Chapter 7, Part 2
Rigid Pavement Design

AN-NAJAH NATIONAL UNIVERSITY
NABLUS, PALESTINE

Outline: Chapter 7

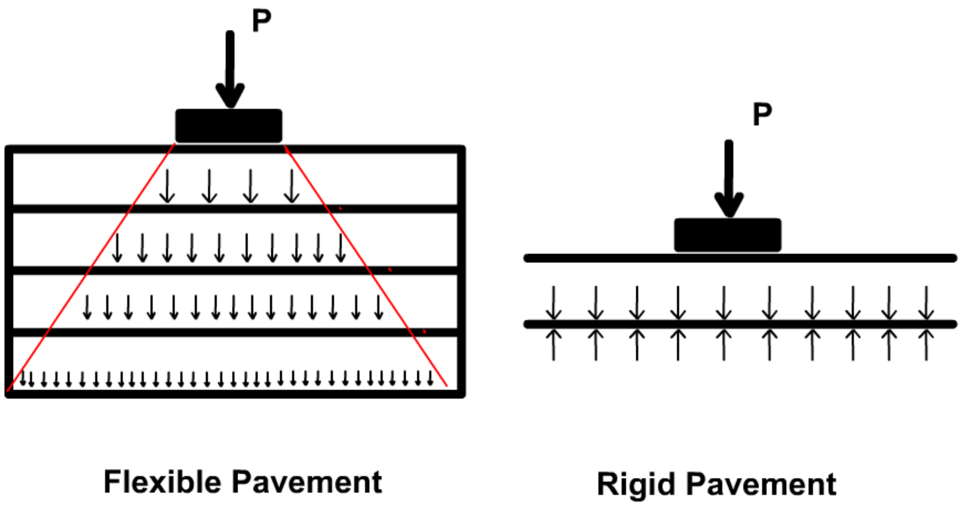
7.1 Flexible Pavement Design

7.2 Rigid Pavement Design

7.2 Rigid Pavement Design

Rigid Pavement Design

- Rigid highway pavements are normally constructed of Portland cement concrete (PCC)
  - may or may not have a base course
- When a base course is used, it is usually referred to as a **subbase course**.
- Concrete surface only is referred to as **rigid pavement**.



Rigid Pavement Design

- Rigid pavements have some flexural strength that permits them to sustain a beam like action
  - across minor irregularities in the underlying material
- Properly designed and constructed rigid pavements have:

  ① **long service lives**

  ② **less expensive to maintain than the flexible pavements**

Materials Used in Rigid Pavements

- The Portland cement concrete consists of:

1. **Portland cement:**
    - It is manufactured by crushing and pulverizing a carefully prepared mix of limestone, marl, and clay or shale.
    - The AASHTO specifications list five main types of Portland cements.

Materials Used in Rigid Pavements

1. Portland cement:

Table 4.13 The AASHTO Specification For Portland Cement Types

Type I	is suitable for general concrete construction, where no special properties are required. A manufacturer will supply this type of cement when no specific type is requested.
Type II	is suitable for user in general concrete construction, where the concrete will exposed to moderate action of sluphate or where moderate heat of hydration is required.
Type III	is suitable for user in general concrete construction that required a high concrete strength in a relatively short time. It is sometimes referred to as high strength cement.
Types IA, IIA, and IIIA	are similar to types I, II, and III respectively, but contain a small amount (4 percent to 8 percent of total mix) of entrapped air. This is achieved during production by thoroughly mixing the cement with air-entraining agents and grinding the mixture. In addition to the properties listed for types I, II, and III, type IA, IIA, and IIIA are more resistant to chloride and de-icing salts and are therefore more durable.
Type IV	is suitable for projects where low heat of hydration is necessary.
Type V	is used in concrete construction projects where the concrete will be exposed to high sulphate action.

Materials Used in Rigid Pavements

2. Coarse aggregates:

- They are inert materials that do not react with cement and are usually comprised of crushed gravel, stone, or blast furnace slag
- Major requirements is gradation

Table 20.2 Gradation Requirements for Aggregates in Portland Cement Concrete (ASTM Designation C33)

	Percent Passing by Weight		
	Aggregate Designation		
Sieve Designation	*2 in. to No. 4 (357)*	*1 in. to No. 4 (467)*	*1 in. to No. 4 (57)*
2½ in. (63 mm)	100	—	—
2 in. (50 mm)	95–100	100	—
1½ in. (37.5 mm)	—	95–100	100
1 in. (25.0 mm)	35–70	—	95–100
¾ in. (19.0 mm)	—	35–70	—
½ in. (12.5 mm)	10–30	—	25–60
⅜ in. (9.5 mm)	—	10–30	—
No. 4 (4.75 mm)	0–5	0–5	0–10
No. 8 (2.36 mm)	—	—	0–5

SOURCE: Adapted from *ASTM Standards, Concrete and Aggregates*, Vol. 04.02, American Society for Testing and Materials, Philadelphia, PA, October 2007.

Materials Used in Rigid Pavements

2. Coarse aggregates:

- Well graded
- It must have the ability to resist abrasion (تآكل) and the soundness (متانة)
- **Soundness:** the ability of the aggregate to resist breaking up due to freezing and thawing.

Materials Used in Rigid Pavements

3. Fine Aggregates:

- Sand is mainly used as the fine aggregate
- **Soundness requirement**: a maximum of 10 percent weight loss is usually specified
- **Cleanliness**: the maximum amounts of different types of deleterious materials contained in the fine aggregates.
  - *It includes limitations in the presence of large amounts of organic material which may reduce the hardening properties of the cement,*

Materials Used in Rigid Pavements

3. Fine Aggregates:

Table 20.3 AASHTO-Recommended Particle Size Distribution for Fine Aggregates Used in Portland Cement Concrete

Sieve (M 92)	*Mass Percent Passing*
⅜ in. (9.5 mm)	100
No. 4 (4.75 mm)	95 to 100
No. 8 (2.36 mm)	80 to 100
No. 16 (1.18 mm)	50 to 85
No. 30 (600 μm)	25 to 60
No. 50 (300 μm)	10 to 30
No. 100 (μm)	2 to 10

SOURCE: Adapted with permission from *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, American Association of State Highway and Transportation Officials, Washington, D.C., 2007.

