Lecture 1 - 04/05/2020

Pavement Structural Design

Introduction

Pavement Design (Highway and Airport):- Involves a study of soils and paving materials, their behaviour under load and the design of pavement to carry that load under all climatic conditions.

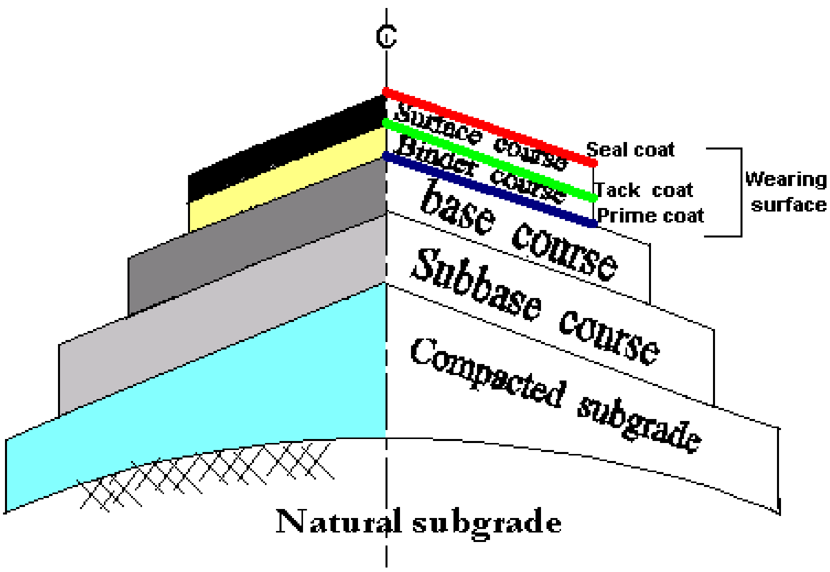
Pavement Structure = Subgrade + Subbase + Base + Surfacing

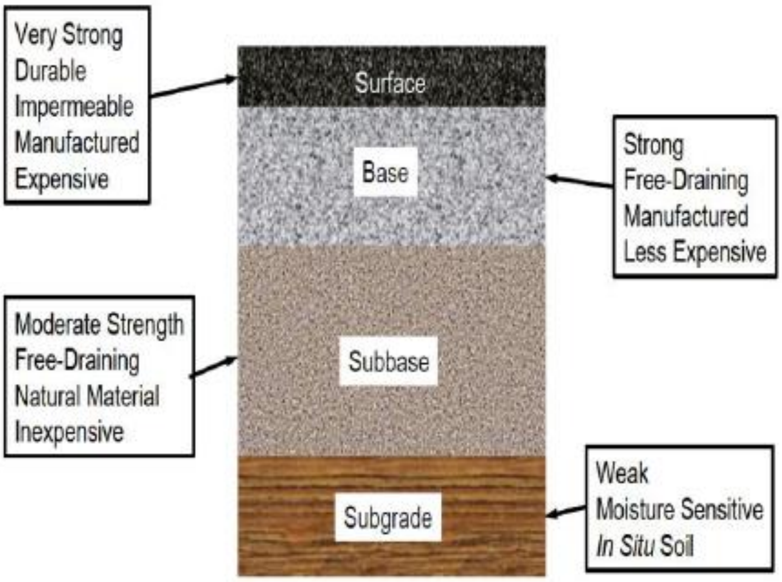
The purpose of the pavement system is to provide a smooth surface over which vehicles may safely pass under all climatic conditions for the specific performance period of the pavement.

Pavement Types:-

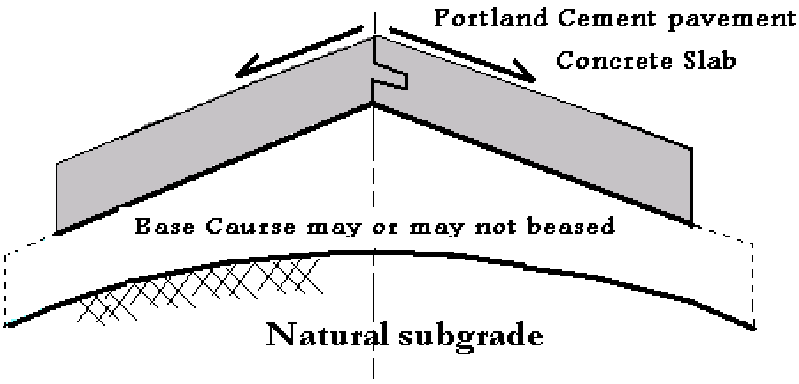
1) Flexible Pavement (Asphalt Pavement) التبليط المرن او التبليط الاسفلتي

The flexible pavement is a multi-layered system has different materials in different layers (better materials on the top and cannot be represented by a homogeneous mass). Multi-layer system consist of:-



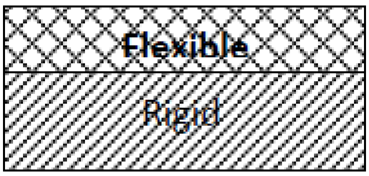


2) Rigid Pavement (Concrete Pavement- Slab)



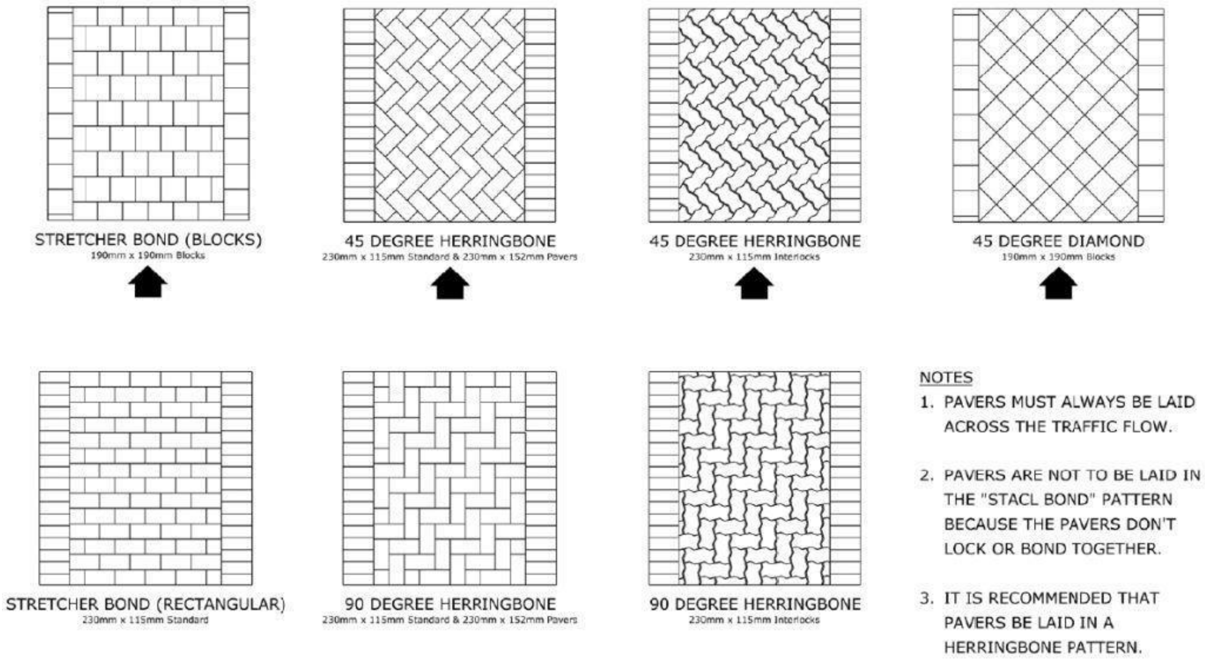
3) Composite Pavement

a- Flexible over rigid.

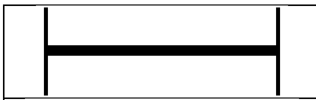
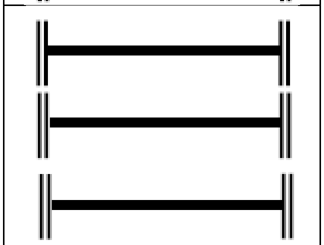


b- Rigid over flexible.

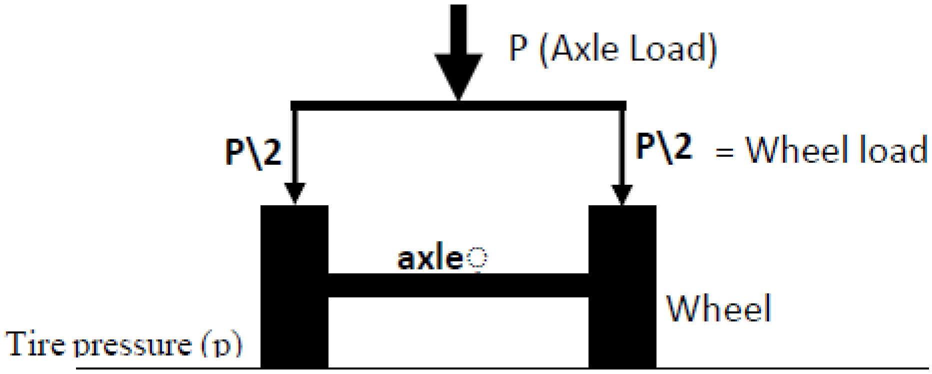
4) Block Pavement



Wheel loads and Axle Loads:

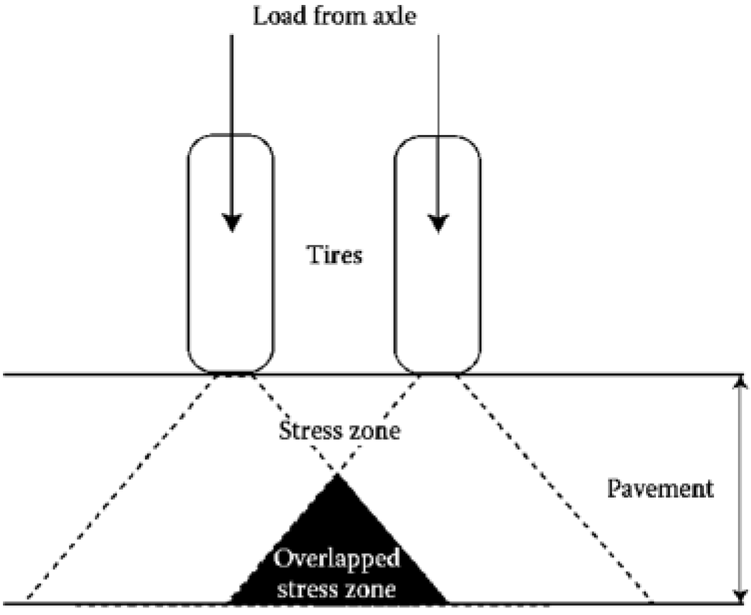
	**Front axle**	Single axle with single tire at each end
	**Rear axle**	Single axle with dual tire at each end
		Tandem axle with dual tire at each end
		Triple axle with dual tire at each end

Wheel configuration and distribution of axle load

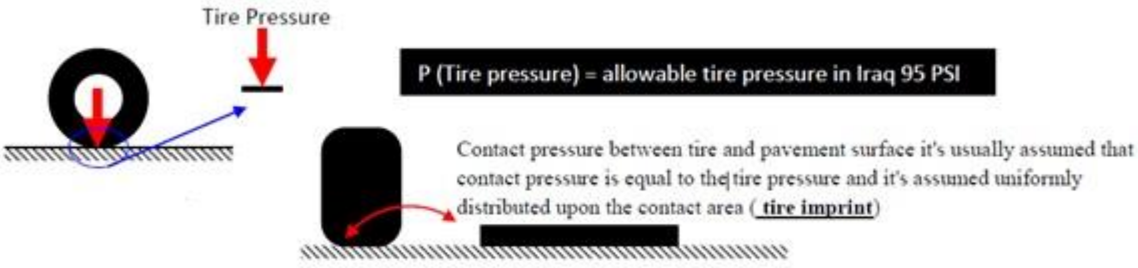


The load (from a vehicle) is transferred to the pavement through loadbearing axles and pressurized tires. The resulting pressure or stress on the pavement, at any depth, is dependent on many factors, such as total load, the number of axles and tires, and the condition of the tires.

The stress on the surface of the pavement gets distributed in an inverted V form the surface downward. In other words, the stress intensity decreases along the depth of the pavement.



Tire Pressure, contact Pressure and the Imprint:-

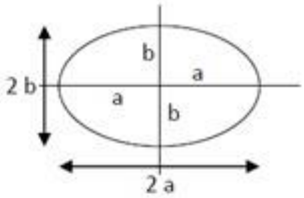


Contact Pressure (P) = Load on wheel \ Contact area

Calculate Contact Area

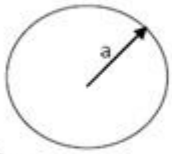
1) **Elliptical Tire Contact Area**

a- Major axis
b- Minor axis



Contact area = area of ellipse
A= π*a*b

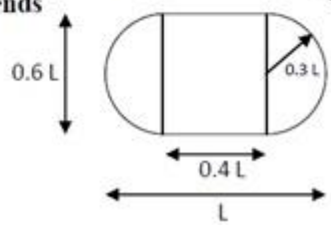
2) **Circular Shape:** most conmen assumptions for contact area (b=a)
Contact Area = πa^2



3) **Rectangular Contact area with semi-circular ends**

$A = 0.4\,L * 0.6\,L + \pi\,(0.3\,L)^2$
$A = 0.52274\,L^2$

PSI = Pound per Square inch



Example :- Wheel load 40 kips and tire pressure = 150 psi. Calculate contact area and "L"?.

Pavement Distresses (Failure)

1) Structural Distress (Structural Failure):-

A collapse of pavement structure or a breakdown of one or more pavement components of such magnitude to make pavement incapable sustaining the loads imposed upon it's surface which needs then complete rebuilding.

2*) Functional Distress (Functional Failure):-*

Is a distress such that the pavement will not carry out it intended function without causing discomfort to passenger or vehicle due to it's roughness.

Causes of Pavement Distresses

1) Over Load

a. Excessive loads (excessive axle load).

b. High number of reputations of axle loads.

c. High tire pressure.

2) Climatic and Environmental Conditions

a. Frost heaving (frost action)

b. Volume change of soil due wetting and drying breakup resulting from freezing and thawing or improper drainage.

3) Disintegration the paving materials

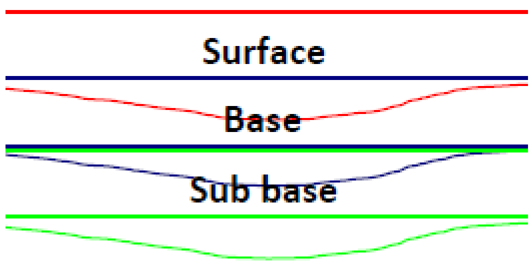
The rate at which a patch deteriorates is influenced by compaction, materials selection, and the quality of the surrounding or underlying pavement. Disintegration is the breakup of a pavement into small pieces that are lost with time and traffic. Ravelling and potholes are the most common types of disintegration.

4) Use dirty aggregate or insufficient during constriction.

5) Lack of maintenance

6) Inadequate structured design

Comparison between Flexible & Rigid Pavements

Flexible Pavement	**Rigid Pavement**
Flexible pavement consists of a series of layers with the highest quality at or near the surface. 	Rigid pavement consists of a Portland cement concrete slabs resting either directly on subgrade or on base course. 
The pavement possesses an asphalt surface.	The pavement possesses a Portland cement concrete slab surface.
Load distribution is primarily based on layered system.	Load carries by slab itself and slight load goes to the underlying layers.
Structural capacity of depends on the characteristics of every single layer	Structural capacity is only dependent on the characteristics of concrete slab.
The thickness design of flexible pavement is influenced by the strength of subgrade.	The rigid pavement distributes the load over a relatively wide area of soils and minor variations in subgrade. (soil strength have little significance upon the structured capacity of the pavement.
The fundamental purpose of base course and subbase course is to provide stresses distributing layers.	Bases under rigid pavement are used mainly for controlled pumping.
Failure mode [rutting, cracking and ravelling] without joints.	Failure mode [cracking and pumping] with joints.
Pavement has very low modulus of elasticity (less strength).	Modulus of elasticity of rigid pavement is very high, because of high strength concrete and more load bearing capacity of the pavement itself.

Lecture 2 - 11/05/2020

Layers Function

Subgrade (Prepared Road Bed)

The subgrade is usually the natural material located along the horizontal alignment of the pavement and serves as the foundation of the pavement structure. It also may consist of a layer of selected borrow materials, well compacted to prescribed specifications. It may be necessary to treat the subgrade material to achieve certain strength properties required for the type of pavement being constructed.

Required number of passes for rolling compactors in soil compaction

- Compactor speed is generally in range of 6 – 12 km/hr.
- Heavy compactor requires less number of passes
- Light compactor is about 20 Ton, (For about 15 cm thickness)
- High capacity compactor is about 40-50 Ton, (For about 30 cm thickness)

$$\textbf{Compactor speed (m/s)} = 1.065 + 0.033\,(\%W.C.) + 0.084\,(N.P.)$$

Where:

W.C. : Water content & N.P. : Number of passes

Ex: Compactor speed is 7.2 km/hr, W.C. is 12%, what is the required number of passes?

Answer:

7.2 km/hr = 2 m/s

2 = 1.065 + 0.033 (12) + 0.084 (N.P.)

N.P. = 6.4 that should be = 7 passes

Subbase Course

Located immediately above the subgrade, the subbase component consists of material of a superior quality which is generally used for subgrade construction. The requirements for subbase materials usually are given in terms of the gradation and strength. In some cases, the subbase may be treated with Portland cement, asphalt, lime, flyash, or combinations of these admixtures to increase its strength and stiffness. A subbase layer is not always included, especially with rigid pavements. A subbase layer is typically included when the subgrade soils are of very poor quality and/or suitable material for the base layer is not available locally, and is, therefore, expensive. This process of treating soils to improve their engineering properties is known as stabilization.

Base Course

The base is a layer or layers of specified or select material of designed thickness placed on a subbase or subgrade (if a subbase is not used) to provide a uniform and stable support for binder and surface courses. The base layer typically provides a significant portion of the structural capacity in a flexible pavement system and improves the foundation stiffness for rigid pavements. This course usually consists of granular materials such as crushed stone, crushed or uncrushed gravel, and sand. The specifications for base course materials usually include more strict requirements than those for subbase materials, particularly with respect to their gradation, and strength. Materials that do not have the required properties can be used as base materials if they are properly stabilized with Portland cement, asphalt, or lime.

Surface course

The surface course is one or more layers of a pavement structure designed to accommodate the traffic load, the top layer of which resists skidding, traffic abrasion, and the disintegrating effects of climate. The surface layer may consist of asphalt (also called bituminous) concrete, resulting in “flexible” pavement, or Portland cement concrete (PCC), resulting in “rigid” pavement. It was shown that the quality of the surface course of a flexible pavement depends on the mix design of the asphalt concrete used.

Properties of Highway Materials:

Soil Characteristics

The distribution of particle size in soils can be determined by conducting a sieve analysis (sometimes known as mechanical analysis) on a soil sample if the particles are sufficiently large. This is done by shaking a sample of air-dried soil through a set of sieves with progressively smaller openings. The smallest practical opening of these sieves is 0.075 mm; this sieve is designated No. 200. Other sieves include:

No. 140 (0.106 mm), No. 100 (0.15 mm), No. 60 (0.25 mm), No. 40 (0.425 mm),

No. 20 (0.85 mm), No. 10 (2.0 mm), No. 4 (4.75 mm).

- Gravel: > 2 mm
- Sand size: 2.0-0.06 mm
- Silt: 0.06-0.002
- Clay: less than 0.002

For soils containing particle sizes smaller than the lower limit, the hydrometer analysis is used.

Atterberg Limits

Clay soils with very low moisture content will be in the form of solids. As the water content increases, however, the solid soil gradually becomes plastic—that is, the soil easily can be molded into different shapes without breaking up. Continuous increase of the water content will eventually bring the soil to a state where it can flow as a viscous liquid. The stiffness or consistency of the soil at any time therefore depends on the state at which the soil is, which in turn depends on the amount of water present in the soil.

The water content levels at which the soil changes from one state to the other is the Atterberg limits. They are the shrinkage limit (SL), plastic limit (PL), and liquid limit (LL), as illustrated in Figure below. Atterberg limits are important limits of engineering behaviour, because they facilitate the comparison of the water content of the soil with those at which the soil changes from one state to another. They are used in the classification of fine-grained soils and are extremely useful, since they correlate with the engineering behaviours of such soils.

Shrinkage Limit (SL)

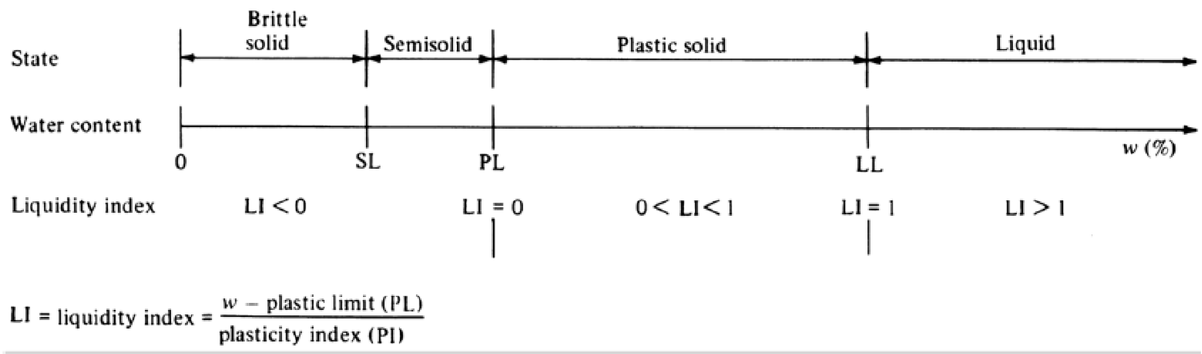
When a saturated soil is slowly dried, the volume shrinks, but the soil continues to contain moisture. Continuous drying of the soil, however, will lead to moisture content at which further drying will not result in additional shrinkage. The volume of the soil will stay constant, and further drying will be accompanied by air entering the voids. The moisture content at which this occurs is the shrinkage limit, or SL, of the soil.

