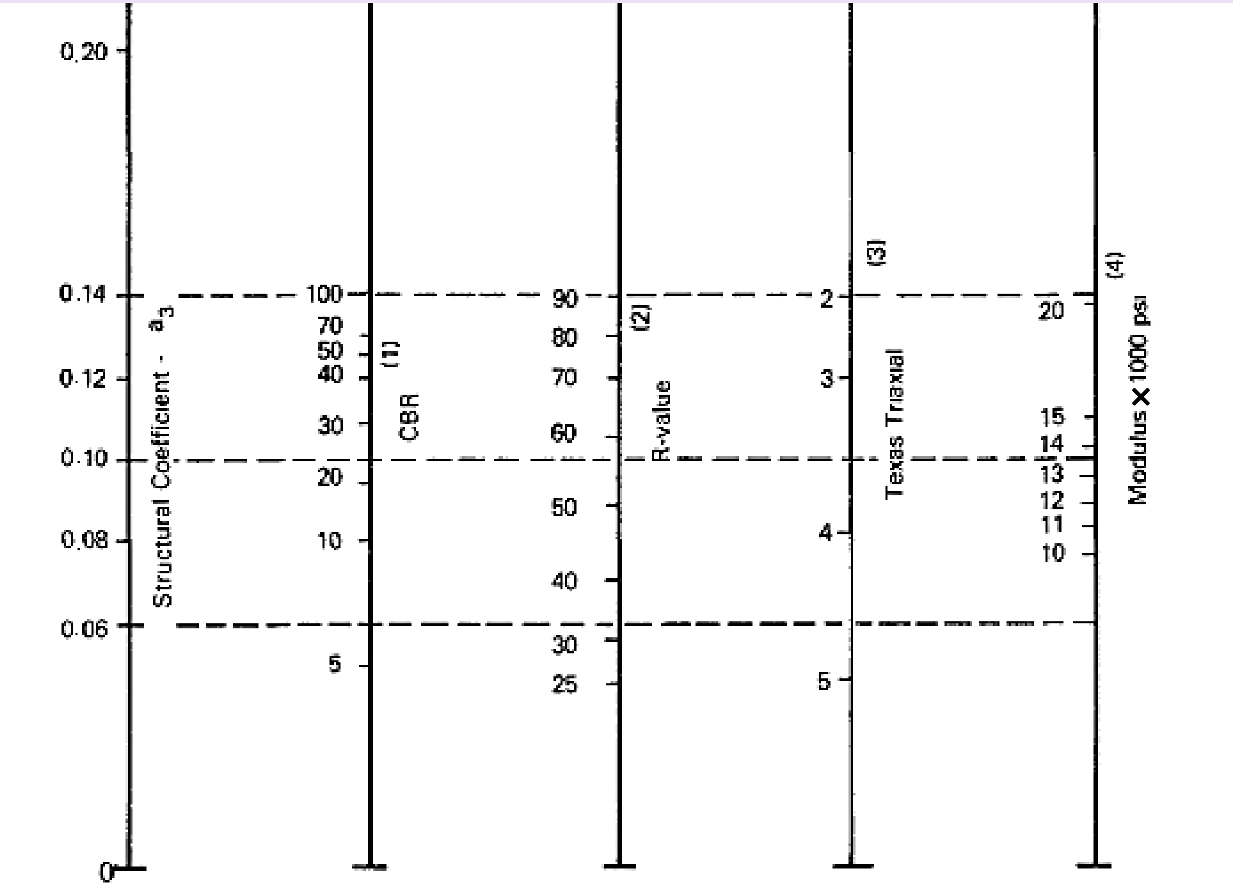


Figure 4.14 Variation in Granular Subbase Layer Coefficient (a_3) with Various Subbase Strength Parameters

❑ Effect of Drainage

To treat the effect of certain levels of drainage on predicted pavement performance. There are various drainage methods to remove moisture from the pavement. The selected method is up to the design engineer to identify what level (or) quality of drainage is achieved under a specific set of drainage conditions. Table 4.5, shows a different drainage quality and time needed to remove the water from the pavement structure.