Materials Used in Rigid Pavements

4. Water:

- The water used should be suitable for drinking.
  - *The quantity of organic matter, oil, acids, and alkalies should not be greater than the allowable amount in drinking water.*

Materials Used in Rigid Pavements

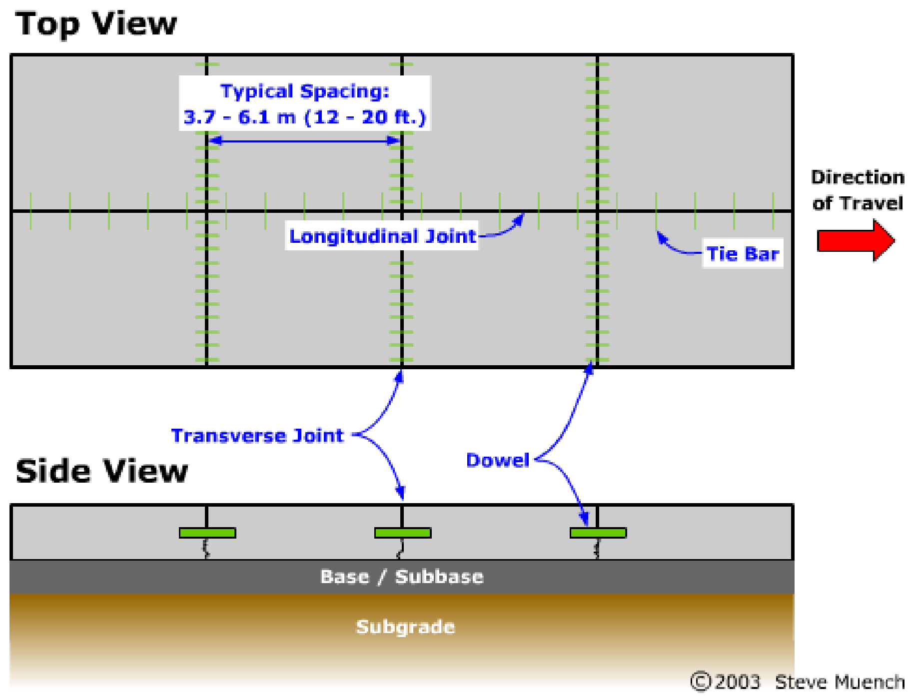
5. Reinforcing steel:

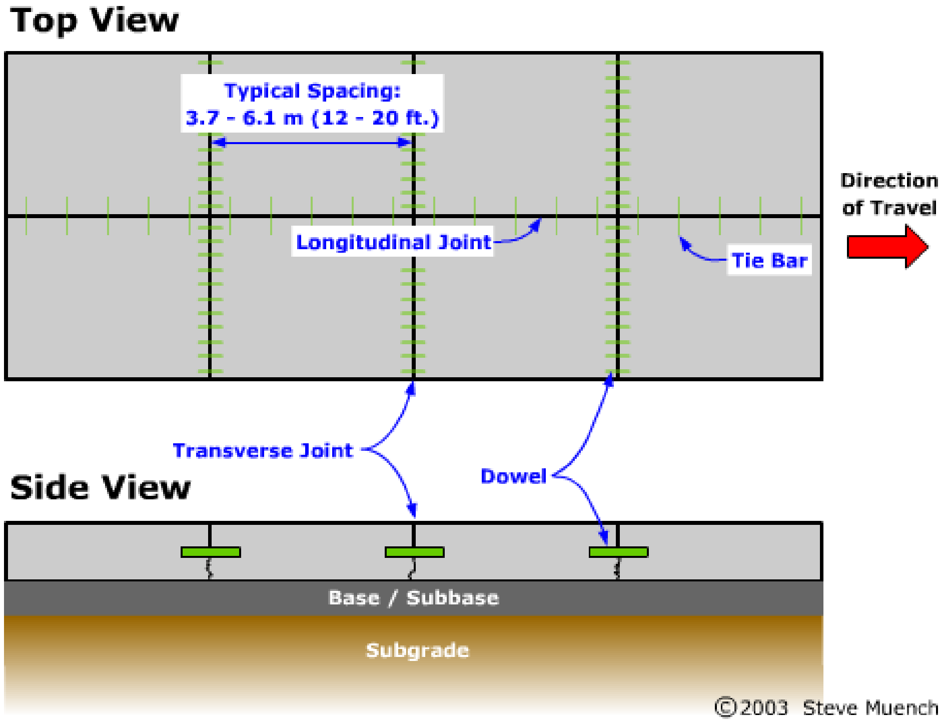
- Steel reinforcing may be used to
  1. reduce and control the amount of cracking that occurs

     Temperature steel
  2. as a load transfer mechanism at joints

     Dowel Bars
  3. as a means of tying two slabs together

     Tie Bars




Top View
Typical Spacing:
3.7 - 6.1 m (12 - 20 ft.)
Longitudinal Joint
Tie Bar
Direction
of Travel
Transverse Joint
Dowel
Side View
Base / Subbase
Subgrade
©2003 Steve Muench


shutterstock
IMAGE ID: 775422733
www.shutterstock.com

Materials Used in Rigid Pavements

a. Temperature Steel:

- Temperature steel does not prevent cracking of the slab,
  - It does control the crack widths because the steel acts as a tie holding the edges of the cracks together
  - It maintains the shearing resistance of the pavement, thereby maintaining its capacity to carry traffic load, even though the flexural strength is not improved.