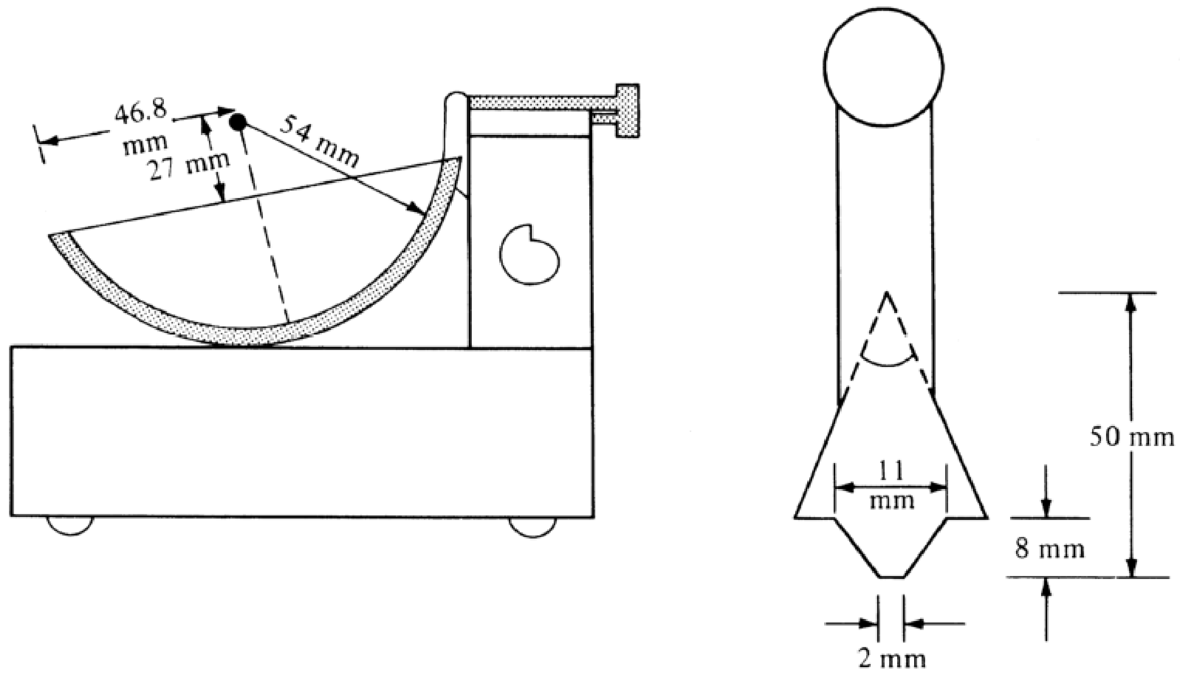
Plastic Limit (PL)

The plastic limit, or PL, is defined as the moisture content at which the soil crumbles when it is rolled down to a diameter of one-eighth of an inch. The moisture content is higher than the PL if the soil can be rolled down to diameters less than one-eighth of an inch, and the moisture content is lower than the PL if the soil crumbles before it can be rolled to one-eighth of an inch diameter.

Liquid Limit (LL)

The liquid limit, or LL, is defined as the moisture content at which the soil will flow and close a groove of one-half inch within it after the standard LL equipment has been dropped 25 times. The equipment used for LL determination is shown in Figure below.





This device was developed by Casagrande, who worked to standardize the Atterberg limits tests. It is difficult in practice to obtain the exact moisture content at which the groove will close at exactly 25 blows. The test is therefore conducted for different moisture contents and the number of blows required to close the groove for each moisture content recorded. A graph of moisture content versus the logarithm of the number of blows (usually a straight line known as the flow curve) is then drawn. The moisture content at which the flow curve crosses 25 blows is the LL.

The range of moisture content over which the soil is in the plastic state is the difference between the LL and the PL and is known as the plasticity index (PI).

$$PI = LL - PL$$

where

PI = plasticity index
LL = liquid limit
PL = plastic limit

Classification of Soils for Highway Use

The most commonly used classification system for highway purposes is

- The American Association of State Highway and Transportation Officials (AASHTO) Classification System.
- The Unified Soil Classification System (USCS)

AASHTO Soil Classification System

The system has been described by AASHTO as a means for determining the relative quality of soils for use in embankments, subgrades, subbases, and bases. Soils are classified into seven groups, A-1 through A-7, with several subgroups, as shown in Table 17.1. The classification of a given soil is based on its particle size distribution, LL, and PI. Soils are evaluated within each group by using an empirical formula to determine the group index (GI) of the soils, given as

$$GI = (F - 35)[0.2 + 0.005(LL - 40)] + 0.01(F - 15)(PI - 10) \qquad (17.18)$$

where

GI = group index
F = percent of soil particles passing 0.075 mm (No. 200) sieve in whole number based on material passing 75 mm (3 in.) sieve
LL = liquid limit expressed in whole number
PI = plasticity index expressed in whole number

The GI is determined to the nearest whole number. A value of zero should be recorded when a negative value is obtained for the GI. Also, in determining the GI for A-2-6 and A-2-7 subgroups, the LL part of Eq. 17.18 is not used–that is, only the second term of the equation is used.

Under the AASHTO system, granular soils fall into classes A-1 to A-3. A-1 soils consist of well-graded granular materials, A-2 soils contain significant amounts of silts and clays, and A-3 soils are clean but poorly graded sands.

Classifying soils under the AASHTO system will consist of first determining the particle size distribution and Atterberg limits of the soil and then reading Table 17.1 from left to right to find the correct group. The correct group is the first one from the left that fits the particle size distribution and Atterberg limits and should be expressed in terms of group designation and the GI. Examples are A-2-6(4) and A-6(10).

In general, the suitability of a soil deposit for use in highway construction can be summarized as follows.

1. Soils classified as A-1-a, A-1-b, A-2-4, A-2-5, and A-3 can be used satisfactorily as subgrade or subbase material if properly drained. In addition, such soils must be properly compacted and covered with an adequate thickness of pavement (base and/or surface cover) for the surface load to be carried.

2. Materials classified as A-2-6, A-2-7, A-4, A-5, A-6, A-7-5, and A-7-6 will require a layer of subbase material if used as subgrade.
3. When soils are properly drained and compacted, their value as subgrade material decreases as the GI increases. For example, a soil with a GI of zero (an indication of a good subgrade material) will be better as a subgrade material than one with a GI of 20 (an indication of a poor subgrade material).

Group Index (GI)	Subgrade Rating
0	Excellent
0–1	Good
2–4	Fair
5–9	Poor
10–20	Very poor

AASHTO Soil Classification System (from AASHTO M 145 or ASTM D3282)

General Classification	Granular Materials (35% or less passing the 0.075 mm sieve)							Silt-Clay Materials (>35% passing the 0.075 mm sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis, % passing											
2.00 mm (No. 10)	50 max	...	...	...	...	...	...	...	...	...	...
0.425 (No. 40)	30 max	50 max	51 min	...	...	...	...	...	...	...	...
0.075 (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425 mm (No. 40)											
Liquid Limit	...		...	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min[1]
Usual types of significant constituent materials	stone fragments, gravel and sand		fine sand	silty or clayey gravel and sand				silty soils		clayey soils	
General rating as a subgrade	excellent to good							fair to poor			

Note (1): Plasticity index of A-7-5 subgroup is equal to or less than the LL - 30. Plasticity index of A-7-6 subgroup is greater than LL - 30

Example 17.3 Classifying a Soil Sample Using the AASHTO Method

The following data were obtained for a soil sample.

Mechanical Analysis

Sieve No.	*Percent Finer*	*Plasticity Tests:*
4	97	LL = 48%
10	93	PL = 26%
40	88	
100	78	
200	70	

Using the AASHTO method for classifying soils, determine the classification of the soil and state whether this material is suitable in its natural state for use as a subbase material.

Lecture 3 - 18/05/2020

Special Tests for Pavement Design

1- California Bearing Ratio (CBR) Test

This test is commonly known as the CBR test and involves the determination of the load-deformation curve of the soil in the laboratory using the standard CBR testing. The test is conducted on samples of soil compacted to required standards and immersed in water for four days, during which time the samples are loaded with a surcharge that simulate the estimated weight of pavement material the soil will support. The objective of the test is to determine the relative strength of a soil with respect to crushed rock, which is considered an excellent coarse base material. This is obtained by conducting a penetration test on the samples still carrying the simulated load and using a standard CBR equipment. The CBR is defined as the penetration resistance of a subgrade soil relative to a standard crushed rock.

$$\text{CBR} = \frac{(\text{unit load for 0.1 piston penetration in test specimen})\ (\text{lb/in}^2.)}{(\text{unit load for 0.1 piston penetration in standard crushed rock})\ (\text{lb/in}^2.)} \qquad (17.24)$$

The unit load for 0.1 piston in standard crushed rock is usually taken as 1000 lb/in^2, which gives the CBR as

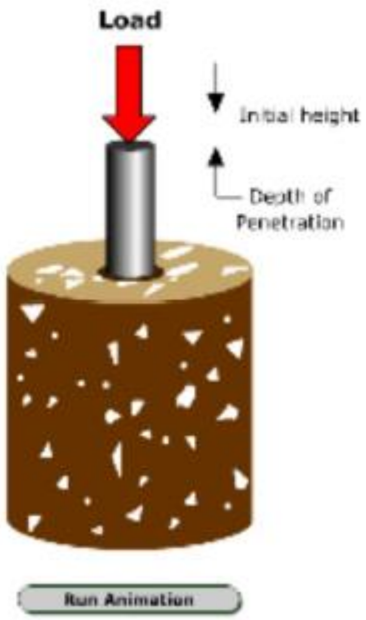
$$\text{CBR} = \frac{(\text{unit load for 0.1 piston penetration in test sample})}{1000} \times 100 \quad (17.25)$$

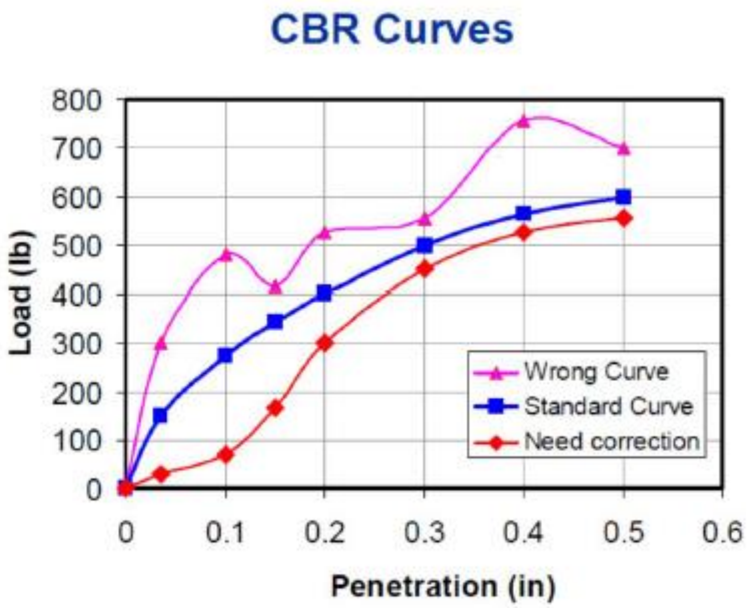
Load a piston (area = 3 in^2) at a constant rate (0.05 in/min)

• Record Load every 0.1 in penetration

• Total penetration not to exceed 0.5 in.

• Draw Load-Penetration Curve.





CBR Calculation

$$CBR = 100\left(\frac{\text{Load or Stress of Soil}}{\text{Load or Stress of Standard Rocks}}\right)$$

Loads and Stresses Corresponding to 0.1 and 0.2 inches Penetration for the Standard Rocks

Penetration	0.1" (2.5 mm)	0.2" (5.0 mm)
Load of Standard Rocks (lb)	3000	4500
Load of Standard Rocks (kN)	13.24	19.96
Stress of Standard Rocks (KPa)	6895	10342
Stress of Standard Rocks (psi)	1000	1500

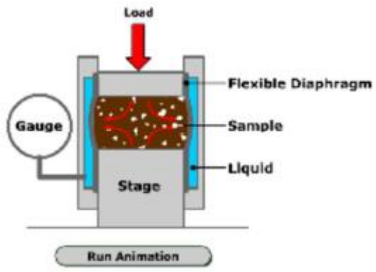
Calculate CBR at 0.1 in (2.5 mm) and 0.2 in (5.0 mm) deformation then use the Maximum value as the design CBR.

2- Resistance Value (R-Value) ASTM D2844

The Resistance Value (R-value) is a test value, which measures the ability of a soil to resist lateral flow due to vertically applied load. This test is developed by California Division of Highways in 1940.

At the completion of the expansion test, the specimen is put into a flexible sleeve and placed in the stabilometer as shown in the figure. Vertical pressure is applied gradually on the specimen at a speed of 0.05 in/min until a pressure of 160 lb/in^2 is attained. The corresponding horizontal pressure is immediately recorded.

$$R = 100 - \frac{100}{\frac{2.5}{D}\left(\frac{P_v}{P_h} - 1\right) + 1} \qquad (17.26)$$



where

R = resistance value
P_v = vertical pressure (160 lb/in.^{2})
P_h = horizontal pressure at P_v of 160 lb/in.^{2} (lb/in.^{2})
D = number of turns of displacement pump

3- Resilient Modulus (MR)

The Resilient Modulus (MR) is a measure of subgrade material stiffness. A material's resilient modulus is actually an estimate of its modulus of elasticity (E). While the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads – like those experienced by pavements. MR is ability of material to absorb energy within the elastic range. Resilient modulus is determined using the triaxial test. The test applies a repeated axial cyclic stress of fixed magnitude, load duration and cycle duration to a cylindrical test specimen. While the specimen is subjected to this dynamic cyclic stress, it is also subjected to a static confining stress provided by a triaxial pressure chamber. It is essentially a cyclic version of a triaxial compression test; the cyclic load application is thought to more accurately simulate actual traffic loading.

Resilient modulus test can be conducted on all types of pavement materials ranging from cohesive to stabilized materials. The test is conducted in a triaxial device equipped for repetitive load conditions.

- Measures "stiffness" of the material under repeated load.
- Determines the load carrying capacity of the material.
- Used for HMA as well as unbound materials.

- Uses a repeated load triaxial test.
- Used in most modern methods of pavement design.

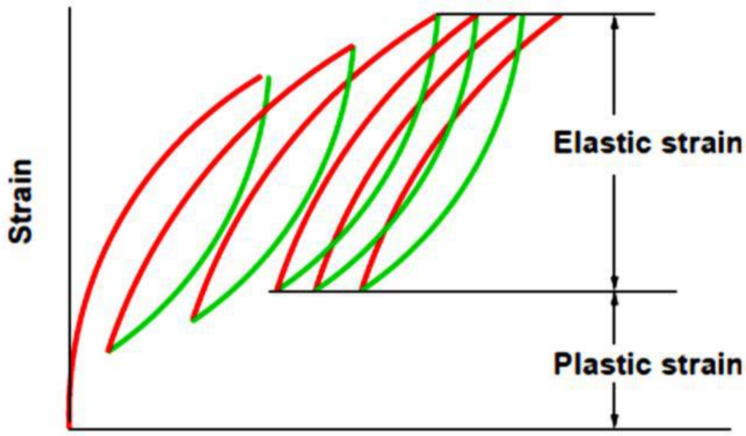
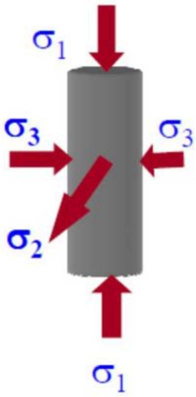


Figure 27:2: Recoverable strain under repeated loads



$$M_R = \frac{\text{Deviator stress}}{\text{Recoverable strain}} = \frac{\sigma_1 - \sigma_3}{\varepsilon_r}$$

$M_R = 1500(CBR)$ Fine-grained materials with soaked CBR ≤ 8

$$M_R = 1000 + 555(\text{R Value})$$

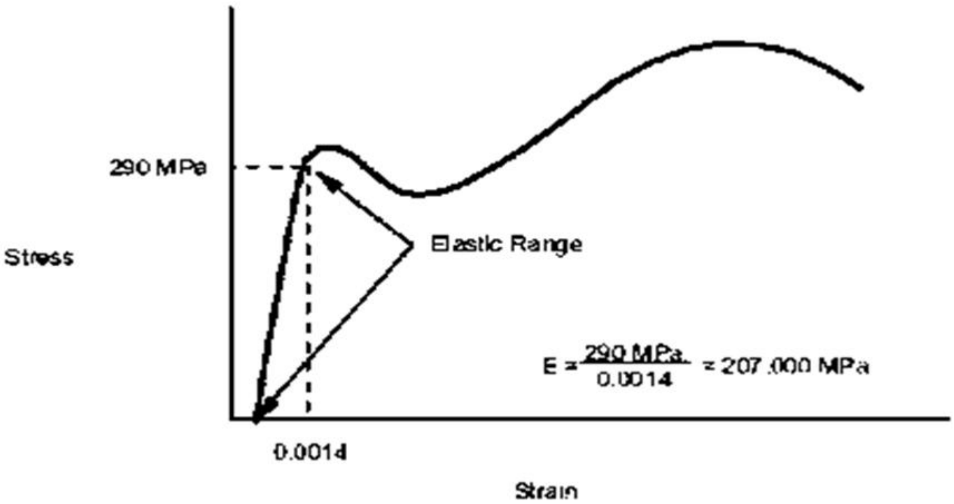
Origin: 1993 AASHTO Guide
Limitation: Fine-grained non-expansive soils with R $\leq$ 20

$$\text{R} - \text{Value} = \frac{1500(CBR) - 1155}{555}$$

Origin: HDOT
Limitation: Fine-grained non-expansive soils with soaked CBR $\leq$ 8

Elastic modulus is sometimes called Young's modulus, an elastic modulus (E) can be determined for any solid material and represents a constant ratio of stress and strain (a stiffness): E = stress/ strain

A material is elastic if it is able to return to its original shape or size immediately after being stretched or squeezed. The modulus of elasticity for a material is basically the slope of its stress-strain plot within the elastic range as shown in Figure:



4- Plate Loading Test

- Measure supporting power of subgrades, subases, bases and a complete pavement.
- Field test.
- Data from the test are applicable for design of both flexible and rigid pavements.
- Results might need some corrections.
- The test site is prepared and loose material is removed so that the 75 cm diameter plate rests horizontally in full contact with the soil sub-grade. The plate is seated accurately and then a seating load equivalent to a pressure of 0.07 kg/cm^2 (320 kg for 75 cm diameter plate) is applied and released after a few seconds. The settlement dial gauge is now set corresponding to zero load.
- A load is applied by means of jack, sufficient to cause an average settlement of about 0.25 cm. When there is no noticeable increase in settlement or when the rate of settlement is less than 0.025 mm per minute (in the case of soils with high moisture content or in clayey soils) the load dial reading and the settlement dial readings are noted.
- Deflection of the plate is measured by means of deflection dials; placed usually at one-third points of the plate near its outer edge.
- To minimize bending, a series of loaded plates should be used.
- Average of three or four settlement dial readings is taken as the settlement of the plate corresponding to the applied load. Load is then increased till the average settlement increase to a further amount of about 0.25 mm, and the load and average settlement readings are noted as before.

Plate Loading Test

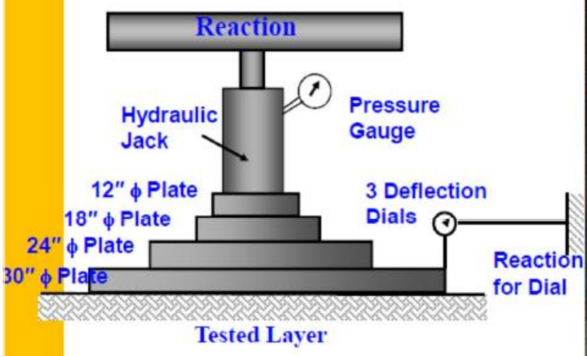
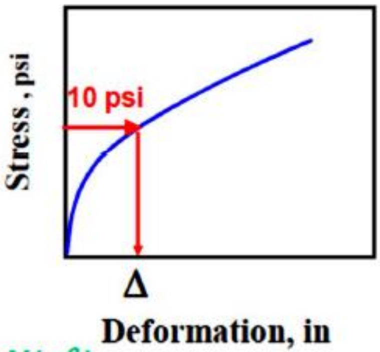


Plate Loading Test Schematic

Plate Loading Test

Required for rigid pavement design.

$$K = \frac{P}{\Delta}$$



K = modulus of subgrade reaction
P = unit load on the plate (stress) (psi)
Δ = deflection of the plate (in)

- *For design use stress P = 10 psi (68.95 kN/m²)*

The 1993 AASHTO Guide offers the following relationship between k-values from a plate bearing test and resilient modulus (MR):

$$K = MR/19.4$$

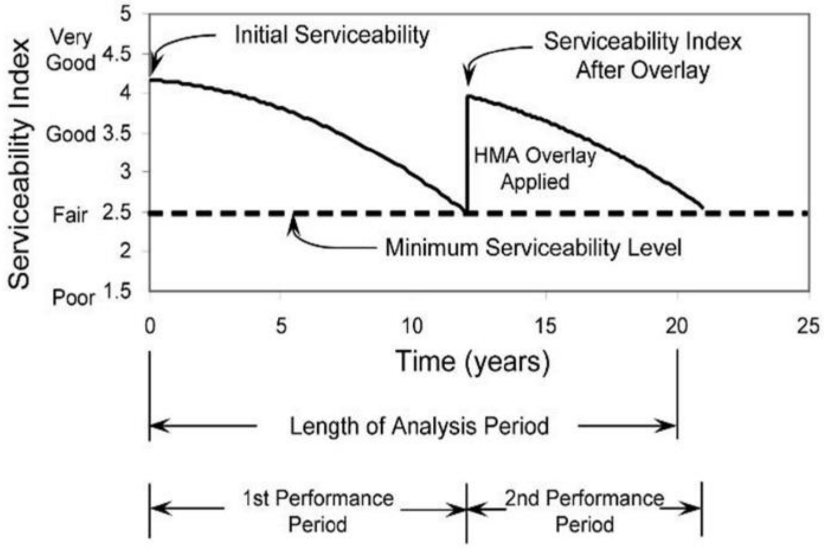
Serviceability

It is the ability of pavement at time to serve high speed and high traffic volume. To quantify pavement performance, a concept known as the serviceability performance was developed. 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 extent of cracking, patching, and rut depth for flexible pavements. The scale PSI ranges from 0 to 5, where 0 is the lowest PSI and 5 is the highest.