Table 4.5.

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

Modified Layer Coefficient Factor Due to Drainage Condition (m_i)

- The treatment for the expected level of drainage for a flexible pavement is through the use of modified layer coefficient. The factor for modifying the layer coefficient is referred to as an (m_i) value.
- The possible effect of drainage on any layer treated by asphalt material is not considered (there is no modification for asphalt concrete layers).
- Table 4.6. presents the recommended m_i values as a function of quality of the drainage and the percent of the time during the year of the pavement structure would normally be exposed to moisture levels approaching.
- The value of this table is used for only **untreated materials** of base and subbase layers.

Example: Appendix H Represents a Flexible Pavement Design Example from AASHTO 1993 (Textbook)

Table 4.6. Recommended m_i Values for Modifying Structural Layer Coefficients of Untreated Base and Subbase Materials in Flexible Pavements

Quality of Drainage	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation: Less Than 1%	1–5%	5–25%	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

AASHTO Formula and Nomograph

$$\log_{10}(W_{18}) = Z_R S_0 + 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log_{10}(M_R) - 8.07 \quad \ldots\ldots \quad \mathbf{4.1}$$

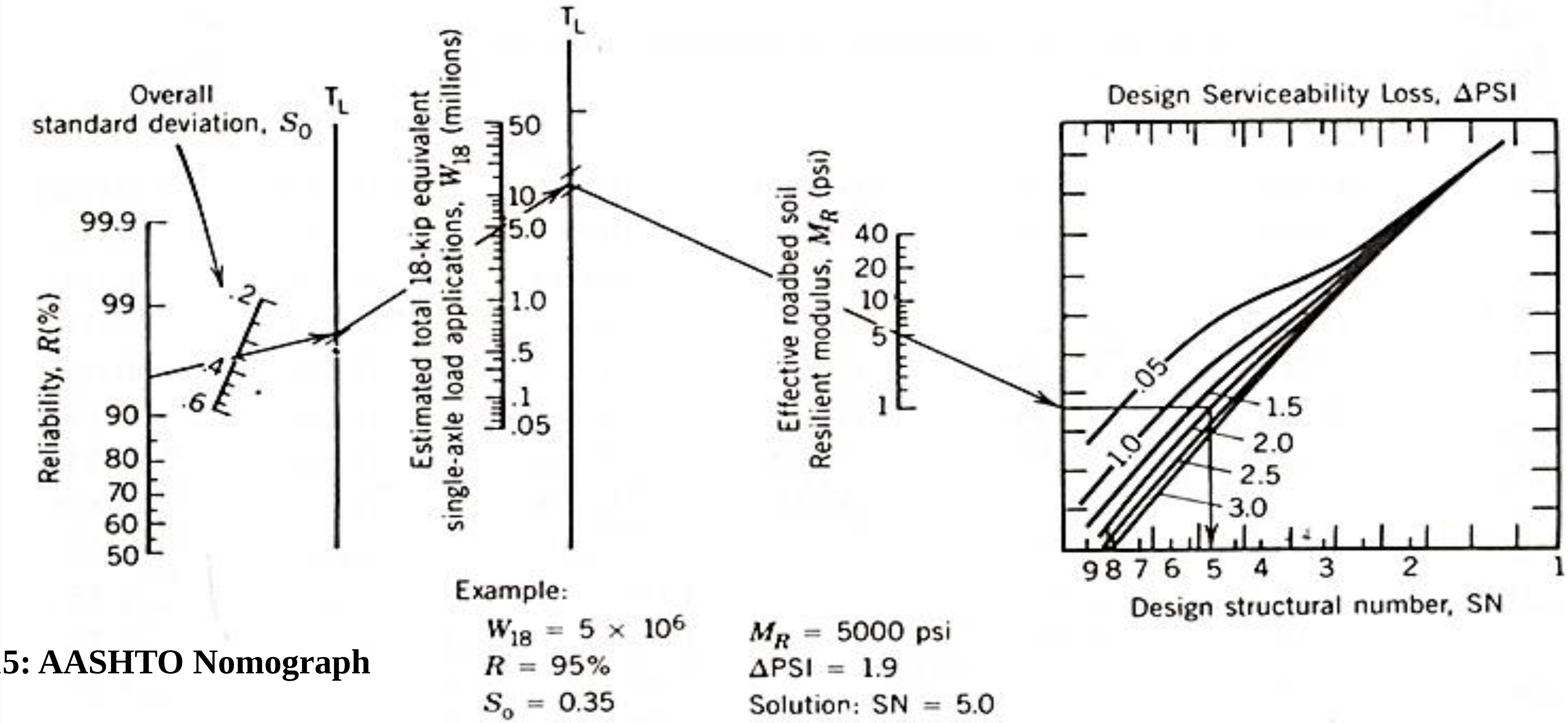


Figure 4-15: AASHTO Nomograph

Steps for Design of flexible pavement by AASHTO 1993 method

Step 1: Traffic calculation in form of $\mathbf{W_{18}}$
Step 2: Effective resilient modulus for roadbed $\mathbf{M_{R\ effective}}$
Step 3: According to functional classification of the designed highway , choose the value of Reliability **R**
Step 4: Estimate the change of serviceability due to traffic and environment **ΔPSI**
Step 5: Estimated the value of total standard deviation $\mathbf{S_o}$
Step 6: From the properties of each layer of flexible pavement , find the values of a_i for each one of layer
Step 7: Enter to nomograph to find ***SN***, then thickness of layers D_i.
Note: Don't forget the effect of drainage for untreated layers (i.e. for granular layers).

Flexible Pavement Design Example: {Appendix H from the AASHTO Guide for design of pavement structures }