Materials Used in Rigid Pavements

a. Temperature Steel:

- A bar mat or wire mesh consisting of longitudinal and transverse steel wires welded at regular intervals.
- Mesh is placed about 3 in. below the surface
- Cross-sectional area of the steel per foot width of the slab depends on the size and spacing of the used steel wires

Materials Used in Rigid Pavements

a. Temperature Steel:

- The amount of steel required depends on
  - Length of the pavement between expansion joints
  - Maximum stress desired in concrete pavement
  - Thickness of the pavement
  - Moduli of elasticity of the concrete and steel

Materials Used in Rigid Pavements

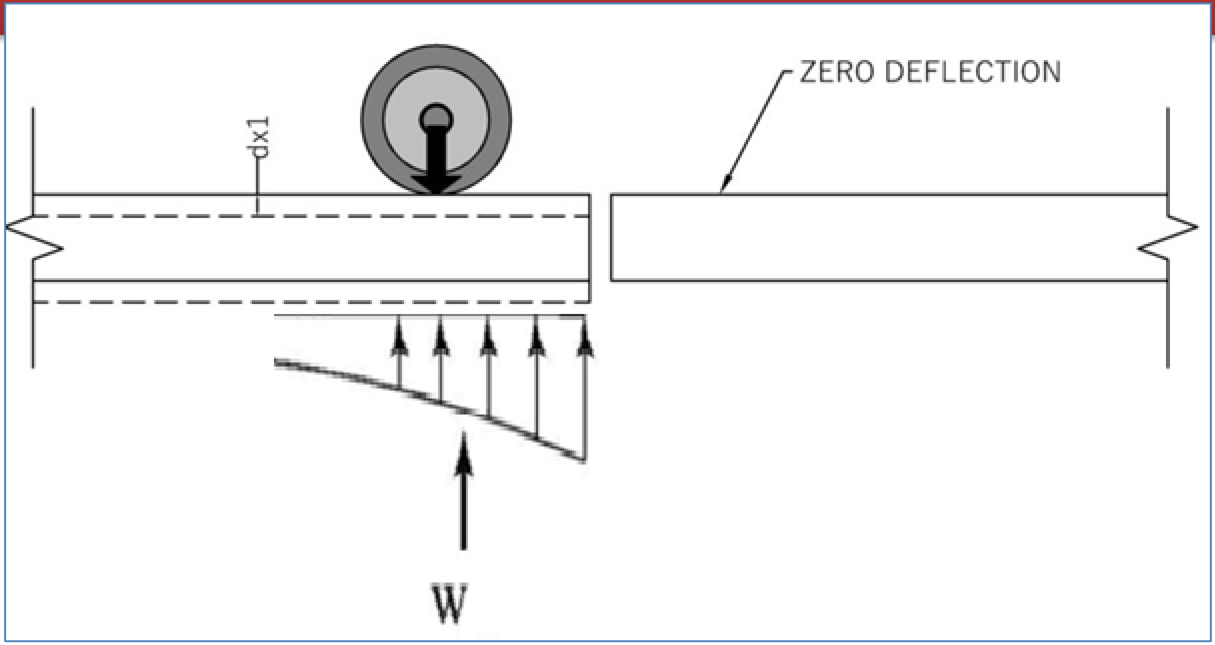
a. Temperature Steel:

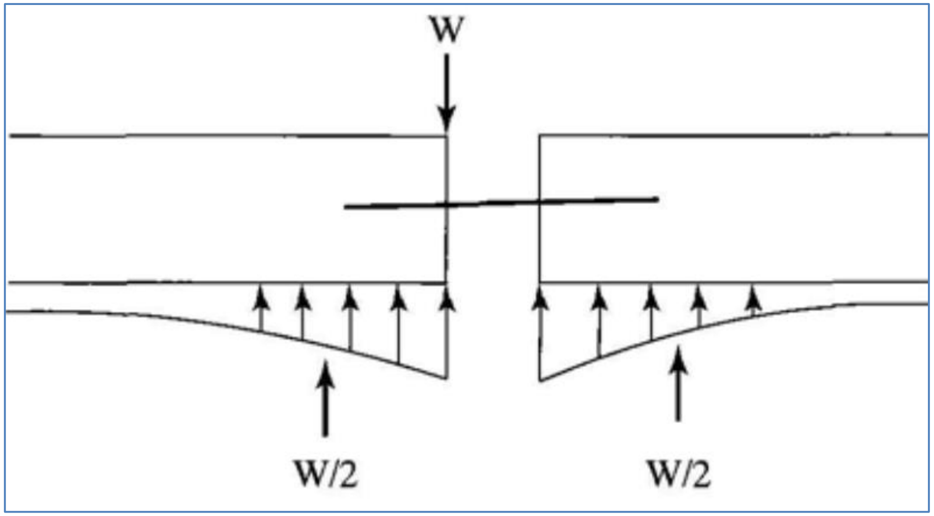
- General guidelines for the minimum cross sectional area of the temperature steel.
  - At least equal to 0.1 percent of the cross-sectional area of the slab
  - Longitudinal wires should not be less than No. 2 (0.258 in, 6.5 mm) gauge, spaced at a maximum distance of 6 in.
  - Transverse wires should not be less than No. 4 (0.2 in, 5.2 mm) gauge, spaced at a maximum distance of 12 in.

Materials Used in Rigid Pavements

b. Dowel Bars:

- **It is used as load-transfer mechanism across joints**
- They provide flexural shearing and bearing resistance
- They must be of a much larger diameter than the wires used in temperature steel
- Diameters of 1 – 1.5 in and lengths of 2-3 ft spaced at 1ft centers across the slab width.