Two serviceability indices are used in the design procedure:

The **Initial Serviceability Index (p_i)**, which is the serviceability index immediately after the construction of the pavement; and the **Terminal Serviceability Index (p_t)**, which is the minimum acceptable value before resurfacing or reconstruction is necessary. Recommended values for the terminal serviceability index are 2.5 or 3.0 for major highways and 2.0 for highways with a lower classification.

1) Express ways, Major highways $P_t = 3.0$
2) Primary Roads $P_t = 2.5$
3) Secondary Roads $P_t = 2.0$



For Flexible Pavement

$$PSI = 5.03 - 1.91 \log_{10}(1 + SV) - 1.38 \times RD^2 - 0.01\,(C+P)^{0.5} + error$$

Where:-

SV: Slope variance

RD: Rut depth (inch)

C & P: Cracking & Patching area ft^2 / 1000 ft^2 of pavement area

For Rigid Pavement

$$PSI = 5.41 - 1.80 \log_{10}(1+SV) - 0.09\,(C+P)^{0.5} + error$$

Ex: Calculate the PSI of a flexible pavement on a section of a highway with the following field data:

Mean slope variance = 4.2 in.

Mean rut depth = 0.35 in.

Cracking of 80 ft per 1000 ft^2

Answer:

$PSI = 5.03 - 1.91 \log_{10}(1+SV) - 1.38 \times RD^2 - 0.01 (C+P)^{0.5}$

$PSI = 5.03 - 1.368 - 0.169 - 0.089$

PSI = **3.404**

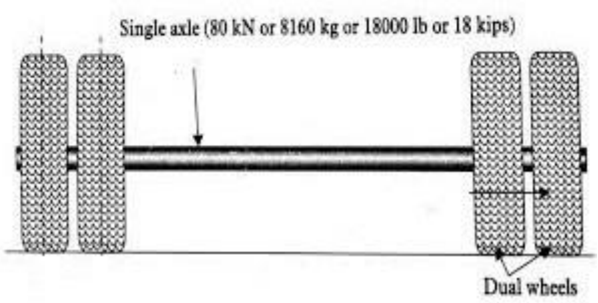
Lecture 4 - 01/06/2020

Traffic Loads

Pavement structural design requires a quantification of all expected loads that pavements will encounter over its design life. This quantification is usually done using **Equivalent Single Axle Loads (ESALs)**. This converts wheel loads of various magnitudes and repetitions (mixed traffic) to an equivalent number of "standard" or "equivalent" loads.

ESAL

The traffic load is determined in terms of the number of repetitions of an 18,000-lb (80 kilo newton (kN)) single-axle load applied to the pavement on two sets of dual tires. This is usually referred to as the equivalent single-axle load (ESAL). The dual tires are represented as two circular plates, each 4.51 in. radius, spaced 13.57 in. apart. This representation corresponds to a contact pressure of 70 lb/in^2.



To determine the ESAL, the number of different types of vehicles such as cars, buses, single-unit trucks, and multiple-unit trucks expected to use the facility during its lifetime must be known. The distribution of the different types of vehicles expected to use the proposed highway can be obtained from results of classification counts that are taken by state highway agencies at regular intervals. These can then be converted to equivalent 18,000-lb loads using the equivalency factors.

Flexible highway pavements are usually designed for a 20-year period. Since traffic volume does not remain constant over the design period of the pavement, it is essential that the rate of growth be determined and applied when calculating the total ESAL. Annual growth rates can be obtained based on traffic volume counts over several years. The overall growth rate in the United States is between 3 and 5 % per year, although growth rates of up to 10 % per year have been suggested for some interstate highways. The growth factors (G_{rn}) for different growth rates and design periods can be obtained from the Equation below:

$$\frac{(1+g)^n - 1}{g}$$

Where : $g = i / 100$, i = growth rate, n = design life, years

OR G_{rn} can be obtained using the table below:

Analysis Period Years (n)	Annual Growth Rate, Percent (g)							
	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

A general equation for the accumulated ESAL for each category of axle load is obtained as:

$$ESAL_i = f_d \times G_{rn} \times AADT_i \times 365 \times N_i \times F_{Ei}$$

Where:

$ESAL_i$ = equivalent accumulated 18000 Ib (80 KN) single axle load for the axle category i

f_d = lane distribution factor (Table 8-6)

G_{rn} = growth factor for a given growth rate and design period n

$AADT_i$ = first year annual average daily traffic for axle category i

N_i = number of axles on each vehicle in category i

F_{Ei} = load equivalency factor for axle category i

TABLE 8.6 Lane Distribution Factor (AASHTO, 1993)

No. of Lanes in Each Direction	% of 18-kip ESAL in the Design Lane
1	100
2	80–100
3	60–80
4	50–70

Example:

Calculate the Accumulated Equivalent Single-Axle Load for a Proposed Eight-Lane Highway Using Load Equivalency Factors. An eight-lane divided highway is to be constructed on a new alignment. Traffic volume forecasts indicate that the average annual daily traffic (AADT) in both directions during the first year of operation will be 12,000 with the following vehicle mix and axle loads.

Passenger cars (2000 lb/axle) 50%

2-axle single-unit trucks (6000 lb/axle) 33%

3-axle single-unit trucks (10,000 lb/axle) 17%

The vehicle mix is expected to remain the same throughout the design life of the pavement. If the expected annual traffic growth rate is 4% for all vehicles, determine the design ESAL, given a design period of 20 years. The pavement has a terminal serviceability index (p_t) of 2.5 and Structural Number (SN) of 5.

Answer:

$ESAL = f_d \times G_{rn} \times AADT \times 365 \times N_i \times FE_i$

ESAL for Passenger cars:

$f_d = 0.6$, Grn = 29.78, AADT=1200×0.5 =6000, $N_i = 2$, $FE_i = 0.0002$

ESAL for Passenger cars = 0.6 × 29.78 × 6000 × 365 × 2 × 0.0002 = 15653

ESAL for 2-axle single-unit trucks:

$f_d = 0.6$, Grn = 29.78, AADT = 1200×0.33 = 3960, $N_i = 2$, $FE_i = 0.01$

ESAL for 2-axle single-unit trucks = 0.6 × 29.78 × 3960 × 365 × 2 × 0.01 = 516529

ESAL for 3-axle single-unit trucks:

$f_d = 0.6$, Grn = 29.78, AADT = 1200×0.17 = 2040, $N_i = 3$, $FE_i = 0.088$

ESAL for 2-axle single-unit trucks = 0.6 × 29.78 × 2040 × 365 × 3 × 0.088 = 3512392

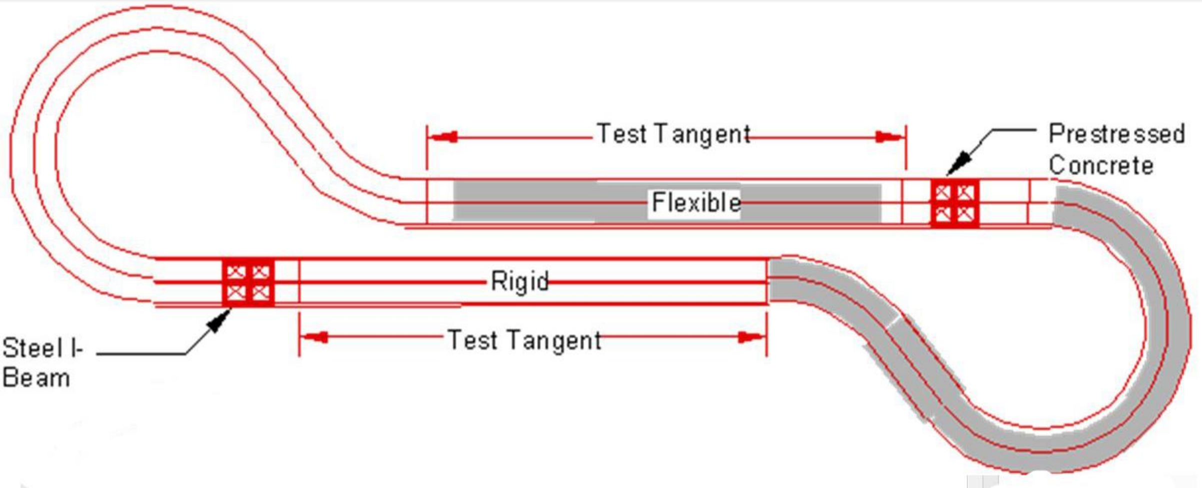
$\mathbf{ESAL_{Total}}$ = 15653 + 516529 + 3512392 = $4044574 = 4 \times 10^6$

Lecture 5 - 08/06/2020

Flexible Pavement Design:

1. AASHTO Design Method

The AASHTO method for design of highway pavements is based primarily on the results of the AASHTO road test that was conducted in Ottawa, USA. It was a cooperative effort carried out under the supports of 49 states, the District of Columbia, Puerto Rico, the Bureau of Public Roads, and several industry groups. Tests were conducted on short-span bridges and test sections of flexible and rigid pavements constructed on A-6 subgrade material. The pavement test sections consisted of two small loops and four larger ones with each being a four-lane divided highway. The tangent sections consisted of a successive set of pavement lengths of different designs, each length being at least 100 feet. The principal of flexible pavement sections were constructed of asphalt mixture surface, a well graded crushed limestone base, and a uniformly graded sand-gravel subbase. Three levels of surface thicknesses ranging from 1 to 6 inches were used in combination with three levels of base thicknesses ranging from 0 to 9 inches. Test traffic consisting of both single-axle and tandem-axle vehicles were then driven over the test sections until several thousand load repetitions had been made. Data were then collected on the pavement condition with respect to extent of cracking and amount of patching required to maintain the section in service. The longitudinal and transverse profiles also were obtained to determine the extent of rutting, surface deflection caused by loaded vehicles moving at very slow speeds. These data then were analyzed thoroughly, and the results formed the basis for the AASHTO method of pavement design.



Design Considerations

The factors considered in the AASHTO procedure for the design of flexible pavement as presented in the 1993 guide are:

1. Pavement performance
2. Roadbed soils (subgrade material)
3. Materials of construction
4. Environment
5. Drainage
6. Reliability

1. Pavement performance

To quantify pavement performance, a concept known as the serviceability performance was developed. 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 extent of cracking, patching, and rut depth for flexible pavements. The original expression developed gave the PSI as a function of the extent and type of cracking and patching and the slope variance in the two wheel paths which is a measure of the variations in the longitudinal profile. The scale PSI ranges from 0 to 5, where 0 is the lowest PSI and 5 is the highest.

2. Roadbed Soils (Subgrade Material):

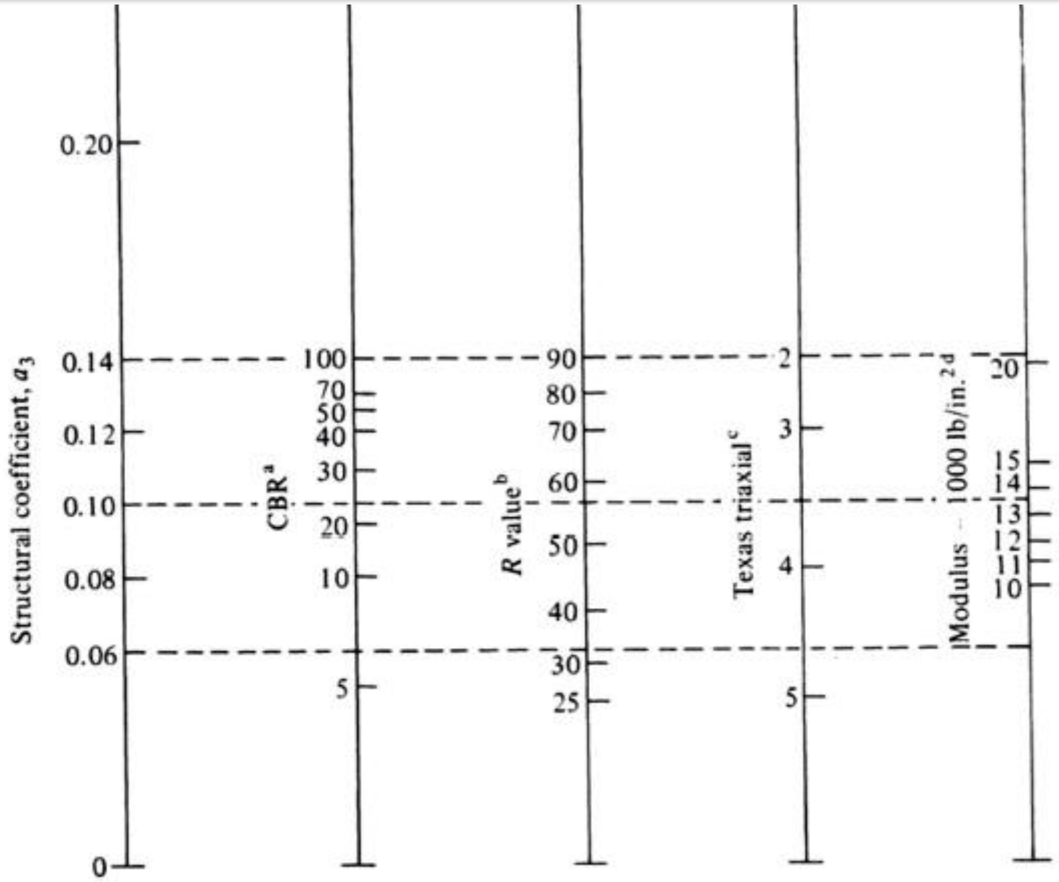
The 1993 AASHTO guide also uses the resilient modulus (Mr) of the soil to define its property. However, the method allows for the conversion of the CBR or R value of the soil to an equivalent Mr value using the following conversion factors:

Mr (lb/in^2) =1500 CBR (for CBR ≤ 10)

Mr (lb/in^2) = 1000+ 555 R value (for R ≤ 20)

3. Materials of construction

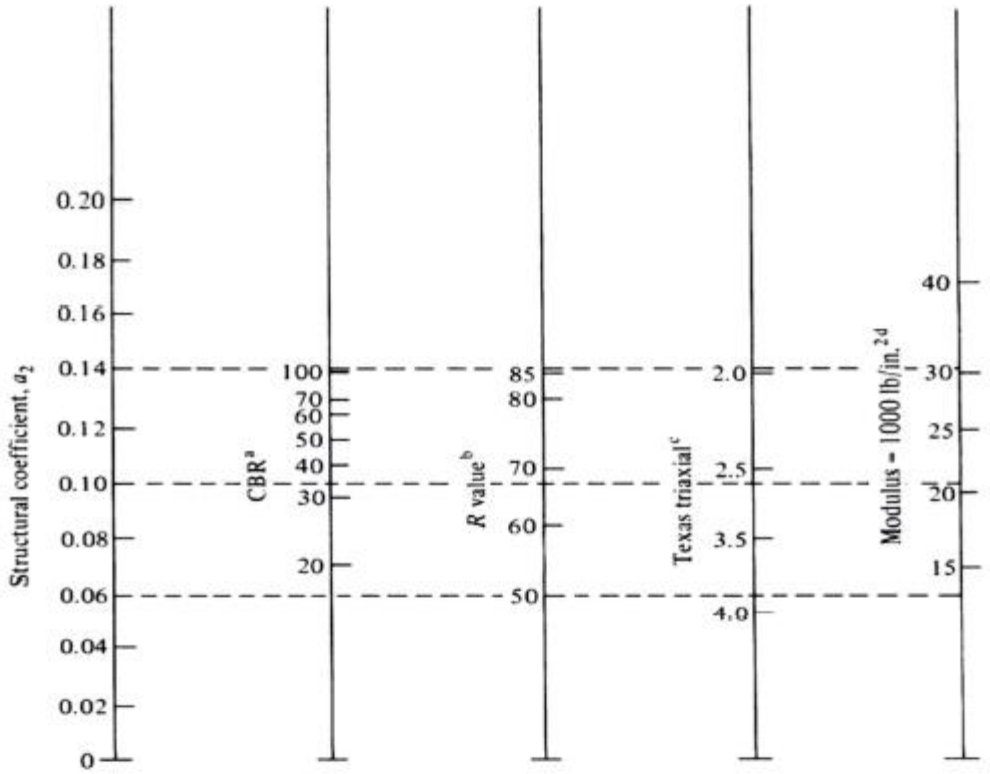
A. Subbase Construction Materials: The quality of the material used is determined in terms of the layer coefficient, a_3, which is used to convert the actual thickness of the subbase to an equivalent SN. The sandy gravel subbase course material used in the AASHTO road test was assigned a value of 0.11. Layer coefficients are usually assigned, based on the description of the material used. Charts correlating the layer coefficients with different soil engineering properties have been developed. Figure 19.3 shows one such chart for granular subbase materials.



[a] Scale derived from correlations from Illinois.
[b] Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico, and Wyoming.
[c] Scale derived from correlations obtained from Texas.
[d] Scale derived on NCHRP project 128, 1972.

Figure (19.3) Variation in Granular Subbase Layer Coefficient, a3, with Various Subbase Strength Parameters

B. 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. This can be done using Figure 19.4.



[a] Scale derived by averaging correlations obtained from Illinois.
[b] Scale derived by averaging correlations obtained from California, New Mexico, and Wyoming.
[c] Scale derived by averaging correlations obtained from Texas.
[d] Scale derived on NCHRP project 128, 1972.

Figure (19.4) Variation in Granular Base Layer Coefficient, a2, with Various Subbase Strength Parameters

C. Surface Course Construction Materials: The most commonly-used material is a hot plant mix of asphalt cement and dense-graded aggregates with a maximum size of 1 inch. The structural layer coefficient (a_1) for the surface course can be extracted from Figure 19.5, which relates the structural layer coefficient of a dense grade asphalt concrete surface course with its resilient modulus at 68°F (20°C).

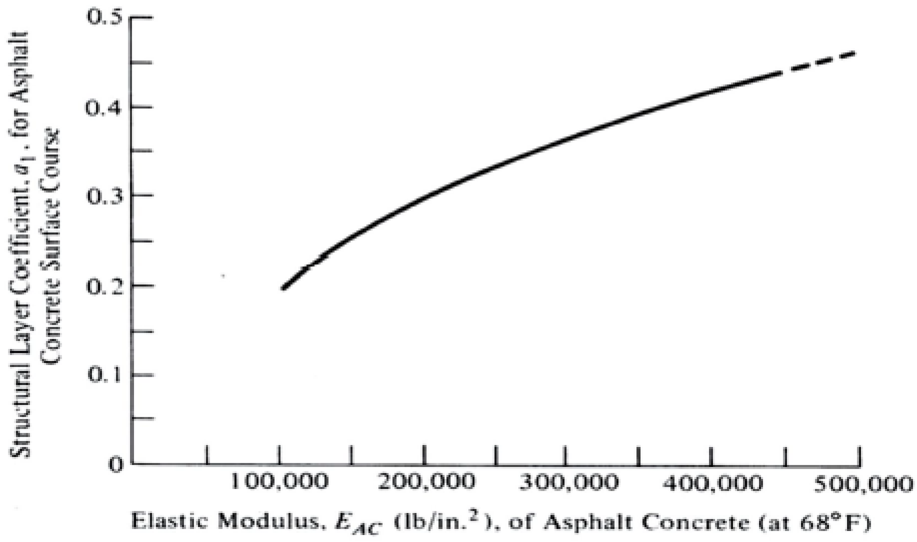


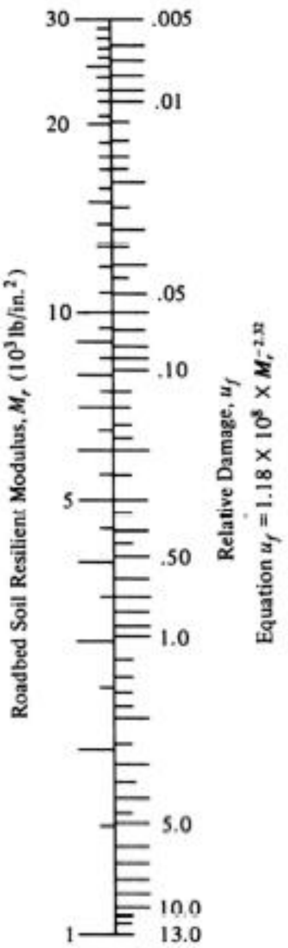
Figure (19.5) Chart for Estimating Structural Layer Coefficient of Dense-Graded/Asphalt Concrete Based on the Elastic (Resilient) Modulus

4. 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, changes in the creep properties, and the effect of freezing and thawing of the subgrade soil. The effect of rainfall is due mainly to the penetration of the surface water into the underlying material. However, this effect is taken into consideration in the design procedure, and the methodology used is presented later under "Drainage."