The followings are given to design the structural layers: Analysis period = 20 years, maximum performance period = 15 years, six lanes in both directions for heavily trafficked state rural highway, S_o overall standard deviation is 0.35, the soil on which the highway to be constructed is considered to be highly active swelling clay, the drainage system will be considered to remove excess moisture in less than 1 day (1-5% moisture exposure), no frost heaving, the estimated two-way 18 kips equivalent single axle load (ESAL) during first year is 2.5×10^6 , the annual growth rate is 3%, $R_{overall}$ = 90%, E_{AC} = 400000psi, E_{BS} = 30000 psi from granular materials, E_{SB} = 11000 psi from granular materials. P_t =2.5 & P_o =4.6. The road bed soil thickness is more than 30 feet, and is tight with PI>20. The moisture conditions and their M_R as listed in Table (4.5). Determine the structural layer thicknesses for initial structure.

Road bed moisture condition	Wet	Dry	Spring-thaw	Frozen
M_R (psi) and time in months	5000 psi for 5 months	6500 psi for 5.5months	4000 psi for 0.5 months	20000 psi for 1 month

Table (4.5) resilient modulus of road bed soil with conditions

Solution:

1- Draw a scaled sketch represents relationship between time and W_{18} $\frac{(1+r)^t-1}{r}$

2- Find the $R_{individual}$, 2 stages (n=2) so $R_{individual} =(0.9)^{0.5} =0.95$

3- From nomograph in step 1 above find W_{18} which covered the maximum performance period = 15 years , is $W_{18} = 18.6\times10^6$

4- Calculate the effective resilient modulus $M_{R\ effective}= 5.7\times10^3$ psi (Figure 4.8)

5- Calculate **$\Delta PSI = P_i – P_t = 4.6-2.5=2.1$ (due to traffic only)**

6- From the data which are found in above steps ($W_{18}= 18.6\times10^6$, $M_{R\ effective}= 5.7\times10^3$ psi , $R_{individual} =0.95$, $\Delta PSI=2.1$, So=0.35,

7- Enter to nomograph (Fig.4-15) to find first SN which is not affected by environment (no effect of swelling) = 5.6

8- Now from relationship between ΔPSI due to swelling and time $\Delta PSI = 0.00335 V_R \times P_s(1 - e^{-\theta t})$ where P_s=swell probability = 84% , V_R= potential vertical rise= 1.2 inches, θ = swell rate constant= 0.075. A scaled sketch must drawn (in this example the soil is susceptible to swelling)

9- For 20 years $\Delta PSI_{environment}=0.262$ and for 15 years $\Delta PSI_{environment} = 0.228$

10- Because it was given that the maximum performance period is 15 years, so we must check this by assuming time less than 15 years so assume that 1st performance period =13 years .