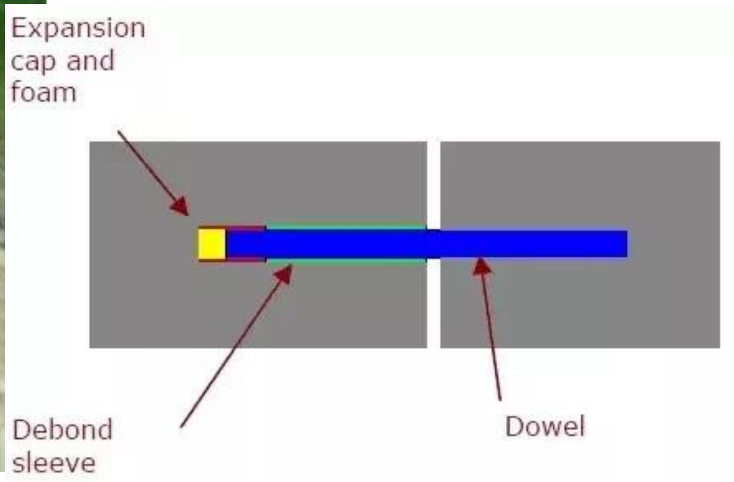

ZERO DEFLECTION
dx1
W


W
W/2
W/2

Materials Used in Rigid Pavements

b. Dowel Bars:

- At least one end of the bar should be smooth and lubricated to facilitate free expansion



Materials Used in Rigid Pavements

c. Tie Bars:

- Tie bars are used to tie two sections of the pavement together
  - 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
- They much smaller in diameter (¾ in) than the dowel bars and are spaced at larger canters (3 ft).

Materials Used in Rigid Pavements

c. Tie Bars:

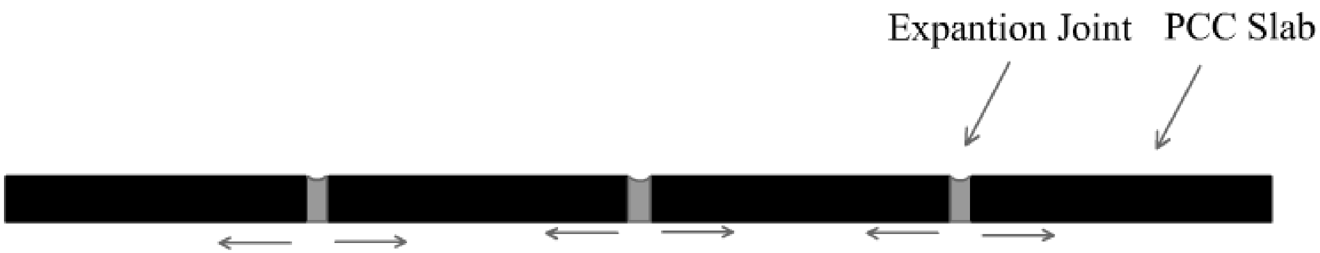
Joints in Concrete Pavements

- Different types of joints are placed to:
  - Limit the stress induced by temperature changes
  - Facilitate proper bonding of two adjacent sections of pavements when there is a time lapse between their construction
- These joints is divided into four categories
  - **Expansion joints**
  - **Contraction joints**
  - **Hinge joints**
  - **Construction joints**

Joints in Concrete Pavements

1. Expansion joints:

- They provide adequate space for the slab to expand
  - *when concrete pavement is subjected to an increase in temperature, it will expand, resulting in an increase in length of the slab*
  - *when the temperature is sufficiently high, the slab may buckle or "blow up"*
- They are placed transversely, at regular intervals