Test results have shown that the normal modulus (that is, modulus during summer and fall seasons) of materials susceptible to frost action can reduce by 50 percent to 80 percent during the thaw period. Also, resilient modulus of a subgrade material may vary during the year, even when there is no specific thaw period. This occurs in areas subject to very heavy rains during specific periods of the year. It is likely that the strength of the material will be affected during the periods of heavy rains.

Month	Roadbed Soil Modulus M_r (lb/in.²)	Relative Damage u_f
Jan.	22000	0.01
Feb.	22000	0.01
Mar.	5500	0.25
Apr.	5000	0.30
May	5000	0.30
June	8000	0.11
July	8000	0.11
Aug.	8000	0.11
Sept.	8500	0.09
Oct.	8500	0.09
Nov.	6000	0.20
Dec.	22000	0.01
Summation: Σu_f =		1.59



$$\text{Average } \bar{u}_f = \frac{\Sigma u_f}{n} = \frac{1.59}{12} = 0.133$$

Effective Roadbed Soil Resilient Modulus, M_r (lb/in.²) = 7250 (corresponds to $\bar{u}_f$)

Figure (19.6) Chart for Estimating Effective Roadbed Soil Resilient Modulus for Flexible Pavements Designed Using the Serviceability Criteria

5. Drainage

The effect of drainage on the performance of flexible pavements is considered by modifying the structural layer coefficient. The modification is carried out by incorporating 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.

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)

*Time required to drain the base layer to 50% saturation.
SOURCE: Adapted with permission from *AASHTO Guide for Design of Pavement Structures,* American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

Table 19.6 Recommended m_i Values

	Percent of Time Pavement Structure Is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	*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

SOURCE: Adapted with permission from *AASHTO Guide for Design of Pavement Structures,* American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

6. Reliability

It has been noted that the cumulative ESAL is an important input to any pavement design method. However, the determination of this input is usually based on assumed growth rates which may not be accurate. 1993 AASHTO guide proposes the use of a reliability factor that considers the possible uncertainties in traffic prediction and performance prediction. Reliability design levels (R%), which determine assurance levels that the pavement section designed using the procedure will survive for its design period, have been developed for different types of highways. For example, a 50 percent reliability design level implies a 50 percent chance for successful pavement performance— that is, the probability of design performance success is 50 percent.

Table 19.7 shows suggested reliability levels based on a survey of the AASHTO pavement design task force. Reliability factors, R% ≥ 1, based on the reliability level selected and the overall variation, So^2 also have been developed. So^2 accounts for the chance variation in the traffic forecast and the chance variation in actual pavement performance for a given design period traffic, W18.

Table 19.7 Suggested Levels of Reliability for Various Functional Classifications

	Recommended Level of Reliability	
Functional Classification	*Urban*	*Rural*
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

Note: Results based on a survey of the AASHTO Pavement Design Task Force.
SOURCE: Adapted with permission from *AASHTO Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

The reliability factor R% is given as $\log_{10} R\% = -Z_R * S_o$

Where Z_R= standard normal deviation for a given reliability (R%)

Z_R Represents the probability that serviceability will be maintained at adequate levels from a user's point of view throughout the design life of the facility.

So= estimated overall standard deviation

Table 19.8 values of Z_R for different reliability levels R. Overall standard deviation ranges have been identified for flexible and rigid pavements as

	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

Reliability (R%)	*Standard Normal Deviation, Z_R*
50	−0.000
60	−0.253
70	−0.524
75	−0.674
80	−0.841
85	−1.037
90	−1.282
91	−1.340
92	−1.405
93	−1.476
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

SOURCE: Adapted with permission from *AASHTO Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

Structural Design

The objective of the design using the AASHTO method is to determine a flexible pavement Structural Number (SN) adequate to carry the projected design ESAL. This design procedure is used for ESALs greater than 50,000 for the performance period. The design for ESALs less than this is usually considered under low volume roads. The 1993 AASHTO guide gives the expression for SN as

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

where

m_i = drainage coefficient for layer i

a_1, a_2, a_3 = layer coefficients representative of surface, base, and subbase course, respectively

D_1, D_2, D_3 = actual thickness in inches of surface, base, and subbase courses, respectively.

The basic design equation given in the 1993 guide is

$$\log_{10} W_{18} = Z_R S_o + 9.36 \log_{10}(\text{SN} + 1) - 0.20 + \frac{\log_{10}[\Delta \text{PSI}/(4.2 - 1.5)]}{0.40 + [1094/(\text{SN} + 1)^{5.19}]} + 2.32 \log_{10} M_r - 8.07 \quad (19.7)$$

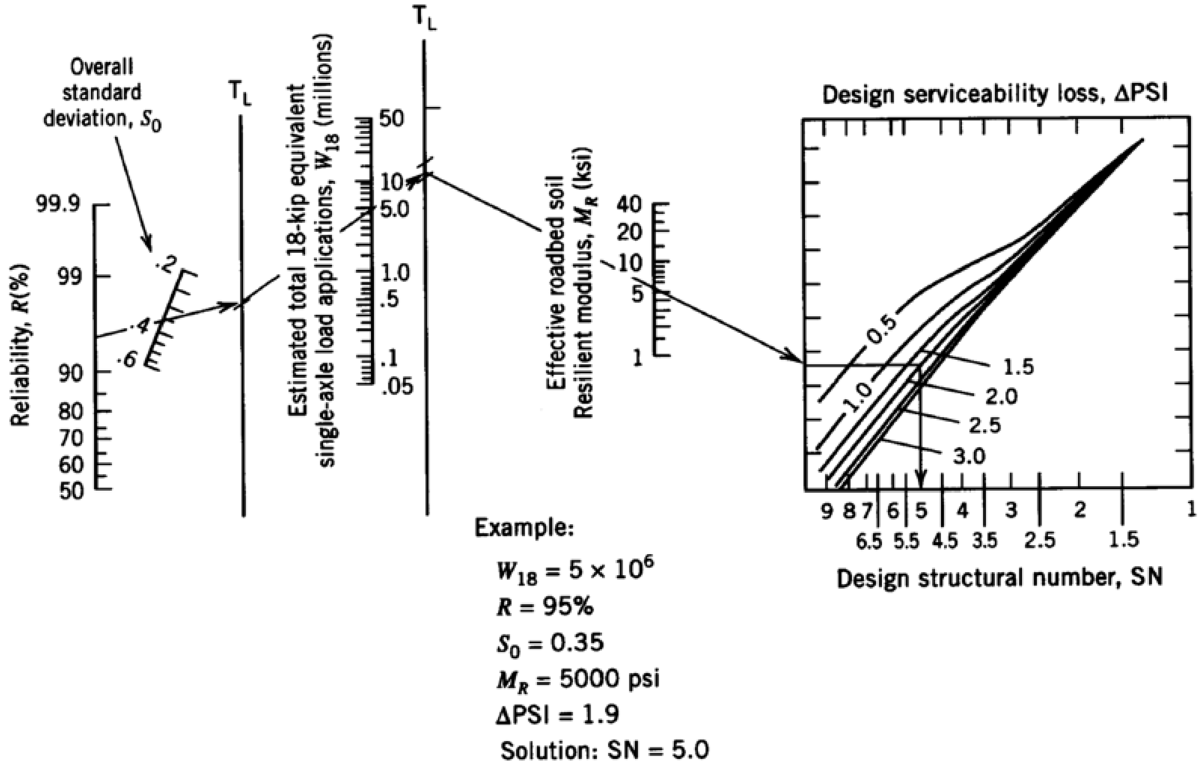


Table 19.9 AASHTO-Recommended Minimum Thicknesses of Highway Layers

	Minimum Thickness (in.)	
Traffic, ESALs	*Asphalt Concrete*	*Aggregate Base*
Less than 50,000	1.0 (or surface treatment)	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

Example

Designing a Flexible Pavement Using the AASHTO Method

A flexible pavement for an urban interstate highway is to be designed using the 1993 AASHTO guide procedure to carry a design ESAL of 2 $*10^6$. It is estimated that it takes about a week for 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:

Resilient modulus of asphalt concrete at 68° F = 450,000 lb/in^2

CBR value of base course material = 100, Mr = 31,000 lb/in^2

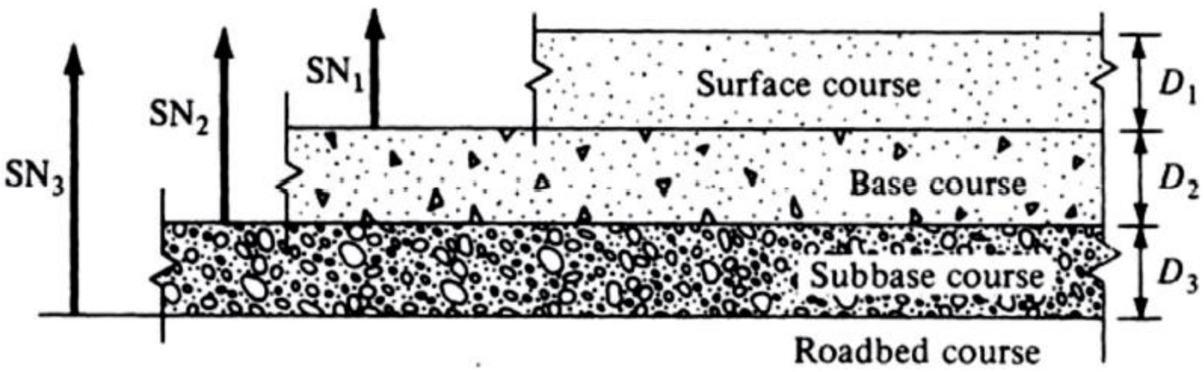
CBR value of subbase course material = 22, Mr = 13,500 lb/in^2

CBR value of subgrade material = 6

Initial serviceability index p_i = 4.2

Terminal serviceability index p_t = 2.2

Determine a suitable pavement structure?



Solution: Since the pavement is to be designed for an interstate highway, the following assumptions are made:

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

Reliability level (R) = **99%** (range is 85 to 99.9 from Table 19.7)

Standard deviation (S_o) = **0.49** (range is 0.4 to 0.5)

Initial serviceability index $p_i = 4.5$

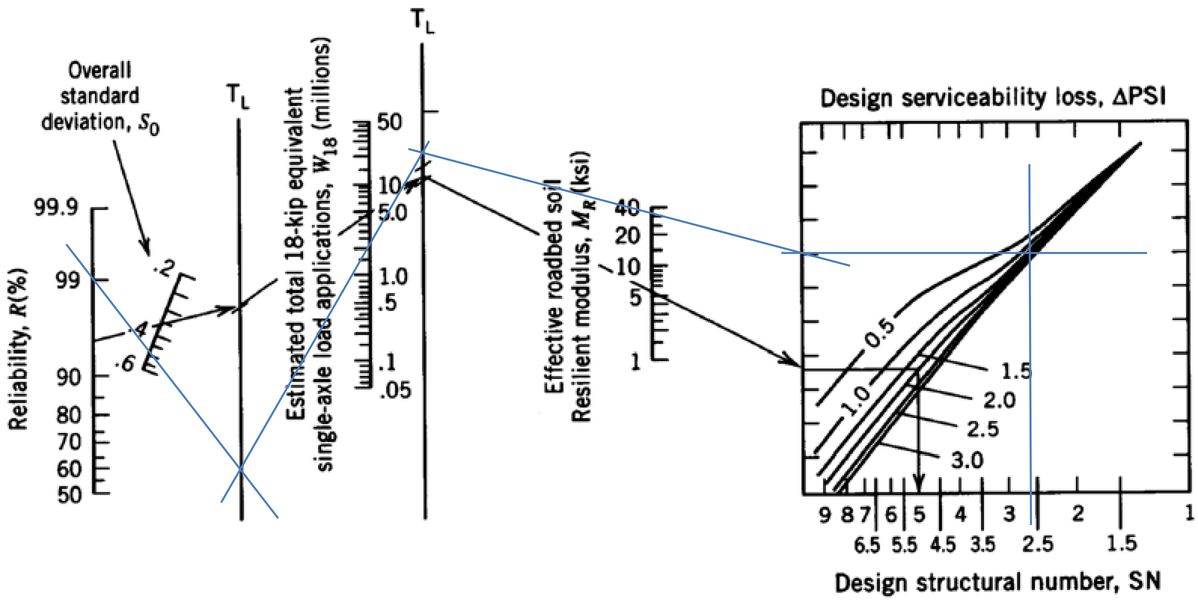
Terminal serviceability index $p_t = 2.5$

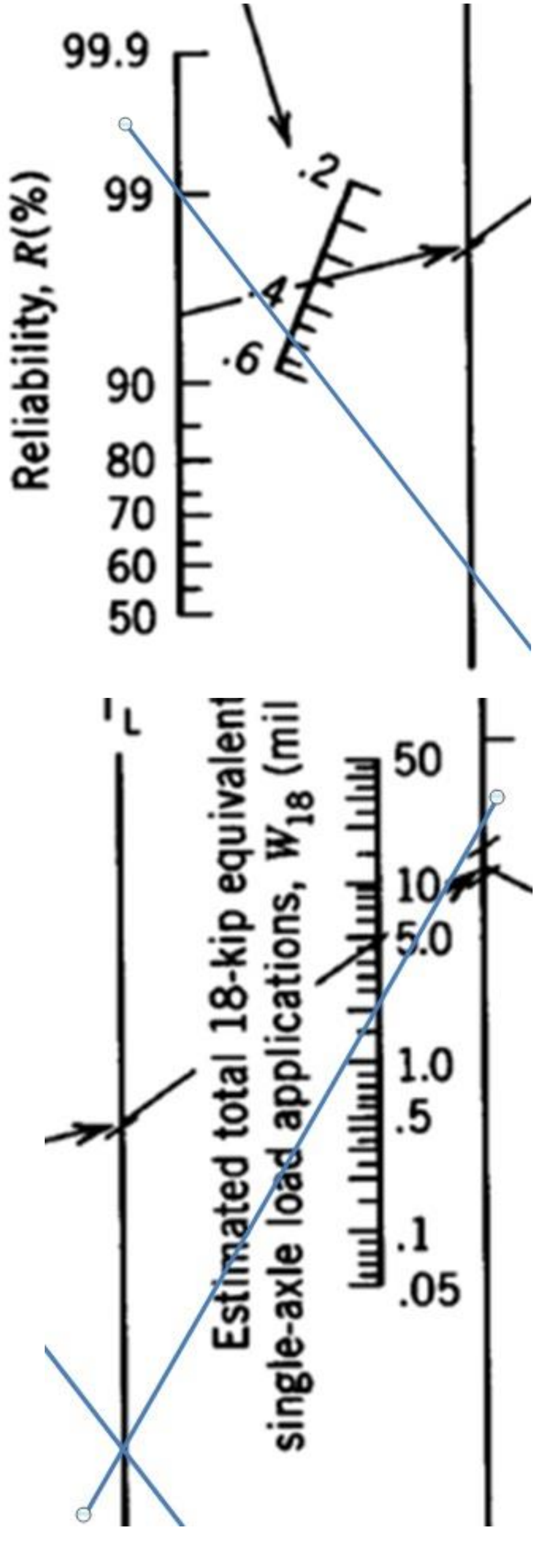
ΔPSI = 4.5 – 2.5 = **2**

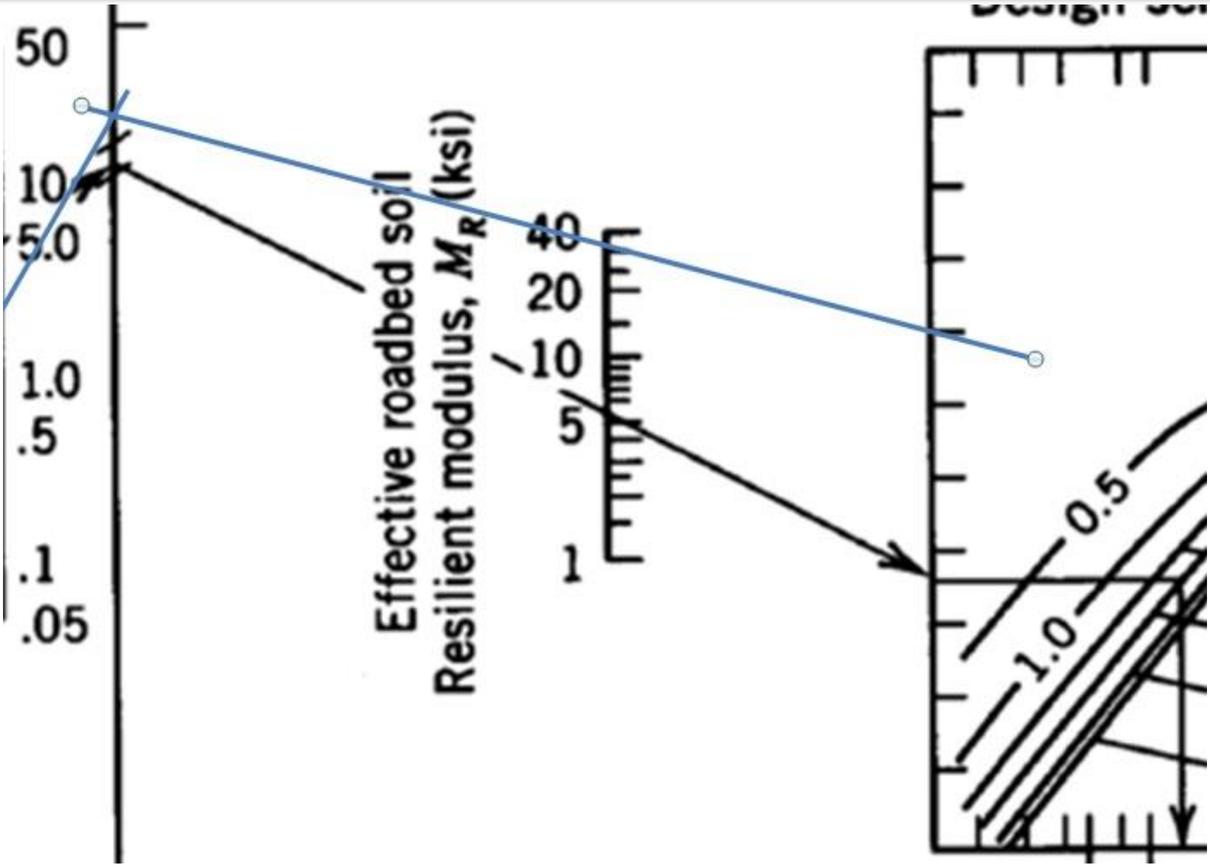
1. To find D_1:

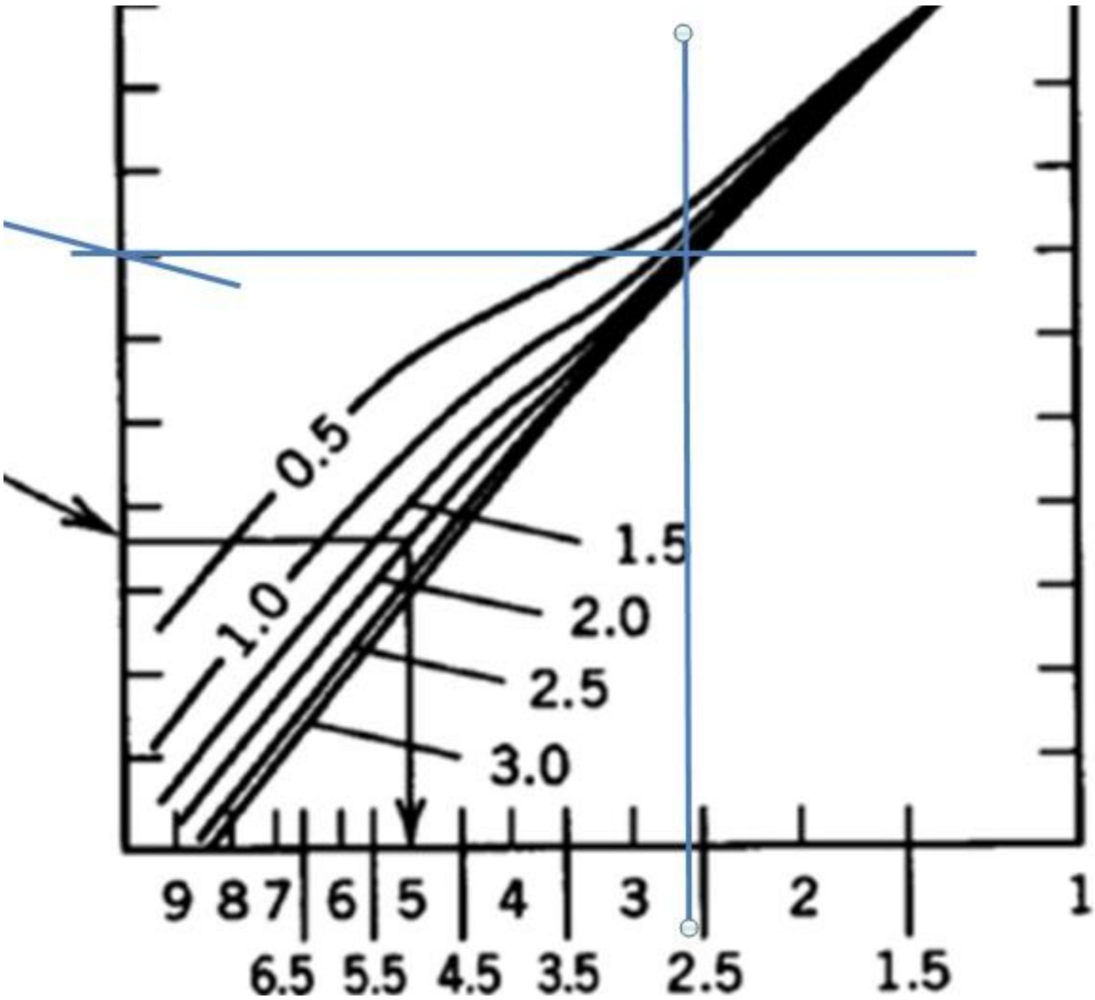
$SN_1 = a_1 D_1$ ⇨ $D_1 = SN_1/a_1$

Mr for base course = 31,000 lb/in^2 from figure **$SN_1 = 2.6$**



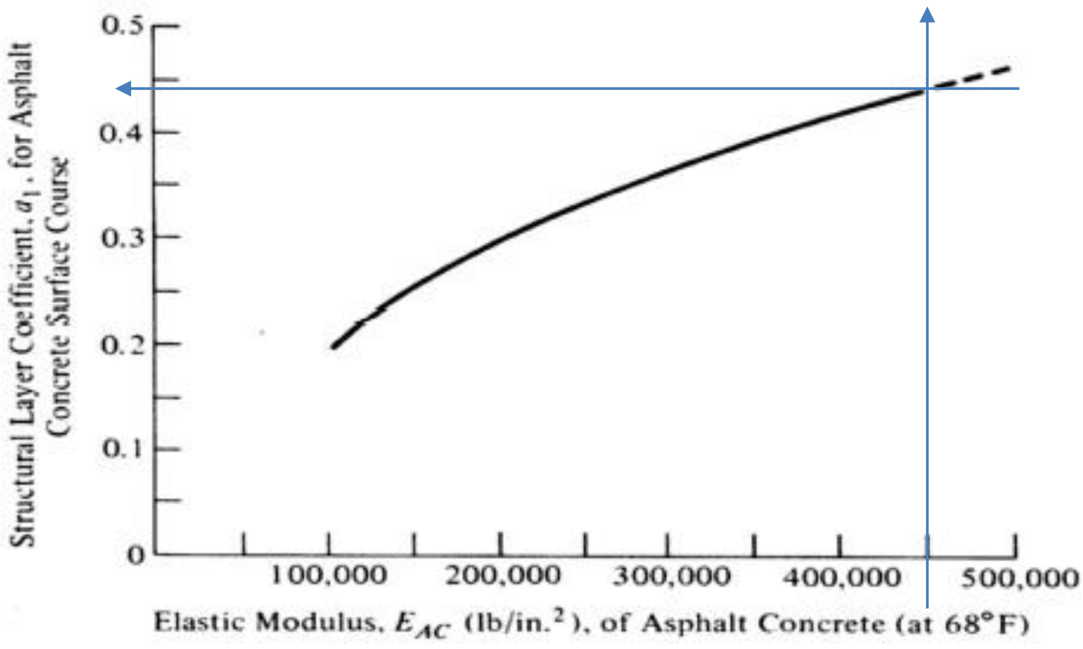

Reliability, R(%)
99.9
99
90
80
70
60
50
.2
.4
.6
Estimated total 18-kip equivalent
single-axle load applications, W18 (mil
50
10
5.0
1.0
.5
.1
.05


50
10
5.0
1.0
.5
.1
.05
Effective roadbed soil
Resilient modulus, M_R (ksi)
40
20
10
5
1
0.5
1.0


0.5
1.0
1.5
2.0
2.5
3.0
9 8 7 6 5 4 3 2 1
6.5 5.5 4.5 3.5 2.5 1.5

Determine the appropriate structure layer coefficient for each construction material:

Resilient value of asphalt = 450,000 lb/in^2. From Figure 19.5, **a_1 = 0.44**



D_1 = 2.6/0.44 = 5.9 in ⇨ Use 6 in for the thickness of the surface course

$SN_1^* = a_1 \times D_1 = 0.44 \times 6 = 2.64$

2. To find D_2:

$SN_2 = a_1 D_1 + a_2 D_2 m_2$ OR $SN_2 = SN_1^* + a_2 D_2 m_2$

Using the appropriate values for Mr in the Figure, $SN_2 = 3.8$

CBR of base course material = 100, From Figure 19.4, $a_2 = 0.14$

Determine appropriate drainage coefficient mi. Since only one set of conditions is given for both the base and subbase layers, the same value will be used for m_2 and m_3. The time required for water to drain from within pavement=1week, and from Table 19.5, drainage quality is fair. The percentage of time pavement structure will be exposed to moisture levels approaching saturation = 30%, and from Table 19.6, **$m_2 = m_3 = 0.80$**.

$SN_2 = a_1 D_1 + a_2 D_2 m_2$ ⇨ $3.8 = 0.44 \times 6 + 0.14 \times D_2 \times 0.8$ ⇨ $3.8 = 2.64 + 0.112 D_2$

D_2 = 10.36 in ⇨ Use 11 in for the thickness of the base course

$SN_2^* = a_1 D_1 + a_2 D_2 m_2 = 0.44 \times 6 + 0.14 \times 11 \times 0.8 = 3.872$

3. To find D_3:

$SN_3 = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3$ OR $SN_3 = SN_2^* + a_3 D_3 m_3$

Using the appropriate values for Mr in the Figure, $SN_3 = 4.4$

CBR of subbase course material = 22, From Figure 19.3, $a_3 = 0.10$

$SN_3 = SN_2^* + a_3 D_3 m_3 \Rightarrow 4.4 = 3.872 + 0.1 \times D_3 \times 0.8$

$D_3 = 6.6$ in Use 7 in for the thickness of the subbase course

$SN_3^* = SN_2^* + a_3 D_3 m_3 = 3.872 + 0.1 \times 7 \times 0.8 = 4.432$

Table 19.9 AASHTO-Recommended Minimum Thicknesses of Highway Layers

	Minimum Thickness (in.)	
Traffic, ESALs	*Asphalt Concrete*	*Aggregate Base*
Less than 50,000	1.0 (or surface treatment)	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

The pavement will therefore consist of 6 in asphalt concrete surface, 11 in granular base, and 7 in subbase.

Lecture 6 - 15/06/2020

Asphalt Institute Design Method

The Asphalt Institute's component analysis design approach (termed "effective thickness" by the Asphalt Institute) uses relationships between subgrade strength, pavement structure, and traffic (Asphalt Institute, 1983). The existing structural integrity of the pavement is converted to an equivalent thickness of HMA, which is then compared to that required for a new design. The structural evaluation procedure developed by the Asphalt Institute allows for either determining the required thickness of asphalt concrete overlay or estimating the length of time until an overlay is required. The essential parts of this overlay design procedure will be briefly described:

• Traffic loading (volume) in terms of ESAL.

• Material Properties in terms of Subgrade properties.

Example:

Subgrade MR = 11,000 psi

Traffic = 1.1×10^{6} ESAL

Thickness = ?

Answer:

From the figure: Thickness is about 9.5 in.

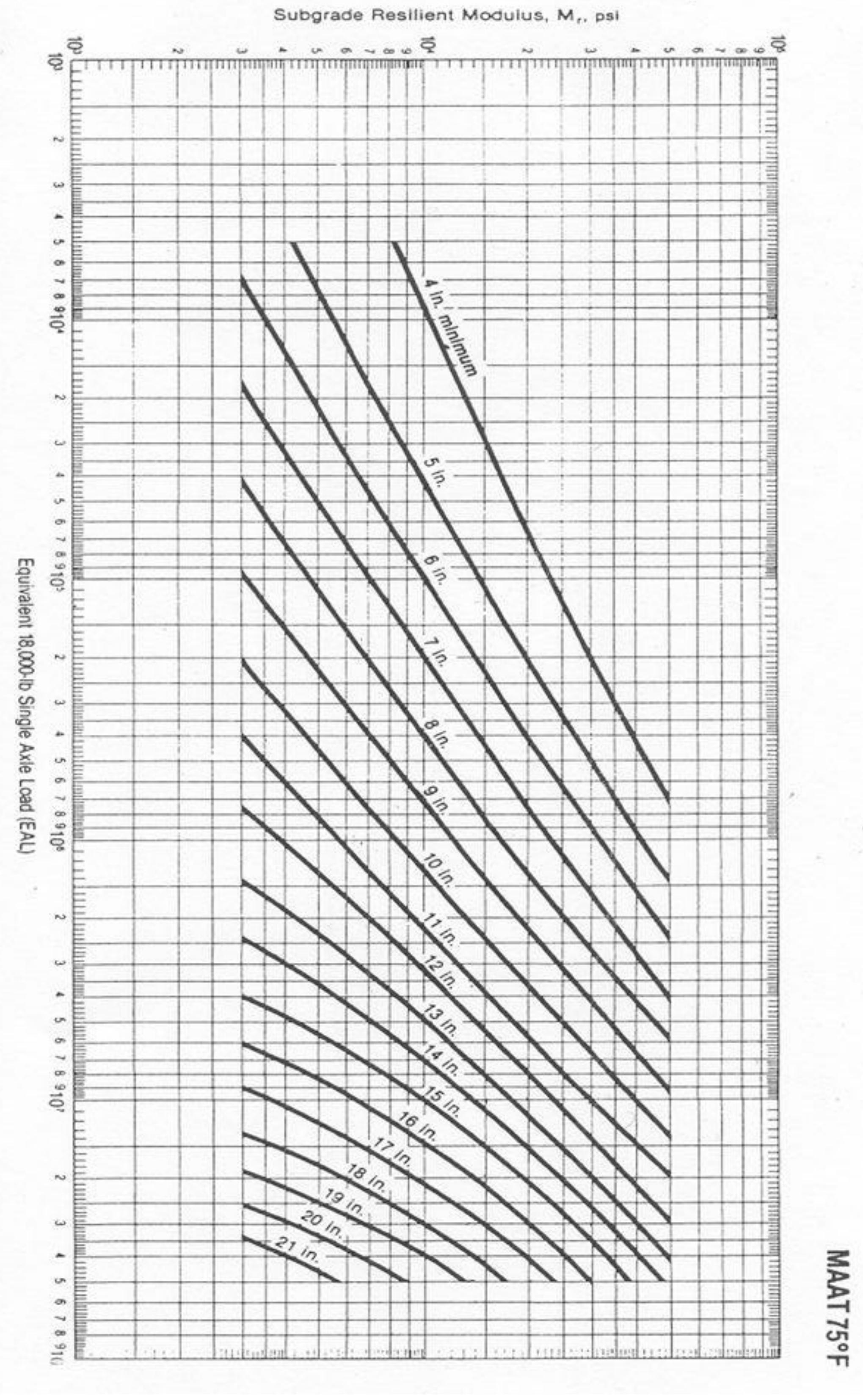


FIGURE 16-7 The Asphalt Institute design chart for full-depth asphalt concrete pavement. (Courtesy the Asphalt Institute.)

California Design Method

Elements to be Defined/Identified for Design

1. Traffic loading (volume) in terms of ESAL.
2. Strength of subgrade.
3. Strength of construction materials.

1. Traffic loading:

$$T_I = 9.0 \times \left(\frac{ESAL}{10^6}\right)^{0.119}$$

T_I = Traffic Index.

2. Strength of subgrade:
In terms of R value of subgrade.

3. Strength of construction materials

$$GE = 0.975 \times T_I\,(100 - R)$$

GE = Gravel Equivalent Thickness (mm)
R = California R-value of the material below the layer or layers for which the GE is being calculated

Example: Determine the layers thickness of a flexible pavement with the following data using California Design Method assume a subgrade with a California R-value of 10, R-value for the subbase AS layer is 50, R-value for the base AB layer is 78. ESAL is 3×10^6

Answer: $T_I = 10.26 = 10.5$

GE (surface) = 225 mm thickness of equivalent gravel
From the table: Surface thickness is 132 mm of HMA.

GE (base) = 512 mm thickness of equivalent gravel
From the table: Base thickness is 315 mm of AB – Aggregate Base.

GE (subbase) = 922 mm thickness of equivalent gravel
From the table: Subbase thickness is 390 mm of AS – Aggregate Subbase.

Table 633.1
Gravel Equivalents (GE) and Thickness of Structural Layers (mm)

Actual Layer Thickness (mm) (5)	HMA (1), (2)											Base and Subbase (3)					
	Traffic Index (TI)											TI is not a factor					
	5.0 & below	5.5 6.0	6.5 7.0	7.5 8.0	8.5 9.0	9.5 10.0	10.5 11.0	11.5 12.0	12.5 13.0	13.5 14.0	14.5 15.0	HMAB LCB	CTPB; CTB (Cl. A)	ATPB	CTB (Cl. B)	AB	AS
	Gf (For HMA thickness equal to or less than 150 mm, Gf decreases with TI)(4)											Gf (constant for any base or subbase material irrespective of TI or thickness)					
	GE for HMA layer (mm)											GE for Base or Subbase layer (mm)					
	2.54	2.32	2.14	2.01	1.89	1.79	1.71	1.64	1.57	1.52	1.46	1.9	1.7	1.4	1.2	1.1	1.0
	GE for HMA layer (mm)											GE for Base or Subbase layer (mm)					
45	114	104	96	90	85	81	77	74	71	68	66	--	--	--	--	--	--
60	152	139	128	121	113	107	103	98	94	91	88	--	--	--	--	--	--
75	191	174	161	151	142	134	128	123	118	114	110	--	--	105	--	--	--
90	229	209	193	181	170	161	154	148	141	137	131	--	--	126	--	--	--
105	267	244	225	211	198	188	180	172	165	160	153	200	180	147	126	116	105
120	305	278	257	241	227	215	205	197	188	182	175	228	204	168	144	132	120
135	343	313	289	271	255	242	231	221	212	205	197	257	230	189	162	149	135
150	381	348	321	302	284	269	257	246	236	228	219	285	255	210	180	165	150
165	421	392	362	338	318	301	287	275	264	254	247	314	281	231	198	182	165
180	473	441	407	380	357	338	322	308	296	285	278	342	306	252	216	198	180
195	526	490	453	422	397	377	359	343	329	317	309	371	332	273	234	215	195
210	--	541	500	466	439	416	396	379	363	350	341	399	357	--	252	231	210
225	--	593	548	511	481	456	434	415	399	384	374	428	383	--	270	248	225
240	--	647	597	557	524	497	473	452	434	418	407	456	408	--	288	264	240
255	--	--	647	604	568	538	513	491	471	453	442	485	434	--	306	281	255
270	--	--	698	652	613	581	553	529	508	489	477	513	459	--	324	297	270
285	--	--	--	701	659	625	595	569	546	526	512	542	485	--	342	314	285
300	--	--	--	750	706	669	637	609	585	563	548	570	510	--	360	330	300
315	--	--	--	801	753	714	680	650	624	601	585	599	536	--	378	347	315
330	--	--	--	--	802	759	723	692	664	639	623	--	--	--	--	--	330
345	--	--	--	--	851	806	767	734	705	679	661	--	--	--	--	--	345
360	--	--	--	--	900	853	812	777	746	718	699	--	--	--	--	--	360
375	--	--	--	--	--	901	858	820	787	758	738	--	--	--	--	--	375
390	--	--	--	--	--	949	904	864	830	799	778	--	--	--	--	--	390
405	--	--	--	--	--	998	950	909	873	840	818	--	--	--	--	--	--
420	--	--	--	--	--	--	997	954	916	882	859	--	--	--	--	--	--
435	--	--	--	--	--	--	1045	1000	960	924	900	--	--	--	--	--	--
450	--	--	--	--	--	--	1094	1046	1004	967	942	--	--	--	--	--	--
465	--	--	--	--	--	--	--	1093	1049	1010	984	--	--	--	--	--	--
480	--	--	--	--	--	--	--	1140	1094	1054	1026	--	--	--	--	--	--
495	--	--	--	--	--	--	--	1188	1140	1098	1069	--	--	--	--	--	--
510	--	--	--	--	--	--	--	--	1187	1143	1113	--	--	--	--	--	--
525	--	--	--	--	--	--	--	--	1233	1188	1156	--	--	--	--	--	--
540	--	--	--	--	--	--	--	--	1280	1233	1201	--	--	--	--	--	--
555	--	--	--	--	--	--	--	--	--	1279	1245	--	--	--	--	--	--
570	--	--	--	--	--	--	--	--	--	1325	1290	--	--	--	--	--	--
585	--	--	--	--	--	--	--	--	--	1372	1336	--	--	--	--	--	--
600	--	--	--	--	--	--	--	--	--	--	1382	--	--	--	--	--	--

Notes:

(1) Open Graded Friction Course (conventional and rubberized) is a non-structural wearing course and provides no structural value.

(2) Top portion of HMA surface layer (maximum 60 mm) may be replaced with equivalent RHMA-G thickness. See Topic 631.3 for additional details.

(3) See Table 663.1B for additional information on Gravel Factors (G_f) and California R-values for base and subbase materials.

(4) These G_f values are for TIs shown and HMA thickness equal to or less than 150 mm only. For HMA thickness greater than 150 mm, appropriate G_f should be determined using the equation in Index 633.1(1)(c).

(5) For HMA layer, select TI range, then go down to the appropriate GE and across to the thickness column. For base or subbase layer, select material type, then go down to the appropriate GE and across to the thickness column.

CTB-A – Cement Treated Base Class A
CTB-B – Cement Treated Base Class B
CTP-B – Cement Treated Permeable Base
AB – Aggregate Base
AS – Aggregate Subbase
ATPB – Asphalt Treated Permeable Base
LCB - Lean Concrete Base

Lecture 7 - 22/06/2020-

Rigid Pavement

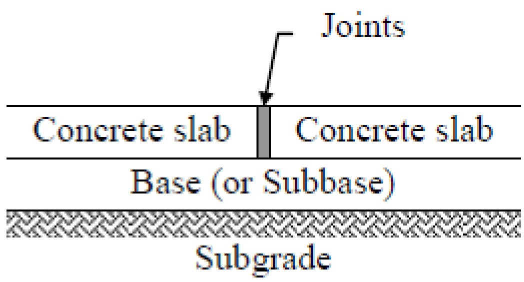
Function of Base or Subbase if used:

1) Drainage purpose

2) Reduce the effect of subgrade volume change on concrete layer

3) Prevent pumping of fines through joints & edges

4) Increase "K" modulus of subgrade reaction



Rigid Pavement Characteristics:

- Can resist unlimited loading.

- More skid resistance, safe.

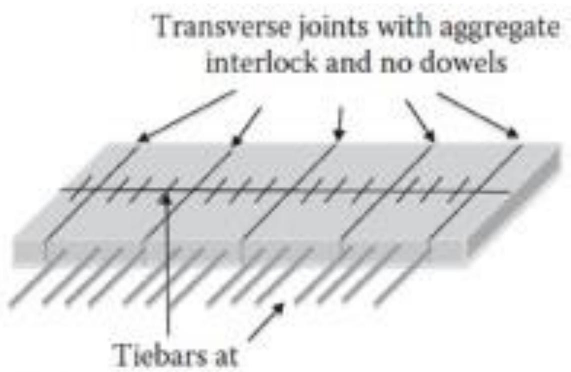
- More economical for some projects at certain location.

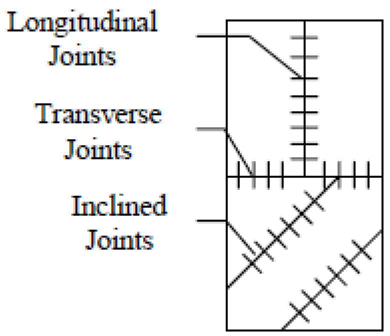
- Concrete layer is less thickness than other layers.

Rigid Pavement Types:

a) Plain concrete pavement:

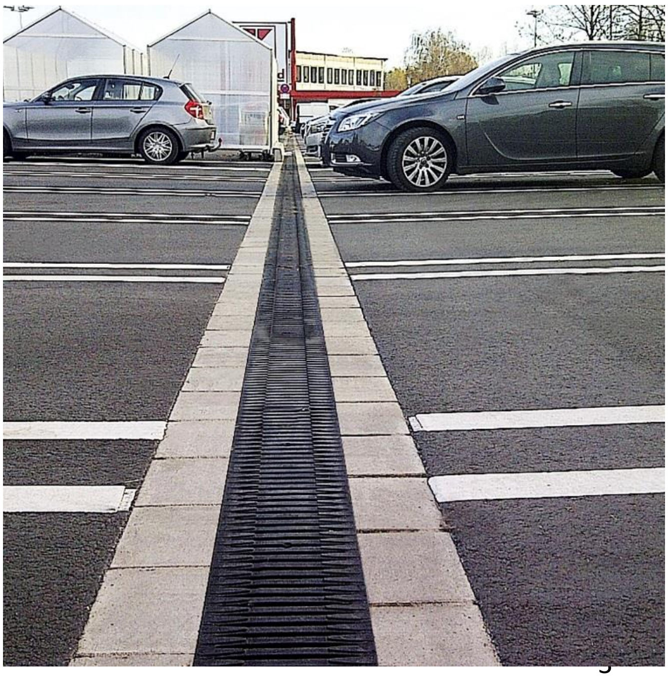
1. No reinforcement except of using tie bars for longitudinal joints and dowel bars for transverse joints.