11- Find its $\Delta PSI_{environment}= 0.21$(i.e. for13 years) (part II section 3.1.3 AASHTO Guide 1993)

12- Calculate the total ΔPSI =due to traffic +due to environment=4.6-2.5-0.21=1.89 (for 13 years)

Important Note: Because of the relatively small effect the Structural number (SN) has on minimizing swelling and frost, **the maximum initial SN recommended is that derived for conditions assuming no swelling or frost heave.**

According to AASHTO 1993 guide, article 3.1.3, step 1 the maximum initial Structural number (SN) is that for 15 years = 5.6 which is adopted in calculations and taken with no environmental effect.

1- For SN= 5.6, $M_{R\ effective}$= 5.7×10^3 psi , R $_{individual}$ =0.95, ΔPSI=1.89 , So=0.35. Find the W_{18} related to these data from nomograph as W_{18} = 16 ×10^6

2- From time vs W_{18} curve find the time for W_{18} = 16 ×10^6 which is 13.2 years

3- Compare the calculated (13.2 years) and assumed (13 years) . Her the calculated > assumed so OK if it is not reduce the assumed time (for example 10 years and repeat the steps until to reach the accepted time)

4- Now we have that the maximum initial Structural number (**SN3= 5.6**), so the layer thickness can be determined:

1. For SN of structure above the subbase course the needed data are : E_{SB}= 11×10^3 psi , R =0.95, ΔPSI=1.89 , So=0.35, W_{18} = 16 ×10^6 , so from nomograph its **SN2= 4.5 .**
2. For SN of structure above the base course the needed data are : E_{BS}= 30×10^3 psi , R =0.95, ΔPSI=1.89 , So=0.35, W_{18} = 16 ×10^6 , so from nomograph its **SN1= 3.2**
3. Now determine the thickness of **D_1** as follows , no effect for drainage so m=1

asphalt concrete can be Surface+ binder+ base ,

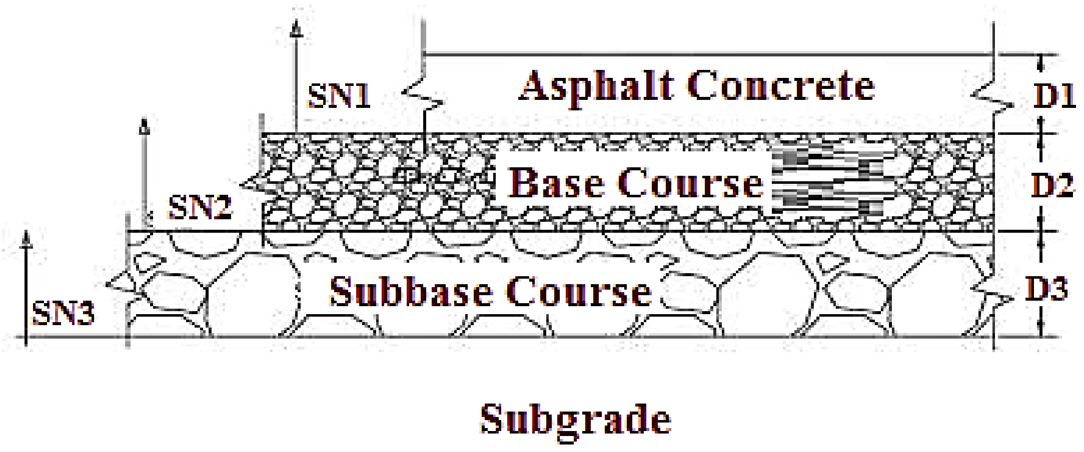
from Figure 4.10, **a_1= 0.42** for surface course and use **a_1 =0.38** for binder course, and for stabilized asphalt concrete

a_1 =0.30 : SN=3.2= 0.42 ×5/2.54+ **0.38** ×7/2.54 +**0.30** ×**t/2.54**

t= 11.2 cm use 12 cm (for t thickness more than 10 cm it is constructed in 2 layers).