Joints in Concrete Pavements

1. Expansion joints:

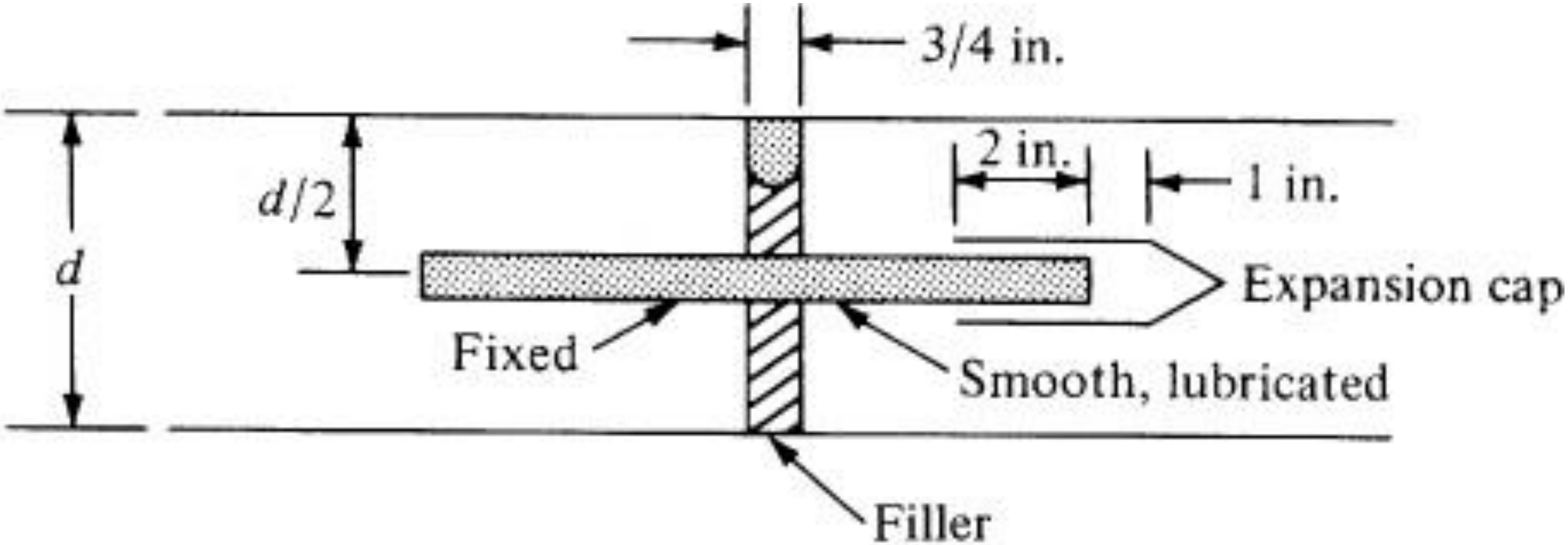


Figure 20.1 Typical Expansion Joint

Joints in Concrete Pavements

1. Expansion joints:

- They are placed across the full width of the slab and are **3/4 to 1 in**. wide
- The joint space is filled with a compressible filler material that permits the slab to expand.
- A smooth dowel bar is used as means of transferring the load across the joint space
  - Bars are lubricated on one side
  - Expansion cap is installed to provide a space for the dowel to occupy during expansion

Joints in Concrete Pavements

1. Expansion joints:

- Many countries no longer use it due to the inability of the load transfer mechanism to adequately transfer the load

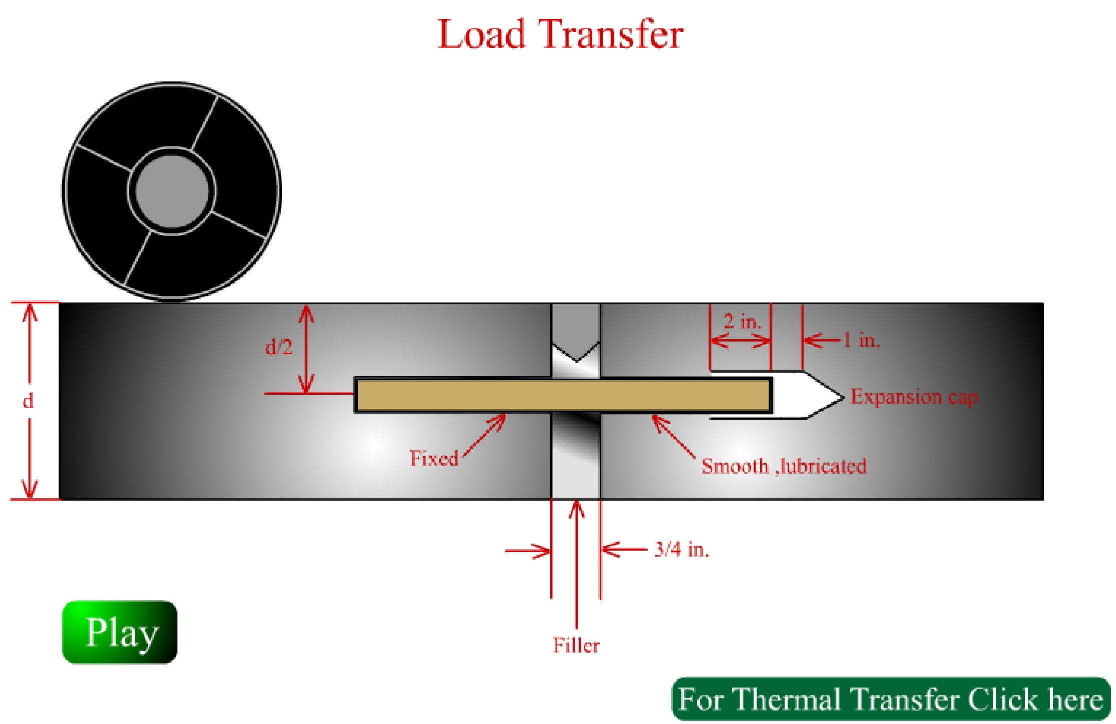
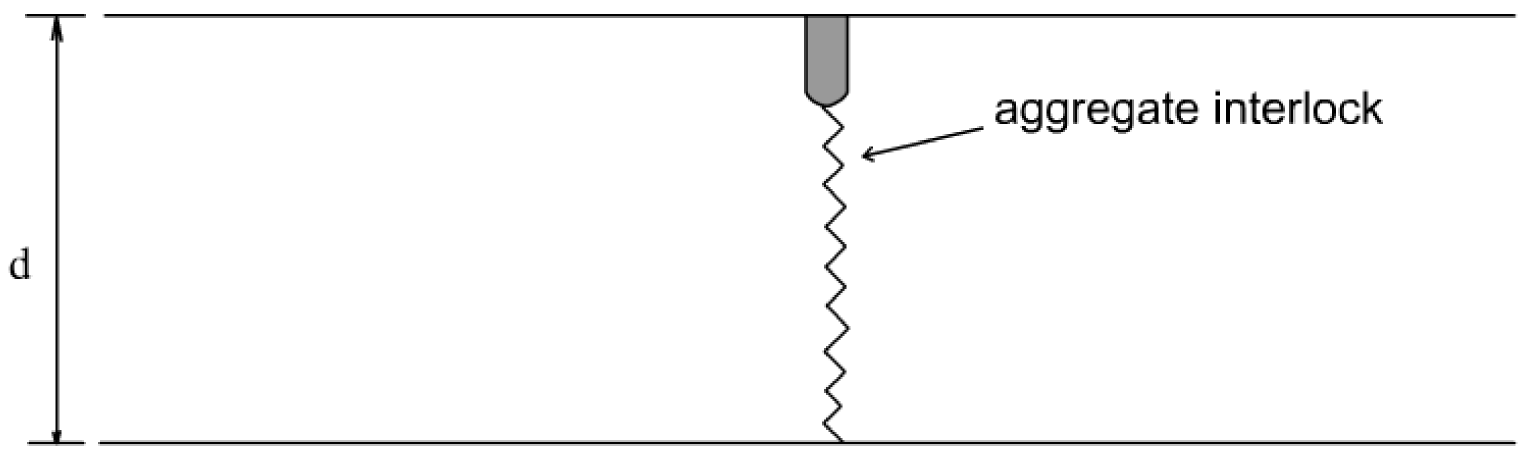