CPCD After
Concrete Paving
Dowel Bars
Tie Bars
CPCD Before
Concrete Paving
ACP Base

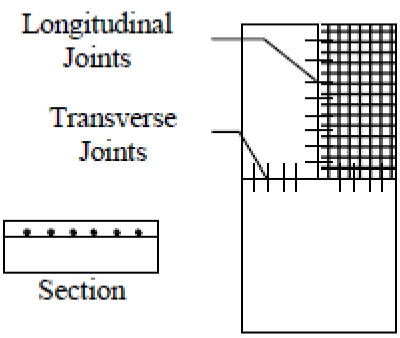
2. Closer spacing between contractions joint as transverse joints, 3-6 m.



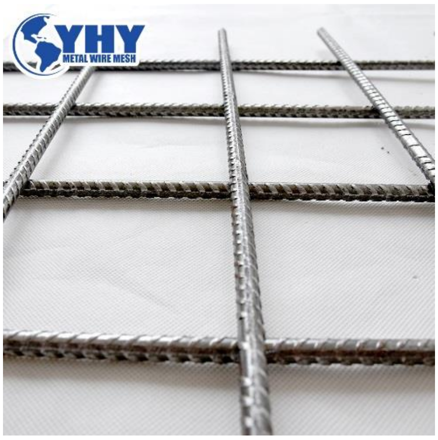
3. Inclined joints may be used (for better load transfer)

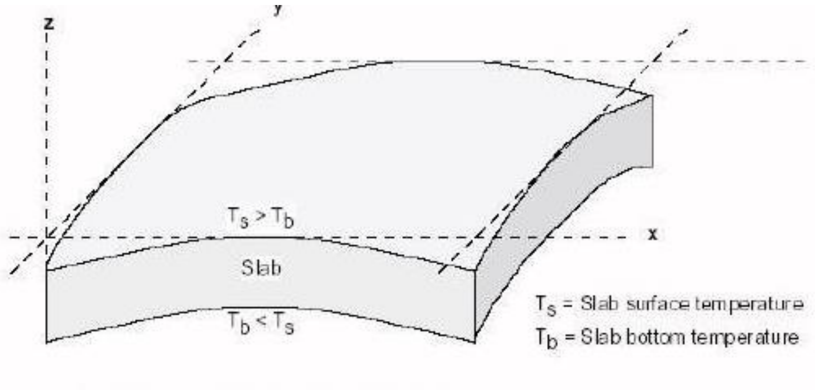
4. Very limited use

b) Simply reinforced concrete pavement:



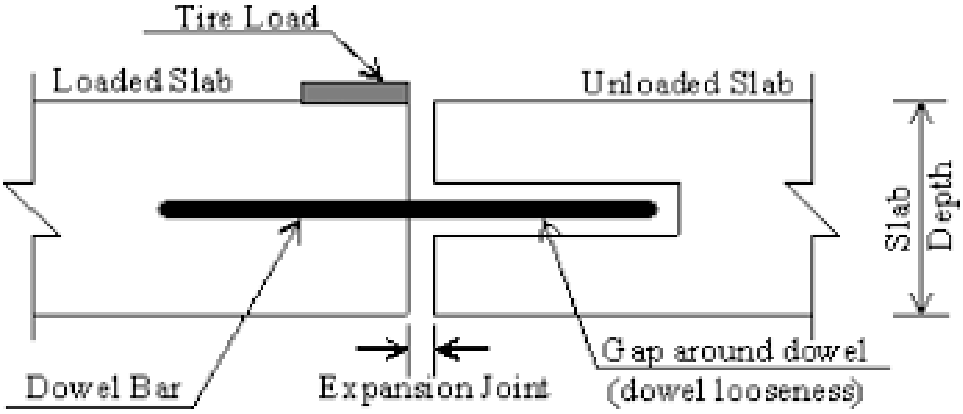
1. Temperature (wire-mesh, B. R. C.) reinforcement between joints to control cracking (close to the upper surface).



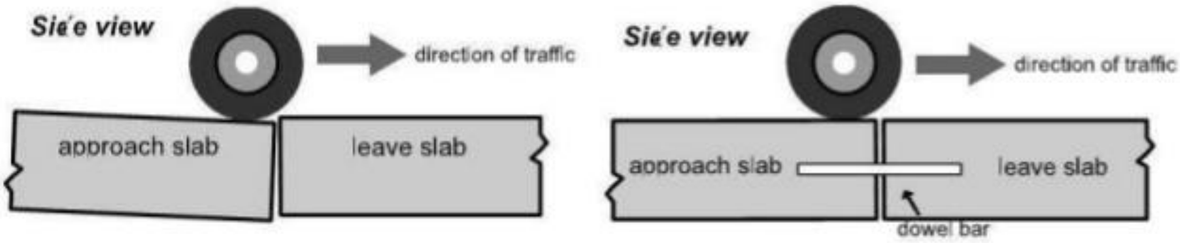


2. Longer slabs

3. Dowel bars across transverse joints



EFFECT OF DOWEL BARS ON CONCRETE PAVEMENT



3. Tie bars across longitudinal joints to control warping

4. Wider spacing between joints (from 3-6m to 7-14m)

5. Widely used

c) Continuously reinforced concrete pavement:

1. No joints except some expansion joints & may be some contraction joints

2. Heavy reinforcement (≈ > 0.6% of cross section area)

3. High cost

4. Used in very-weak subgrade & high traffic load

d) Pre-stressed concrete pavement:

1. More expensive

Rigid Pavements

For all conventional rigid pavement types, a concrete slab is usually poured directly on a subgrade, base, or subbase. The base or subbase could be a bonded or unbonded material that provides adequate support and drainage.

Materials used in Rigid Pavements

The Portland cement concrete commonly used for rigid pavements consists of Portland cement, coarse aggregate, fine aggregate, and water. Steel reinforcing rods may or may not be used, depending on the type of pavement being constructed.

Reinforcing Steel

Steel reinforcing used in concrete pavements for

- reduce the amount of cracking that occurs,
- as a load transfer mechanism at joints,
- as a means of tying two slabs together.

Types of steel reinforcement can be classified as follows:

- Steel reinforcement used to control cracking is usually referred to as temperature steel,
- steel rods used as load transfer mechanisms are known as dowel bars,
- and those used to connect two slabs together are known as tie bars.

A) Temperature Steel

Temperature steel is provided in the form of a bar mat or wire mesh consisting of longitudinal and transverse steel wires welded at regular intervals. The mesh usually is placed about 3 in. below the slab surface. The cross-sectional area of the steel provided per foot width of the slab depends on the size and spacing of the steel wires forming the mesh. The amount of steel required depends on the length of the pavement between expansion joints, the maximum stress desired in the concrete pavement, the thickness of the pavement, and the moduli of elasticity of the concrete and steel. Temperature steel does not prevent cracking of the slab, but it does control the crack widths because the steel acts as a tie holding the edges of the cracks together.

B) Dowel Bars

Dowel bars are used mainly as load-transfer mechanisms across joints. They provide flexural, shearing, and bearing resistance. The dowel bars must be of a much larger diameter than the wires used in temperature steel. Diameters of 1 to 1.5 in. and lengths of 2 to 3 ft have been used, with the bars usually spaced at 1 ft centers across the width of the slab. At least one end of the bar should be smooth and lubricated to facilitate free expansion.

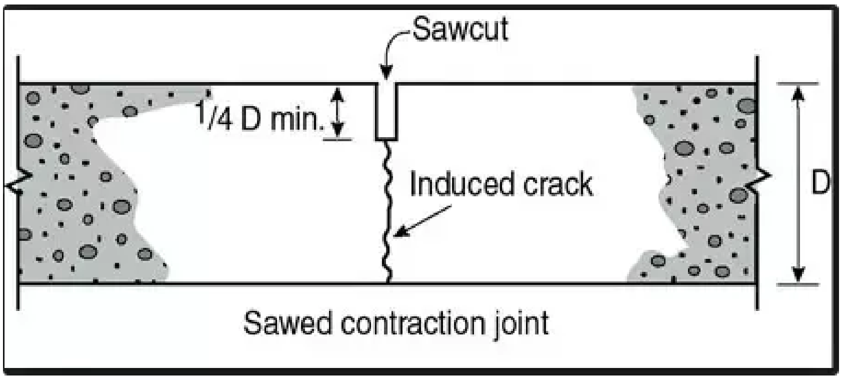
C) Tie Bars

Tie bars are used to tie two sections of the pavement together, and therefore they should be either deformed bars or should contain hooks to facilitate the bonding of the two sections of the concrete pavement with the bar. These bars are usually much smaller in diameter than the dowel bars and are spaced at larger centers. Typical diameter and spacing for these bars are 3/4 in. and 3 ft, respectively.

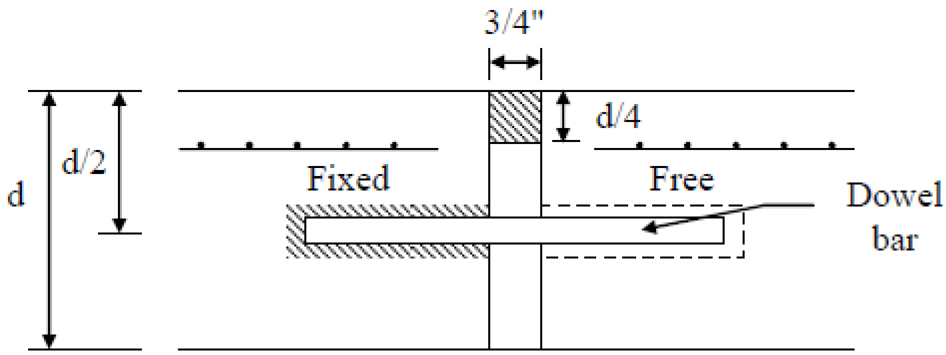
Lecture 8 - 29/06/2020

Type of Joints in Rigid Pavement:

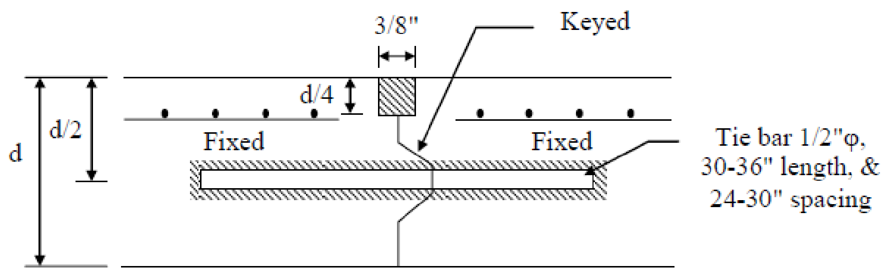
1) Contraction joints: to relieve excessive tensile stress due to drop in temperature. It is a joint that is put in the concrete to control cracking. For example, when they sawcut joints into the concrete pavement, these are control joints. These are necessary, because we know the concrete will crack. We just need to try to control where it cracks. These are called contraction joints, because concrete tends to contract when it is curing.

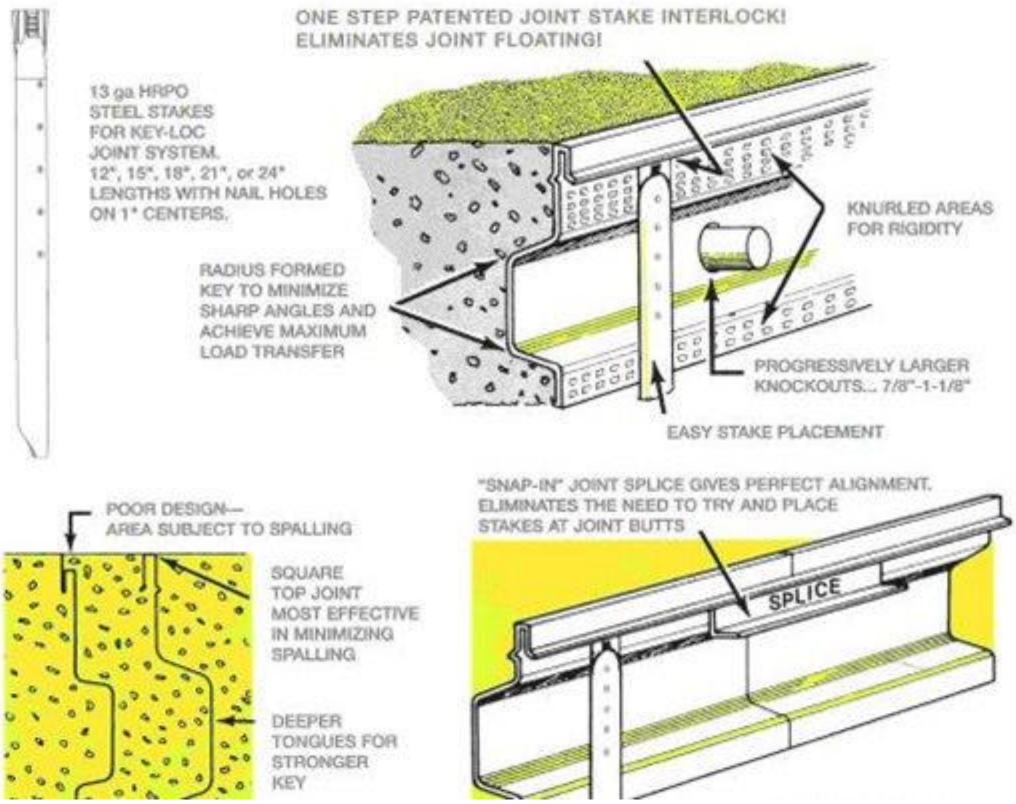


2) Expansion Joints: provide a clear spacing along the depth to relieve excessive compressive stresses due to rise in temperature. It is used in concrete and steel. An expansion joint allows the concrete or steel to expand or contract with daily temperature variations. If you don't allow this, you may get buckling, or spalling, or total failures.

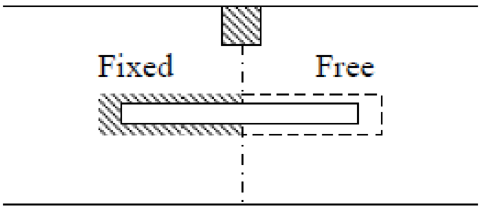


3) Warping joints: are provided along the longitudinal direction to prevent warping of the concrete slab due to temperature and subgrade moisture variation



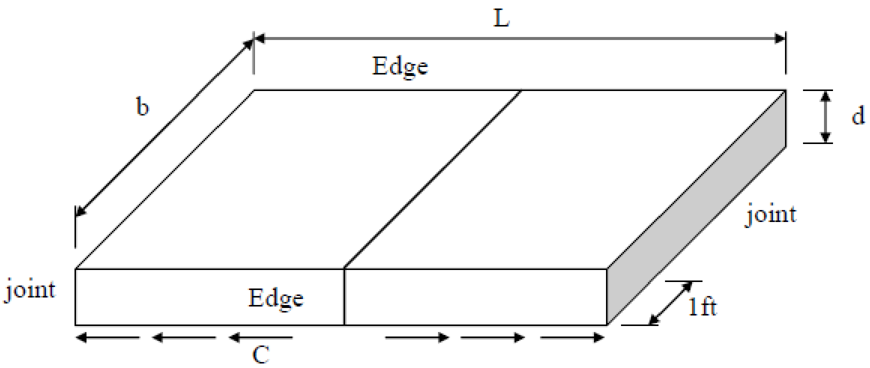

ONE STEP PATENTED JOINT STAKE INTERLOCK!
ELIMINATES JOINT FLOATING!
13 ga HRPO STEEL STAKES FOR KEY-LOC JOINT SYSTEM. 12", 15", 18", 21", or 24" LENGTHS WITH NAIL HOLES ON 1" CENTERS.
RADIUS FORMED KEY TO MINIMIZE SHARP ANGLES AND ACHIEVE MAXIMUM LOAD TRANSFER
KNURLED AREAS FOR RIGIDITY
PROGRESSIVELY LARGER KNOCKOUTS... 7/8"-1-1/8"
EASY STAKE PLACEMENT
POOR DESIGN— AREA SUBJECT TO SPALLING
SQUARE TOP JOINT MOST EFFECTIVE IN MINIMIZING SPALLING
DEEPER TONGUES FOR STRONGER KEY
"SNAP-IN" JOINT SPLICE GIVES PERFECT ALIGNMENT. ELIMINATES THE NEED TO TRY AND PLACE STAKES AT JOINT BUTTS
SPLICE

4) Construction joints: A construction joint is a type of concrete joint that is used when a new section of concrete is poured adjacent to another concrete section that has already set. The purpose of a construction joint is to allow for some horizontal movement, while being rigid against rotational and vertical movement.



BRC (British Reinforcement Company) Design:

There are 3 three reasons for using BRC reinforcement in concrete pavements. To prevent cracking under traffic load by providing most of the tensile strength required in the concrete slab. To prevent the cracking that normally occurs when a large slab of concrete cures and shrinks. To minimise the width of any cracks (that form in the concrete, for whatever reason) and to hold the slab together as an entity for as long as possible



L = Allowable spacing for contraction joint (for longitudinal reinforcement), (ft)

b = Slab width, (ft)

C = Coefficient of friction (1 – 2 use 1.5)

γ = Unit wt. of concrete (pcf)

d = Slab thickness (ft)

Friction resistance = Allowable tensile strength

Friction resistance = Concrete tensile strength + Steel tensile strength

$(L/2 * b * d) * \gamma * C = b * d * f_{tc} + A_s * f_s$

For one unit of width use b =1ft

For safety assume concrete tensile strength $(b * d * f_{tc}) = 0$

f_{tc} = Allowable tensile strength of concrete

f_s = Allowable tensile strength of steel

A_s = Area of steel (in^2/ft) in longitudinal direction

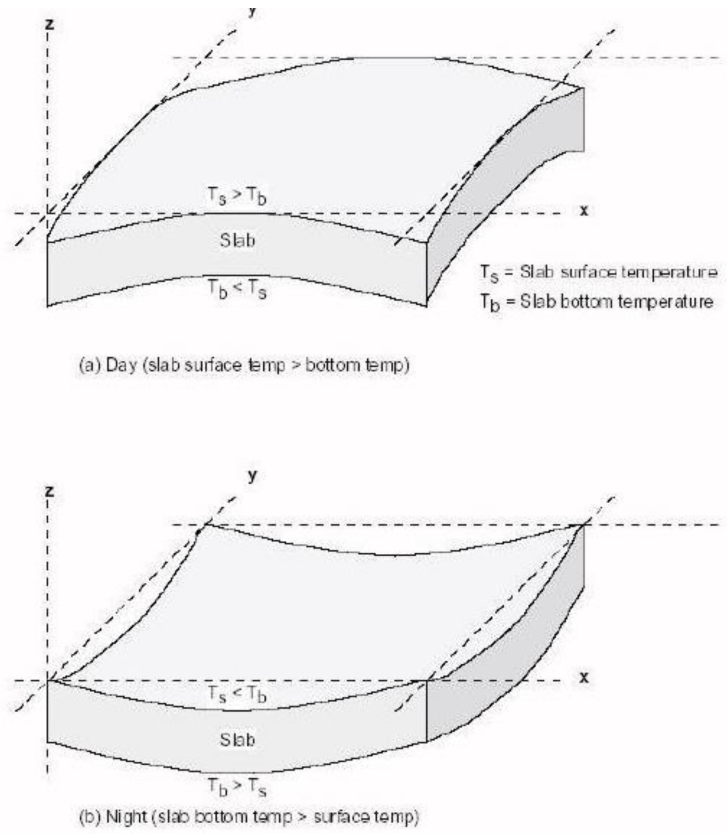
$W = d * \gamma$ (Ib/ft^2)

where: W = Weight of $1ft^2$ of slab

$L/2 * 1 * W * C = A_s * f_s$

$$As = \frac{L * W * C}{2F_s}$$

To calculate the area of steel in the transverse direction, use b instead of L.



(a) Day (slab surface temp > bottom temp)

(b) Night (slab bottom temp > surface temp)

Example: A 2 lane highway rigid pavement is 24 ft wide with a longitudinal warping joint in the centre, transverse construction joints were placed at 50 ft intervals, calculate the amount of longitudinal and transverse reinforcement in the pavement if the slab thickness is 12 in, assume unit weight of concrete (γ) =150 pcf, allowable tensile strength of steel =43000 psi.

Lecture 9 - 06/07/2020

Rigid Pavement Design

Portland Cement Association (PCA) Method:

Design Considerations

The basic factors considered in the PCA design method are:

• Flexural strength of the concrete

• Subgrade and subbase support

• Traffic load

Subgrade and Subbase Support: The modulus of subgrade reaction (k) is used to define the subgrade and subbase support. This can be determined by performing a loading plate test or by correlating with other test results.

Table 20.10 Design *k* Values for Untreated and Cement-Treated Subbases

(a) Untreated Granular Subbases

Subgrade k Value (lb/in^3)	Subbase k Value (lb/in^3)			
	4 in.	6 in.	9 in.	12 in.
50	65	75	85	110
100	130	140	160	190
200	220	230	270	320
300	320	330	370	430

(b) Cement-Treated Subbases

Subgrade k Value (lb/in^3)	Subbase k Value (lb/in^3)			
	4 in.	6 in.	9 in.	12 in.
50	170	230	310	390
100	280	400	520	640
200	470	640	830	—

The design also incorporates a load safety factor (LSF) which is used to multiply each axle load. The recommended LSF values are:

• 1.2 for interstate and multilane projects with uninterrupted traffic flow and high truck volumes

• 1.1 for highways and arterials with moderate truck volume

• 1.0 for roads and residential streets with very low truck volume

Design Procedure

The design procedure consists of two parts: fatigue analysis and erosion analysis. The objective of fatigue analysis is to determine the minimum thickness of the concrete required to control fatigue cracking. This is done by comparing the expected axle repetitions with the allowable repetitions for each axle load and ensuring that the cumulative repetitions are less than those allowable. Allowable axle repetitions depend on the stress ratio factor, which is the ratio of the equivalent stress of the pavement to the modulus of rupture of the concrete. The equivalent stress of the pavement depends on the thickness of the slab and the subbase-subgrade k. The chart in Figure 20.15 can be used to determine the allowable load repetitions based on the stress ratio factor. Tables 20.11 and 20.12 give equivalent stress values for pavements without concrete shoulders and with concrete shoulders, respectively. The objective of the erosion analysis is to determine the minimum thickness of the pavement required to control foundation and shoulder erosion, pumping, and faulting. These pavement distresses are related more closely to deflection, as will be seen later. The erosion criterion is based mainly on the rate of work expended by an axle load in deflecting a slab, as it was determined that a useful correlation existed between pavement performance and the product of the corner deflection and the pressure at the slab-subgrade interface.