Determine actual SN for this layer

0.42 ×5/2.54+ **0.38** ×7/2.54 +**0.30** ×**12/2.54 = 3.29**



4. Determine thickness of granular base course $\mathbf{D_2}$: SN2= 4.5 the above SN1= 3.29 so the remaining SN = 4.5-3.29=1.21 $\mathbf{m_2}$ for drainage effect is taken as **1.2** because % of saturation is **3% and for good drainage quality condition.**

For $\mathbf{a_2}$ value can be found from Figure 4.11 with E_{BS} = 30000 psi, $\mathbf{a_2}$ =0.14

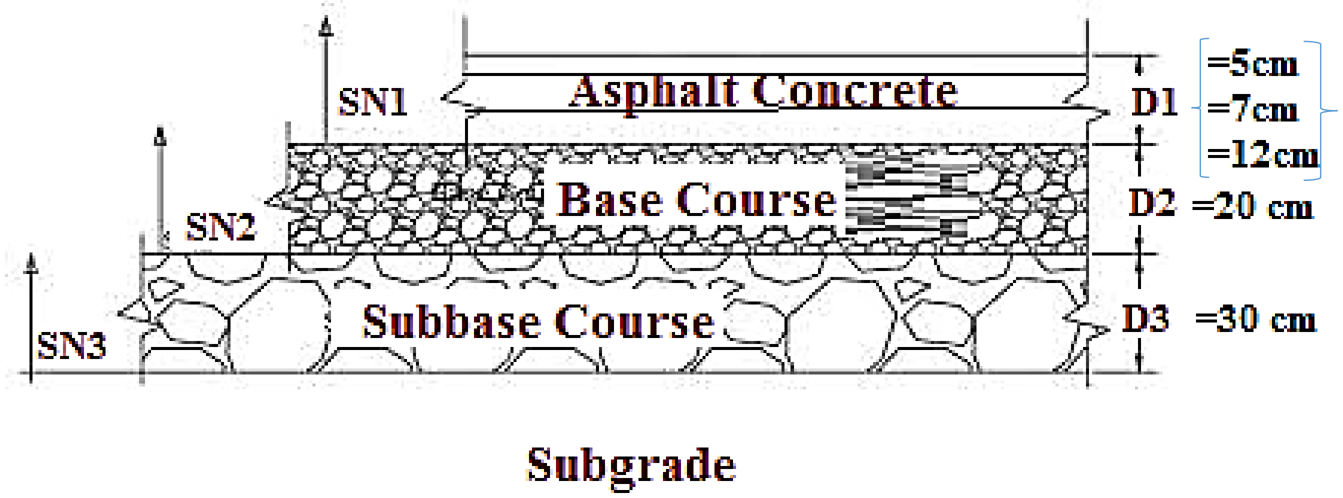
1.21= $\mathbf{m_2 \times D_2 \times a_2}$ = **1.2**$\mathbf{\times D_2 \times}$**0.14 gives** $\mathbf{D_2}$ =7.2 inches=**18.29 cm use 20 cm for granular base course ,**

determine actual SN2= 0.14×1.2×20/2.54= 1.32

5. Determine thickness of subbase course $\mathbf{D_3}$: SN= 5.6 -1.32-3.29= 0.99 = $\mathbf{a_3 \times m_3 \times D_3}$**. find the value of** $\mathbf{a_3}$ **from Figure 4.14 for** $\mathbf{E_{SB}}$ **=11000 psi ,** $\mathbf{a_3}$ **is =0.08 and** $\mathbf{m_3}$=1.2 so D_3=0.99/ (0.08×**1.2) =10.31 inches =26.19 cm use 30 cm**

Actual SN= 1.13 =0.08 ×1.2× 30/2.54

The total SN3=1.13+3.29+1.32= 5.74



Final design thicknesses of flexible pavement for first stage

Thank you for your attention