Figure 4.14 Load and Thermal Transfer

Joints in Concrete Pavements

2. Contraction joints:

- They are placed transversely at regular intervals across the width of the pavement
  - to release some of the tensile stresses that are induced due to the contraction **resulted from a decrease in temperature**



Joints in Concrete Pavements

2. Contraction joints:

- Load-transfer mechanism might be installed (**dowel bar**) when there is doubt about the ability of interlocking grains to transfer the load

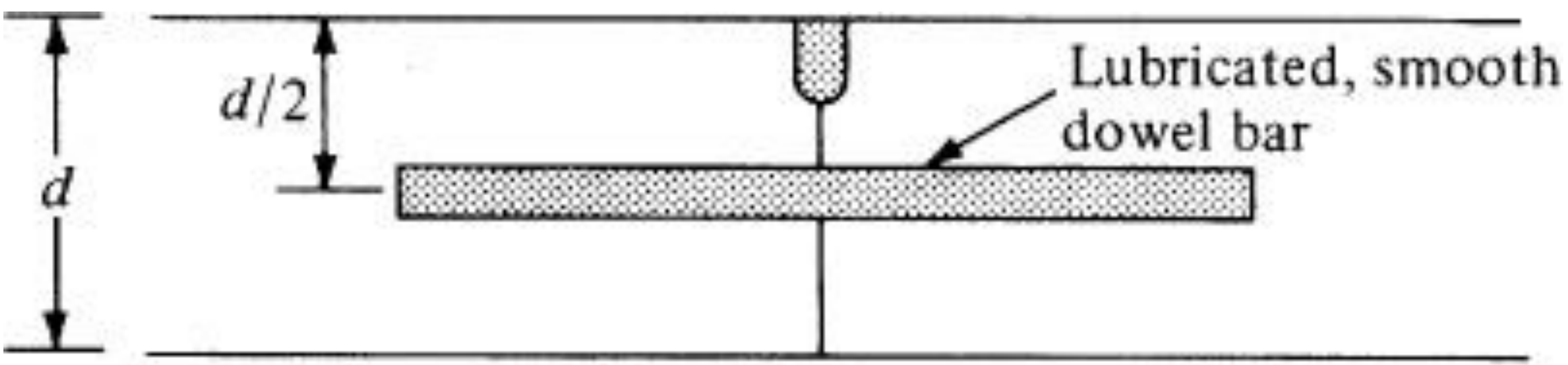


Figure 20.2 Typical Contraction Joint

Joints in Concrete Pavements

3. Hinge joints (keyed):

- They are used mainly to reduce cracking along the center line of highway pavements.

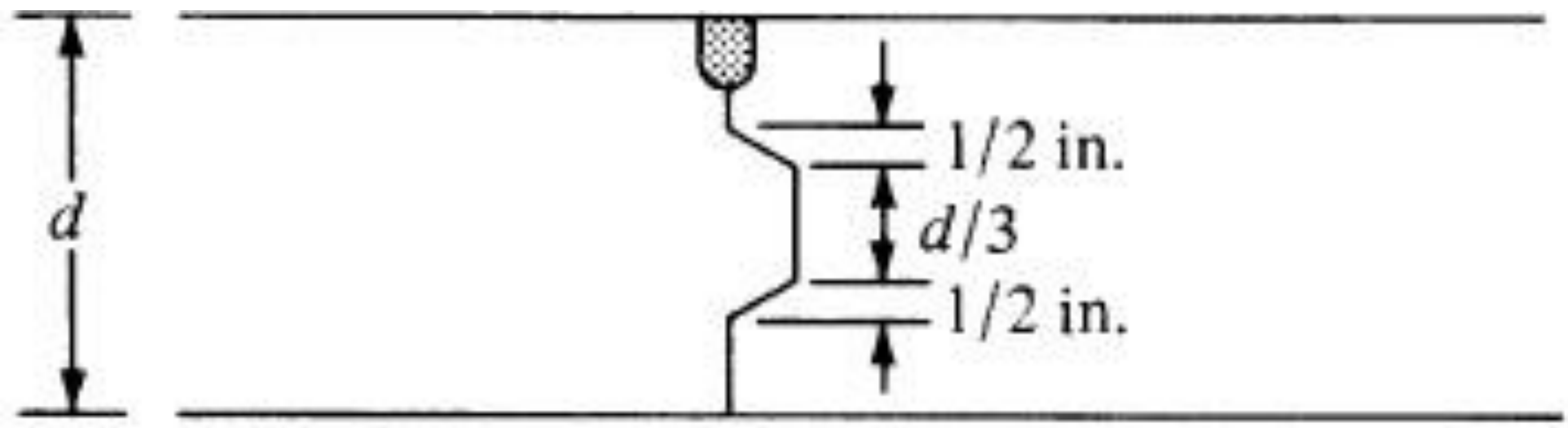


Figure 20.3 Typical Hinge Joint (Keyed Joint)

Joints in Concrete Pavements

4. Construction joints (Butt) :

- **They are placed transversely across the pavement width to provide suitable transition between concrete laid at different times**
- A keyed joint may also be used in the longitudinal direction when only a single lane is constructed at a time