The erosion analysis is similar to that of fatigue analysis, except that an erosion factor is used instead of the stress factor. The erosion factor is also dependent on the thickness of the slab and the subgrade-subbase k. Tables 20.13 through 20.16 give erosion factors for different types of pavement construction. Figures 20.16 and 20.17 are charts that can be used to determine the allowable load repetitions based on erosion. The minimum thickness that satisfies both analyses is the design thickness. Design thicknesses for pavements carrying light traffic and pavements with doweled joints carrying medium traffic will usually be based on fatigue analysis, whereas design thicknesses for pavements with undoweled joints carrying medium or heavy traffic and pavements with doweled joints carrying heavy traffic will normally be based on erosion analysis.

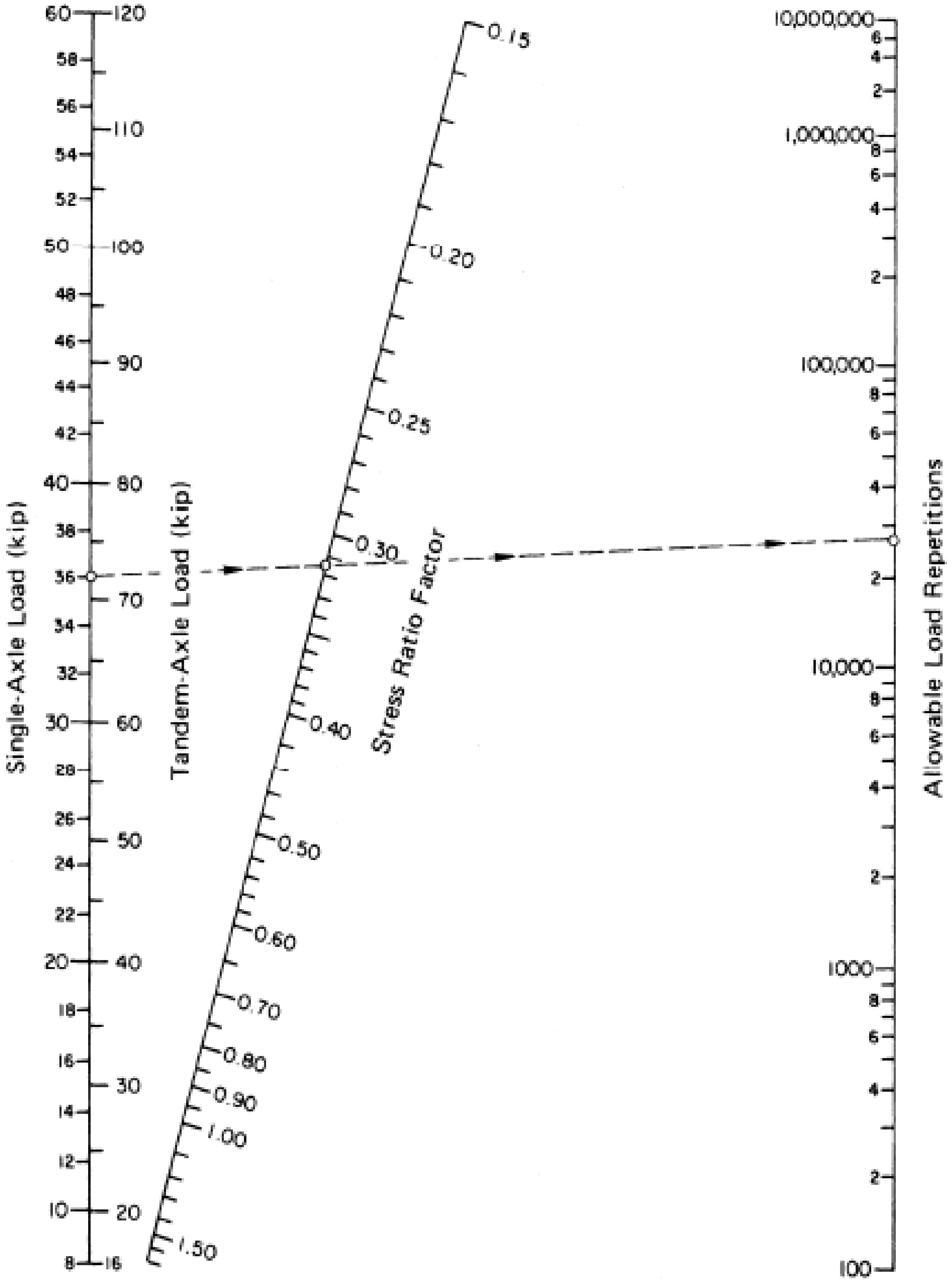


Figure 20.15 Allowable Load Repetitions for Fatigue Analysis Based on Stress Ratio

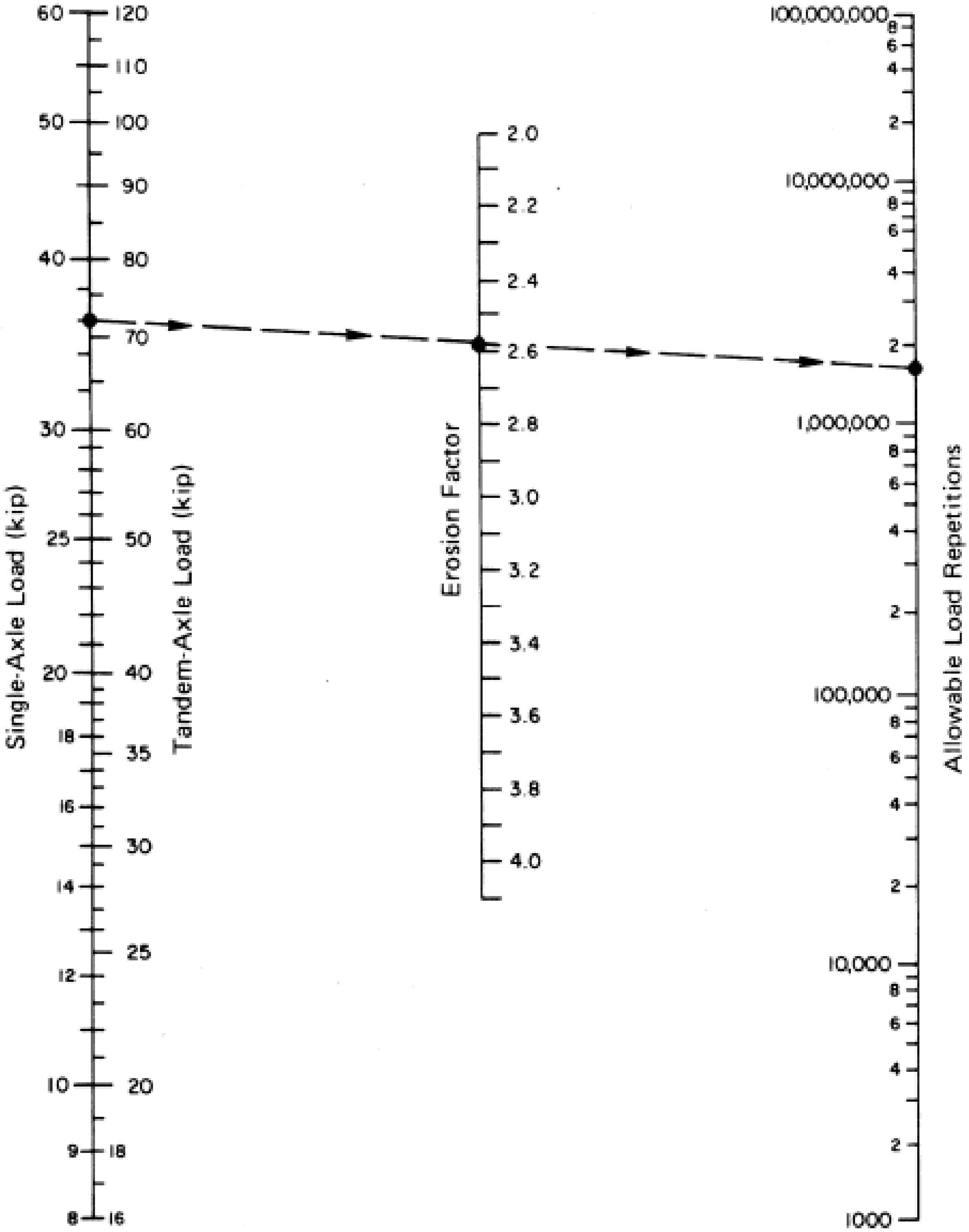


Figure 20.16 Allowable Load Repetitions for Erosion Analysis Based on Erosion Factors (Without concrete shoulder).

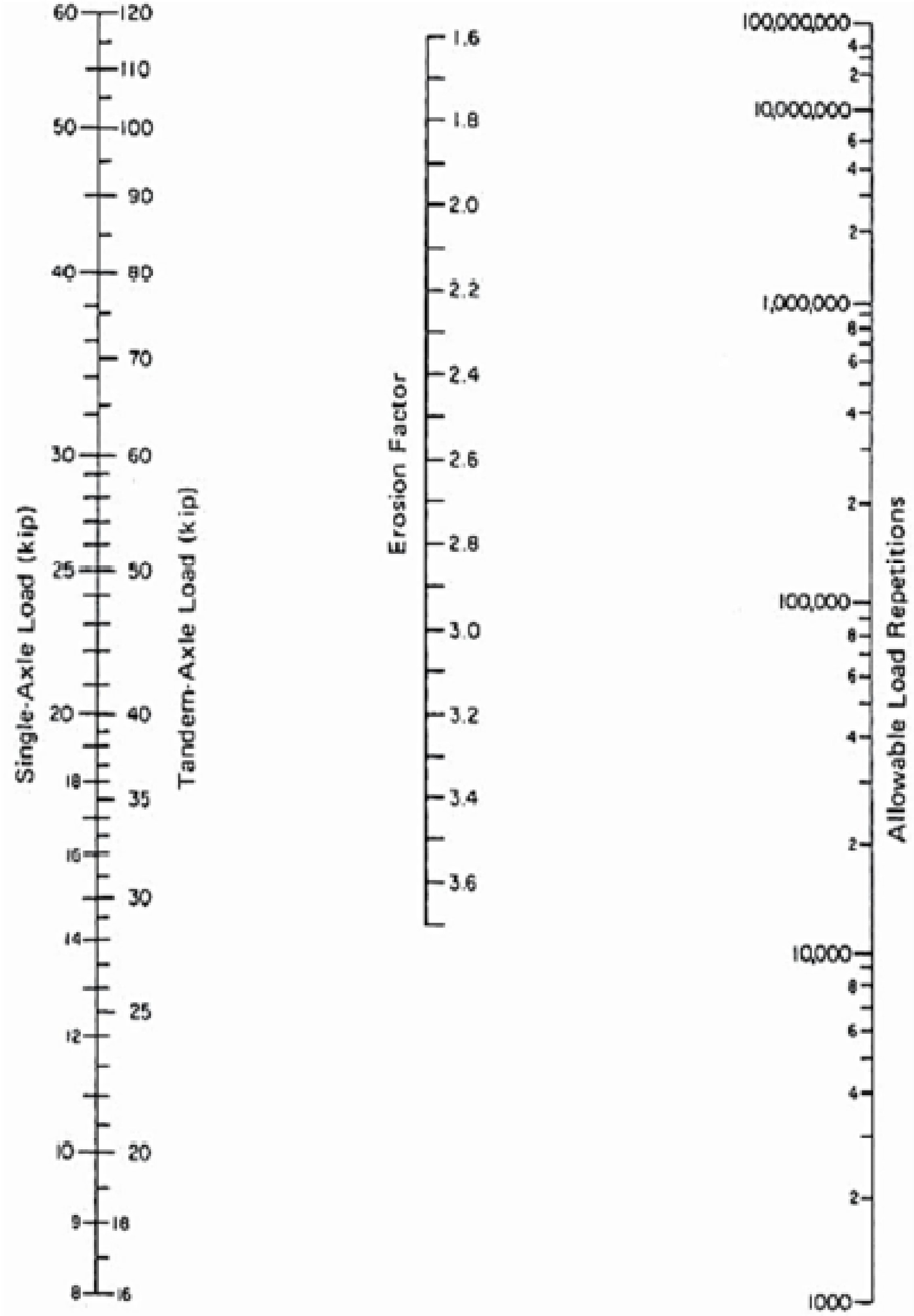


Figure 20.17 Allowable Load Repetitions for Erosion Analysis Based on Erosion Factors (With concrete shoulder).

Table 20.11 Equivalent Stress Values for Single Axles and Tandem Axles (without concrete shoulder)

Slab Thickness (in.)	*k of Subgrade-Subbase (lb/in³) (Single Axle/Tandem Axle)*						
	50	*100*	*150*	*200*	*300*	*500*	*700*
4	825/679	726/585	671/542	634/516	584/486	523/457	484/443
4.5	699/586	616/500	571/460	540/435	498/406	448/378	417/363
5	602/516	531/436	493/399	467/376	432/349	390/321	363/307
5.5	526/461	464/387	431/353	409/331	379/305	343/278	320/264
6	465/416	411/348	382/316	362/296	336/271	304/246	285/232
6.5	417/380	367/317	341/286	324/267	300/244	273/220	256/207
7	375/349	331/290	307/262	292/244	271/222	246/199	231/186
7.5	340/323	300/268	279/241	265/224	246/203	224/181	210/169
8	311/300	274/249	255/223	242/208	225/188	205/167	192/155
8.5	285/281	252/232	234/208	222/193	206/174	188/154	177/143
9	264/264	232/218	216/195	205/181	190/163	174/144	163/133
9.5	245/248	215/205	200/183	190/170	176/153	161/134	151/124
10	228/235	200/193	186/173	177/160	164/144	150/126	141/117
10.5	213/222	187/183	174/164	165/151	153/136	140/119	132/110
11	200/211	175/174	163/155	154/143	144/129	131/113	123/104
11.5	188/201	165/165	153/148	145/136	135/122	123/107	116/98
12	177/192	155/158	144/141	137/130	127/116	116/102	109/93
12.5	168/183	147/151	136/135	129/124	120/111	109/97	103/89
13	159/176	139/144	129/129	122/119	113/106	103/93	97/85
13.5	152/168	132/138	122/123	116/114	107/102	98/89	92/81
14	144/162	125/133	116/118	110/109	102/98	93/85	88/78

Table 20.12 Equivalent Stress Values for Single Axles and Tandem Axles (with concrete shoulder)

Slab Thickness (in.)	*k of Subgrade-Subbase (lb/in³) (Single Axle/Tandem Axle)*						
	50	*100*	*150*	*200*	*300*	*500*	*700*
4	640/534	559/468	517/439	489/422	452/403	409/388	383/384
4.5	547/461	479/400	444/372	421/356	390/338	355/322	333/316
5	475/404	417/349	387/323	367/308	341/290	311/274	294/267
5.5	418/360	368/309	342/285	324/271	302/254	276/238	261/231
6	372/325	327/277	304/255	289/241	270/225	247/210	234/203
6.5	334/295	294/251	274/230	260/218	243/203	223/188	212/180
7	302/270	266/230	248/210	236/198	220/184	203/170	192/162
7.5	275/250	243/211	226/193	215/182	201/168	185/155	176/148
8	252/232	222/196	207/179	197/168	185/155	170/142	162/135
8.5	232/216	205/182	191/166	182/156	170/144	157/131	150/125
9	215/202	190/171	177/155	169/146	158/134	146/122	139/116
9.5	200/190	176/160	164/146	157/137	147/126	136/114	129/108
10	186/179	164/151	153/137	146/129	137/118	127/107	121/101
10.5	174/170	154/143	144/130	137/121	128/111	119/101	113/95
11	164/161	144/135	135/123	129/115	120/105	112/95	106/90
11.5	154/153	136/128	127/117	121/109	113/100	105/90	100/85
12	145/146	128/122	120/111	114/104	107/95	99/86	95/81
12.5	137/139	121/117	113/106	108/99	101/91	94/82	90/77
13	130/133	115/112	107/101	102/95	96/86	89/78	85/73
13.5	124/127	109/107	102/97	97/91	91/83	85/74	81/70
14	118/122	104/103	97/93	93/87	87/79	81/71	77/67

Table 20.13 Erosion Factors for Single Axles and Tandem Axles (doweled joints, without concrete shoulder)

Slab Thickness (in.)	k of Subgrade-Subbase (lb/in^3) (Single Axle/Tandem Axle)					
	50	100	200	300	500	700
4	3.74/3.83	3.73/3.79	3.72/3.75	3.71/3.73	3.70/3.70	3.68/3.67
4.5	3.59/3.70	3.57/3.65	3.56/3.61	3.55/3.58	3.54/3.55	3.52/3.53
5	3.45/3.58	3.43/3.52	3.42/3.48	3.41/3.45	3.40/3.42	3.38/3.40
5.5	3.33/3.47	3.31/3.41	3.29/3.36	3.28/3.33	3.27/3.30	3.26/3.28
6	3.22/3.38	3.19/3.31	3.18/3.26	3.17/3.23	3.15/3.20	3.14/3.17
6.5	3.11/3.29	3.09/3.22	3.07/3.16	3.06/3.13	3.05/3.10	3.03/3.07
7	3.02/3.21	2.99/3.14	2.97/3.08	2.96/3.05	2.95/3.01	2.94/2.98
7.5	2.93/3.14	2.91/3.06	2.88/3.00	2.87/2.97	2.86/2.93	2.84/2.90
8	2.85/3.07	2.82/2.99	2.80/2.93	2.79/2.89	2.77/2.85	2.76/2.82
8.5	2.77/3.01	2.74/2.93	2.72/2.86	2.71/2.82	2.69/2.78	2.68/2.75
9	2.70/2.96	2.67/2.87	2.65/2.80	2.63/2.76	2.62/2.71	2.61/2.68
9.5	2.63/2.90	2.60/2.81	2.58/2.74	2.56/2.70	2.55/2.65	2.54/2.62
10	2.56/2.85	2.54/2.76	2.51/2.68	2.50/2.64	2.48/2.59	2.47/2.56
10.5	2.50/2.81	2.47/2.71	2.45/2.63	2.44/2.59	2.42/2.54	2.41/2.51
11	2.44/2.76	2.42/2.67	2.39/2.58	2.38/2.54	2.36/2.49	2.35/2.45
11.5	2.38/2.72	2.36/2.62	2.33/2.54	2.32/2.49	2.30/2.44	2.29/2.40
12	2.33/2.68	2.30/2.58	2.28/2.49	2.26/2.44	2.25/2.39	2.23/2.36
12.5	2.28/2.64	2.25/2.54	2.23/2.45	2.21/2.40	2.19/2.35	2.18/2.31
13	2.23/2.61	2.20/2.50	2.18/2.41	2.16/2.36	2.14/2.30	2.13/2.27
13.5	2.18/2.57	2.15/2.47	2.13/2.37	2.11/2.32	2.09/2.26	2.08/2.23
14	2.13/2.54	2.11/2.43	2.08/2.34	2.07/2.29	2.05/2.23	2.03/2.19

Table 20.14 Erosion Factors for Single Axles and Tandem Axles (aggregate interlock joints, without concrete shoulder)

Slab Thickness (in.)	k of Subgrade-Subbase (lb/in^3) (Single Axle/Tandem Axle)					
	50	100	200	300	500	700
4	3.94/4.03	3.91/3.95	3.88/3.89	3.86/3.86	3.82/3.83	3.77/3.80
4.5	3.79/3.91	3.76/3.82	3.73/3.75	3.71/3.72	3.68/3.68	3.64/3.65
5	3.66/3.81	3.63/3.72	3.60/3.64	3.58/3.60	3.55/3.55	3.52/3.52
5.5	3.54/3.72	3.51/3.62	3.48/3.53	3.46/3.49	3.43/3.44	3.41/3.40
6	3.44/3.64	3.40/3.53	3.37/3.44	3.35/3.40	3.32/3.34	3.30/3.30
6.5	3.34/3.56	3.30/3.46	3.26/3.36	3.25/3.31	3.22/3.25	3.20/3.21
7	3.26/3.49	3.21/3.39	3.17/3.29	3.15/3.24	3.13/3.17	3.11/3.13
7.5	3.18/3.43	3.13/3.32	3.09/3.22	3.07/3.17	3.04/3.10	3.02/3.06
8	3.11/3.37	3.05/3.26	3.01/3.16	2.99/3.10	2.96/3.03	2.94/2.99
8.5	3.04/3.32	2.98/3.21	2.93/3.10	2.91/3.04	2.88/2.97	2.87/2.93
9	2.98/3.27	2.91/3.16	2.86/3.05	2.84/2.99	2.81/2.92	2.79/2.87
9.5	2.92/3.22	2.85/3.11	2.80/3.00	2.77/2.94	2.75/2.86	2.73/2.81
10	2.86/3.18	2.79/3.06	2.74/2.95	2.71/2.89	2.68/2.81	2.66/2.76
10.5	2.81/3.14	2.74/3.02	2.68/2.91	2.65/2.84	2.62/2.76	2.60/2.72
11	2.77/3.10	2.69/2.98	2.63/2.86	2.60/2.80	2.57/2.72	2.54/2.67
11.5	2.72/3.06	2.64/2.94	2.58/2.82	2.55/2.76	2.51/2.68	2.49/2.63
12	2.68/3.03	2.60/2.90	2.53/2.78	2.50/2.72	2.46/2.64	2.44/2.59
12.5	2.64/2.99	2.55/2.87	2.48/2.75	2.45/2.68	2.41/2.60	2.39/2.55
13	2.60/2.96	2.51/2.83	2.44/2.71	2.40/2.65	2.36/2.56	2.34/2.51
13.5	2.56/2.93	2.47/2.80	2.40/2.68	2.36/2.61	2.32/2.53	2.30/2.48
14	2.53/2.90	2.44/2.77	2.36/2.65	2.32/2.58	2.28/2.50	2.25/2.44

Example Designing a Rigid Pavement Using the PCA Method:

The following project and traffic data are available:

Four-lane interstate highway

Rolling terrain in rural location

Design period = 20 yr

Axle loads and expected repetitions are shown in table below

Subbase-subgrade k = 130 lb/in^3

Concrete modulus of rupture = 650 lb/in^2

Determine minimum thickness of a pavement with doweled joints and without concrete shoulders.