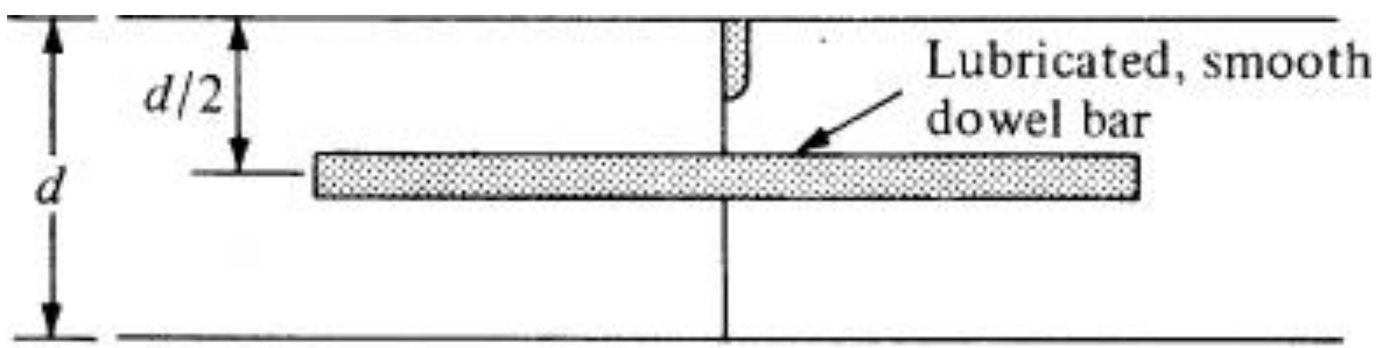


Figure 20.4 Typical Butt Joint

Types of Rigid Pavements

- They can be divided into three general types:

1. **Jointed Plain Concrete Pavements JPCP**
    - Used on low-volume highways or when cement-stabilized soils are used as subbase
    - It has no temperature steel or dowels for load transfer
    - Steel tie bars are often used to provide a hinge effect at longitudinal joints and to prevent the opening of these joints

Types of Rigid Pavements

1. **Jointed Plain Concrete Pavements JPCP**
   - Joints are placed at relatively shorter distances (3 to 6m) to reduce the amount of cracking
   - The traverse joints are skewed about 1.2 to 1.6 m in plan, such that only one wheel of a vehicle passes through the joint at a time
     - This helps to provide a smoother ride

Types of Rigid Pavements

2. Simply Reinforced Concrete Pavements SRCP

- They have dowels for the transfer of traffic loads across joints
- The joints spaced at larger distances, ranging from 10 to 33m
- Temperature steel is used throughout the slab
- Tie bars are also commonly used at longitudinal joints

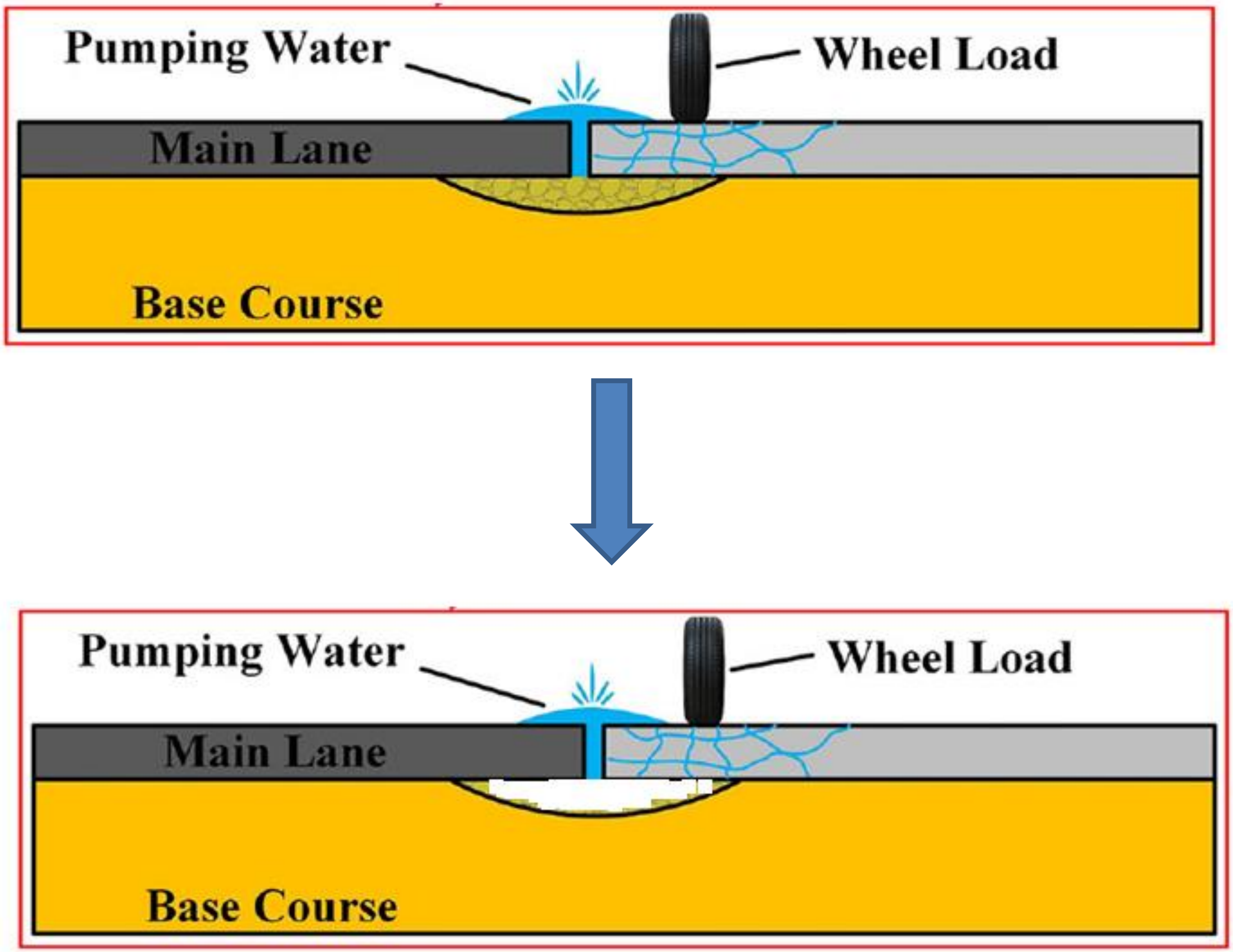
Types of Rigid Pavements

3. Continuously Reinforced Concrete Pavements CRCP

- They have no transverse joints
  - except construction joints or expansion joints when they are necessary
- They have a relatively high percentage of steel, with **the minimum usually at 0.6% of the cross section of the slab.**