Axle load kips	Expected repetitions
Single axles	
30	6310
28	14690
26	30140
24	64410
22	106900
20	235800
18	307200
16	422500
14	586900
12	1837000
Tandem axles	
52	21320
48	42810
44	124900
40	372900
36	885800
32	930700
28	1656000
24	984900
20	1227000
16	1356000

Answer: Step 1. Fatigue Analysis:

1. Select a trial thickness (10 in).

2. Complete columns 1, 2, and 3 as shown (1 & 3 are given):

   LSF = 1.2 (interstate highway)

1	2	3	4	5	6	7
Axle load (kips)	(1) × LSF	Expected repetitions	Fatigue Analysis		Erosion Analysis	
			Allowable repetitions	Fatigue % [(3)÷(4)]×100	Allowable repetitions	Damage % [(3)÷(6)]×100
Single Axles						
30	36	6310	75000	8.4	2300000	0.3
28	33.6	14690	240000	6.1	3500000	0.4
26	31.2	30140	900000	3.3	5600000	0.5
24	28.8	64410	10000000	0.6	9100000	0.7
22	26.4	106900	unlimited	0	19500000	0.5
20	24	235800	unlimited	0	43000000	0.5
18	21.6	307200	unlimited	0	unlimited	0
16	19.2	422500	unlimited	0	unlimited	0
14	16.8	586900	unlimited	0	unlimited	0
12	14.4	1837000	unlimited	0	unlimited	0
Tandem Axles						
52	62.4	21320	6000000	0.36	1400000	1.5
48	57.6	42810	unlimited	0	2000000	2.1
44	52.8	124900	unlimited	0	3500000	3.6
40	48	372900	unlimited	0	7000000	5.3
36	43.2	885800	unlimited	0	15000000	5.9
32	38.4	930700	unlimited	0	40000000	2.3
28	33.6	1656000	unlimited	0	unlimited	0
24	28.8	984900	unlimited	0	unlimited	0
20	24	1227000	unlimited	0	unlimited	0
16	19.2	1356000	unlimited	0	unlimited	0
Total				18.76		23.6

3. Complete column (4): Determine the equivalent stresses for single axle and tandem axle. Table 20.11 is used in this case since there is no concrete shoulder. Interpolating for k = 130

For single axles and 10 in. thick slab:

$$\textbf{Equivalent stress} = 200 - \frac{200-186}{50} \times 30 = 191.6\ lb/in^2 \text{ (Interpolation)}$$

For tandem axles and 10 in. thick slab:

$$\textbf{Equivalent stress} = 193 - \frac{193-173}{50} \times 30 = 181\ Ib/in^2 \text{ (Interpolation)}$$

4. Determine the stress ratio , which is the equivalent stress divided by the modulus of rupture:

For single axles: $\text{Stress ratio} = \frac{\text{equivalent stress}}{\text{modulus of rupture}} = \frac{191.6}{650} = 0.295$

For tandem axles: $\text{Stress ratio} = \frac{\text{equivalent stress}}{\text{modulus of rupture}} = \frac{181}{650} = 0.278$

5. Using Figure 20.15, determine the allowable load repetitions for each axle load based on fatigue analysis.

6. Determine the fatigue percentage for each axle load, which is an indication of the resistance consumed by the expected number of axle load repetitions:

$$\text{Fatigue percentage} = \frac{\text{Column (3)}}{\text{Column (4)}} \times 100$$

7. Determine total fatigue resistance consumed by summing up column 5 (single and tandem axles) which is 18.76%. If this total does not exceed 100%, the assumed thickness is adequate for fatigue resistance for the design period.

Step 2. Erosion Analysis:

1. Determine the erosion factor for the single and tandem axle loads using Table 20.13.

For single axles: $\text{Erosion factor} = 2.54 - \frac{2.54-2.51}{100} \times 30 = 2.531$

For tandem axles: $\text{Erosion factor} = 2.76 - \frac{2.76-2.68}{100} \times 30 = 2.736$

2. Determine the allowable axle repetitions for each axle load based on erosion analysis using either Figure 20.16 or Figure 20.17. In this problem, Figure 20.16 will be used as the pavement has no concrete shoulder. Enter these values under column 6.

3. Determine erosion damage percentage for each axle load; that is, divide column 3 by column 6. Enter these values in column 7.
4. Determine the total erosion damage by summing column 7 (single and tandem axles). In this problem, total damage is 19.08%.

The results indicate that 10 in. is adequate for both fatigue and erosion analysis. Since the total fatigue and erosion damages for each analysis are much lower than 100 %. In order to achieve the most economic section for the design period, trial runs should be made until the minimum pavement thickness that satisfies both analyses is obtained.

Now let's try 9.5 in

1	2	3	4	5	6	7
Axle load (kips)	(1) × LSF	Expected repetitions	Fatigue Analysis		Erosion Analysis	
			Allowable repetitions	Fatigue % [(3)÷(4)]×100	Allowable repetitions	Damage % [(3)÷(6)]×100
Single Axles						
30	36	6310	27000	23.3	1500000	0.4
28	33.6	14690	77000	19.1	2200000	0.7
26	31.2	30140	230000	13.1	3500000	0.9
24	28.8	64410	1200000	5.4	5900000	1.1
22	26.4	106900	Unlimited	0	11000000	1.0
20	24	235800	Unlimited	0	23000000	1.0
18	21.6	307200	Unlimited	0	64000000	0.5
16	19.2	422500	Unlimited	0	Unlimited	0
14	16.8	586900	Unlimited	0	Unlimited	0
12	14.4	1837000	Unlimited	0	Unlimited	0
Tandem Axles						
52	62.4	21320	1100000	1.9	920000	2.3
48	57.6	42810	Unlimited	0	1500000	2.9
44	52.8	124900	Unlimited	0	2500000	5.0
40	48	372900	Unlimited	0	4600000	8.1
36	43.2	885800	Unlimited	0	9500000	9.3
32	38.4	930700	Unlimited	0	24000000	3.9
28	33.6	1656000	Unlimited	0	92000000	1.8
24	28.8	984900	Unlimited	0	Unlimited	0
20	24	1227000	Unlimited	0	Unlimited	0
16	19.2	1356000	Unlimited	0	Unlimited	0
Total				62.8		38.9

The results indicate that 9.5 in. is adequate for both fatigue and erosion analysis and it is more economic than 10 in. Since the total fatigue and erosion damages for each analysis are much lower than 100 %. In order to achieve the most economic section for the design period, trial runs should be made until the minimum pavement thickness that satisfies both analyses is obtained.

Now let's try 9 in

1	2	3	4	5	6	7
Axle load (kips)	(1) × LSF	Expected repetitions	Fatigue Analysis		Erosion Analysis	
			Allowable repetitions	Fatigue % [(3)÷(4)]×100	Allowable repetitions	Damage % [(3)÷(6)]×100
Single Axles						
30	36	6310	5900	106.9		
28	33.6	14690	21500			
26	31.2	30140	61000			
24	28.8	64410	190000			
22	26.4	106900	900000			
20	24	235800	Unlimited			
18	21.6	307200	Unlimited			
16	19.2	422500	Unlimited			
14	16.8	586900	Unlimited			
12	14.4	1837000	Unlimited			
Tandem Axles						
52	62.4	21320	280000			
48	57.6	42810	1300000			
44	52.8	124900	Unlimited			
40	48	372900	Unlimited			
36	43.2	885800	Unlimited			
32	38.4	930700	Unlimited			
28	33.6	1656000	Unlimited			
24	28.8	984900	Unlimited			
20	24	1227000	Unlimited			
16	19.2	1356000	Unlimited			
Total						

Step 1. Fatigue Analysis:

For single axles and 9 in. thick slab:

$$\text{Equivalent stress } = 232 - \frac{232-216}{50} \times 30 = 222.4\ Ib/in^2 \text{ (Interpolation)}$$

For tandem axles and 9 in. thick slab:

$$\text{Equivalent stress } = 218 - \frac{218-195}{50} \times 30 = 204.2\ Ib/in^2 \text{ (Interpolation)}$$

For single axles: $\text{Stress ratio } = \frac{\text{equivalent stress}}{\text{modulus of rupture}} = \frac{222.4}{650} = 0.342$

For tandem axles: $\text{Stress ratio } = \frac{\text{equivalent stress}}{\text{modulus of rupture}} = \frac{204.2}{650} = 0.314$

9 in is not adequate thickness. Select 9.5 in.

Lecture 10 - 13/07/2020

Thickness Design of Rigid Pavements

AASHTO Rigid Pavement Design

Design Considerations:

The factors considered in the AASHTO procedure for the design of rigid pavements as presented in the 1993 guide are:

• Pavement performance

• Subgrade strength

• Subbase strength

• Traffic

• Concrete properties

• Drainage

• Reliability

Joint load transfer coefficient (J):

The load transfer coefficient (J) is a factor used in rigid pavement design to account for the ability of a concrete pavement to distribute (transfer) load across discontinuities, such as longitudinal and transverse joints.

Table 2.6. **Recommended Load Transfer Coefficient for Various Pavement Types and Design Conditions**

Shoulder	Asphalt		Tied P.C.C.	
Load Transfer Devices	Yes	No	Yes	No
Pavement Type				
1. Plain jointed and jointed reinforced	3.2	3.8–4.4	2.5–3.1	3.6–4.2
2. CRCP	2.9–3.2	N/A	2.3–2.9	N/A

Pavement Type (no tied shoulders)	*J*
JCP/JRCP w/ load transfer devices	3.2
JCP/JRCP w/out load transfer devices	3.8-4.4
CRCP	2.9

Drainage coefficient C_d:

Table 20.9 Recommended Values for Drainage Coefficient, C_d, for Rigid 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	1.2–1.20	1.20–1.15	1.15–1.10	1.10
Good	1.20–1.15	1.15–1.10	1.10–1.00	1.00
Fair	1.15–1.10	1.10–1.00	1.00–0.90	0.90
Poor	1.10–1.00	1.00–0.90	0.90–0.80	0.80
Very poor	1.00–0.90	0.90–0.80	0.80–0.70	0.70

PCC Modulus of Elasticity E_c

- Measure directly per ASTM C469
- Correlation w/ compressive strength:

$$E_c = 57{,}000\,(f_c')^{0.5}$$

E_c = elastic modulus (psi)
f_c' = compressive strength (psi) per AASHTO T22, T140, or ASTM C39

Modulus of Subgrade Reaction (k)

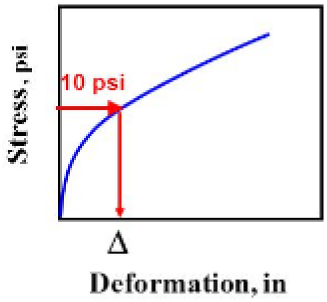
•Required for rigid pavement design.

$$K = \frac{P}{\Delta}$$

K = modulus of subgrade reaction

P = unit load on the plate (stress) (psi)

Δ = deflection of the plate (in)



- ***For design use stress P = 10 psi (68.95 kN/m²)***

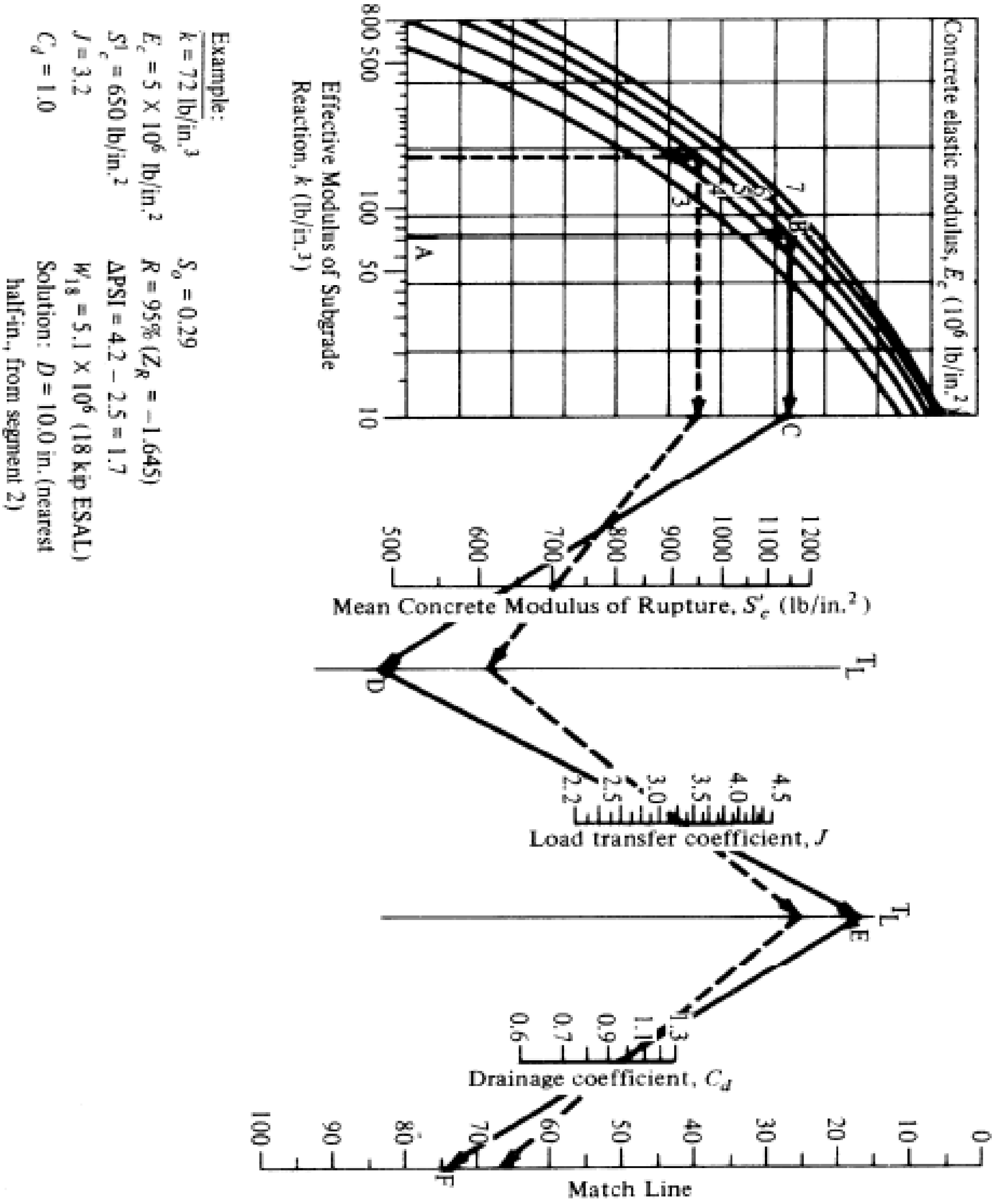
Tensile Strength

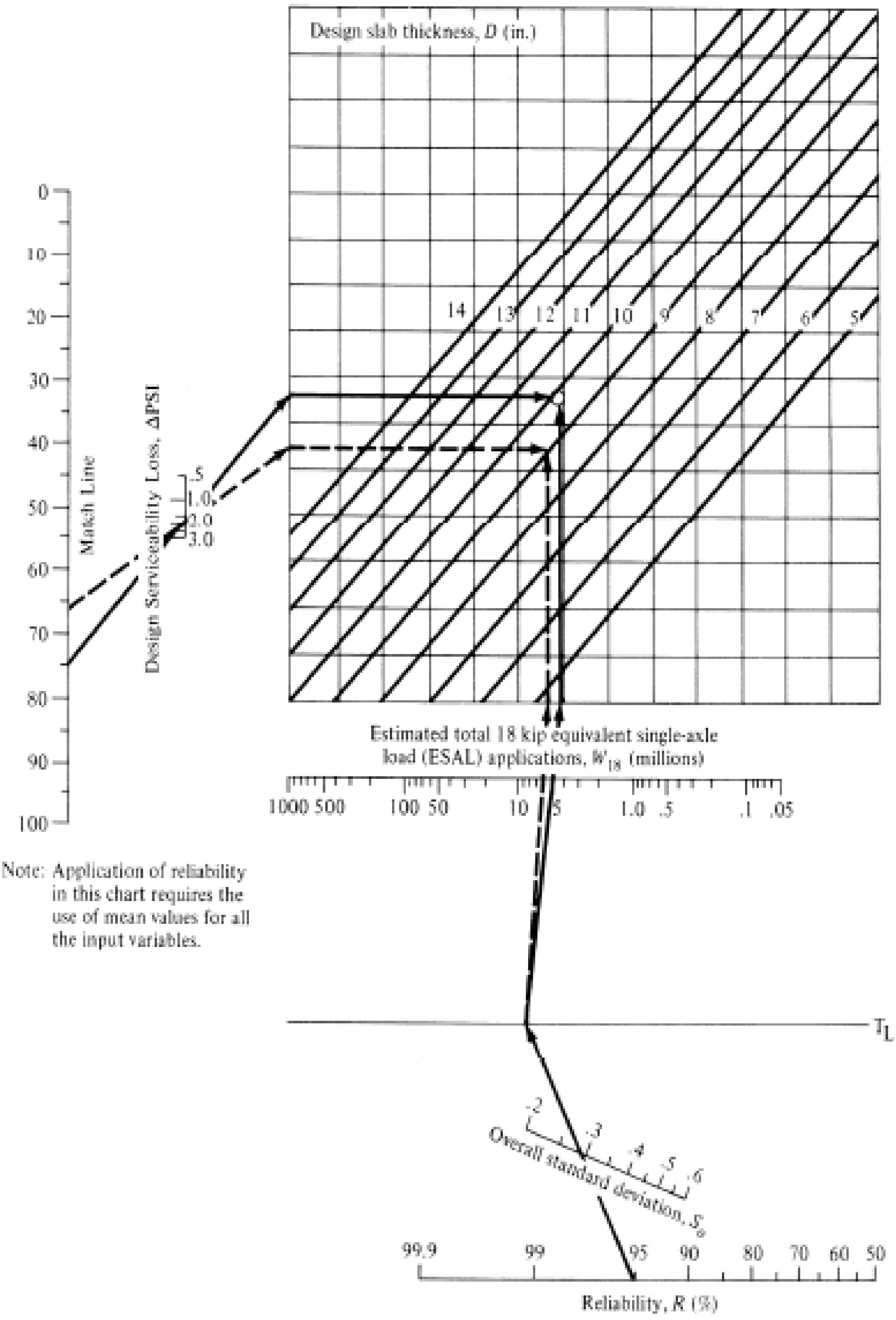
Tensile strength ~ 8% to 15% of f'_c

- Modulus of Rupture, f_r
  - For deflection calculations, use:

$$f_r = 0.7\sqrt{f'_c\ (MPa)} \qquad \text{ACI Eq. 9-10}$$

S_c or f_r = Modulus of rupture (psi)


Concrete elastic modulus, E_c (10^6 lb/in.^{2})
Effective Modulus of Subgrade Reaction, k (lb/in.^{3})
Mean Concrete Modulus of Rupture, S'_c (lb/in.^{2})
T_L
Load transfer coefficient, J
Drainage coefficient, C_d
Match Line
Example:
$k = 72$ lb/in.^{3}
$E_c = 5 \times 10^6$ lb/in.^{2}
$S'_c = 650$ lb/in.^{2}
$J = 3.2$
$C_d = 1.0$
$S_o = 0.29$
$R = 95\%$ ($Z_R = -1.645$)
$\Delta PSI = 4.2 - 2.5 = 1.7$
$W_{18} = 5.1 \times 10^6$ (18 kip ESAL)
Solution: $D = 10.0$ in. (nearest half-in., from segment 2)



Note: Application of reliability in this chart requires the use of mean values for all the input variables.

Example: Designing a Rigid Pavement Using the AASHTO Method

Effective modulus of subgrade reaction, $k = 72\ lb/in^3$

Concrete Elastic Modulus $E_c = 5 \times 10^6\ lb/in^2$

Mean concrete modulus of rupture, $S_c = 650\ lb/in^2$

Load transfer coefficient, J = 3.2

Drainage coefficient, $C_d = 1.0$

Design serviceability loss, ΔPSI = 4.5 - 2.5 = 2.0

Reliability, R% = 95% (ZR = 1.645)

Overall standard deviation, $S_o = 0.29$

Cumulative 18 kip ESAL = $(5 * 10^6)$