Pumping of Rigid Pavements

- Pumping is an important phenomenon associated with rigid pavements
- **Pumping**: the discharge of water and subgrade (or subbase) material through joints, cracks, and along the pavement edges
- It is primarily caused by the repeated deflection of the pavement slab in the presence of accumulated water beneath it


Pumping Water
Wheel Load
Main Lane
Base Course
Pumping Water
Wheel Load
Main Lane
Base Course

Pumping of Rigid Pavements

- Visual manifestations of pumping include:
  - Discharge of water from cracks and joints
  - Spalling (تفتت) near the centerline of the pavement and a transverse crack or joint
  - Mud boils at the edge of the pavement
  - Pavement surface discoloration (caused by the subgrade soil)
  - Breaking of pavement at the corners

Pumping of Rigid Pavements

- Design consideration for preventing pumping:
  - Reduction or elimination of expansion joints, since pumping is usually associated with these joints
    - » This is the main reason why current design limit the number of expansion joints to a minimum
  - Replace soils that are susceptible to pumping with a nominal thickness of granular or sandy soils, or to improve them by stabilization
    - » Since pumping is associated with fine-grained soils

Stresses in Rigid Pavements

- Stresses are developed as the result of:
  - **Traffic wheel loads**
  - **Expansion and contraction of temperature changes**
  - **Yielding of the subbase or subgrade**
  - **Volumetric changes**

Stresses in Rigid Pavements

- The combination of these stresses make the problem complex, thus the following assumptions are made:
  - **Concrete pavement slabs are considered as unreinforced concrete beams**
  - **The combination of flexural and direct tensile stresses will surely result in transverse and longitudinal cracks**
  - **The supporting subbase and/or subgrade layer acts as an elastic material**

Stresses in Rigid Pavements

1. Stresses induced by bending:

– The ability to sustain a beam-like action across irregularities in the underlying materials suggests that the theory of bending is fundamental to the analysis of stresses in such pavements

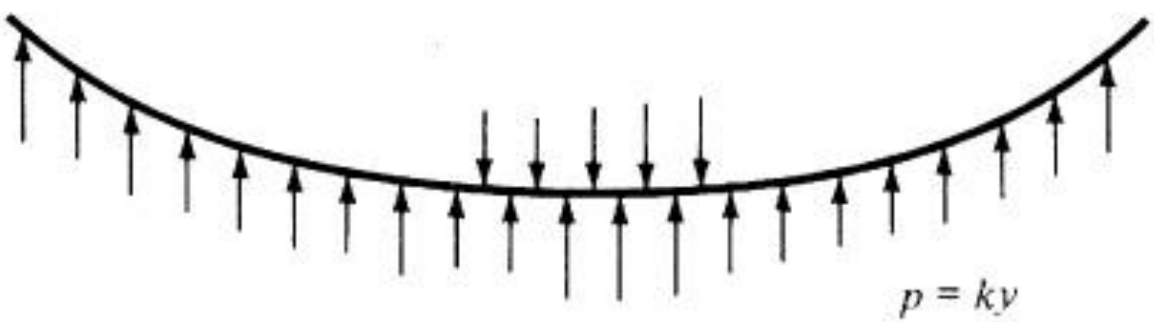


Figure 20.5 Deformation of a Beam on Elastic Foundation

Stresses in Rigid Pavements

1. Stresses induced by bending:

– The following figure shows the deformation sustained by a beam on an elastic foundation when it is loaded externally

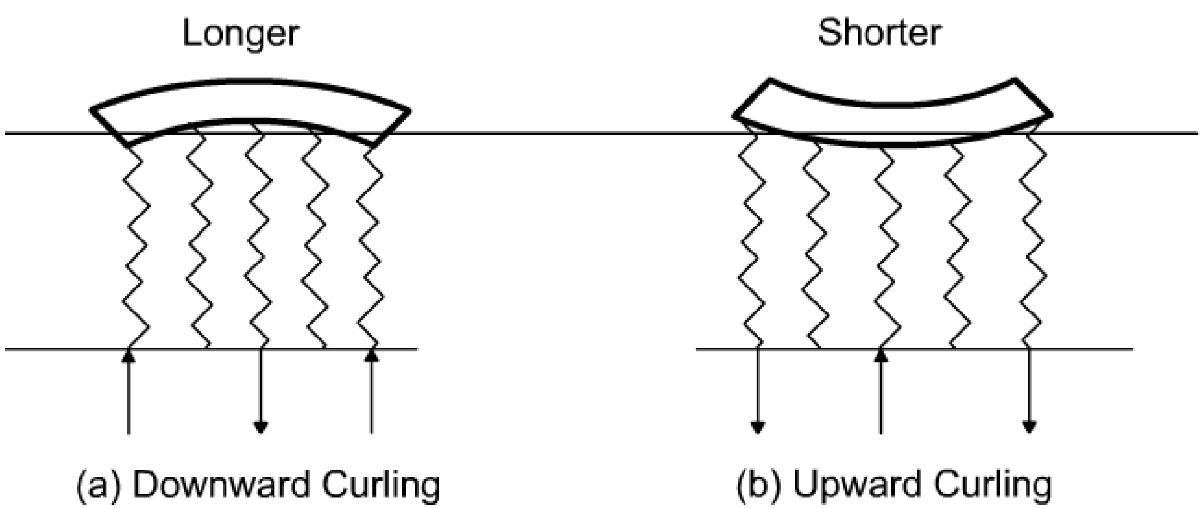
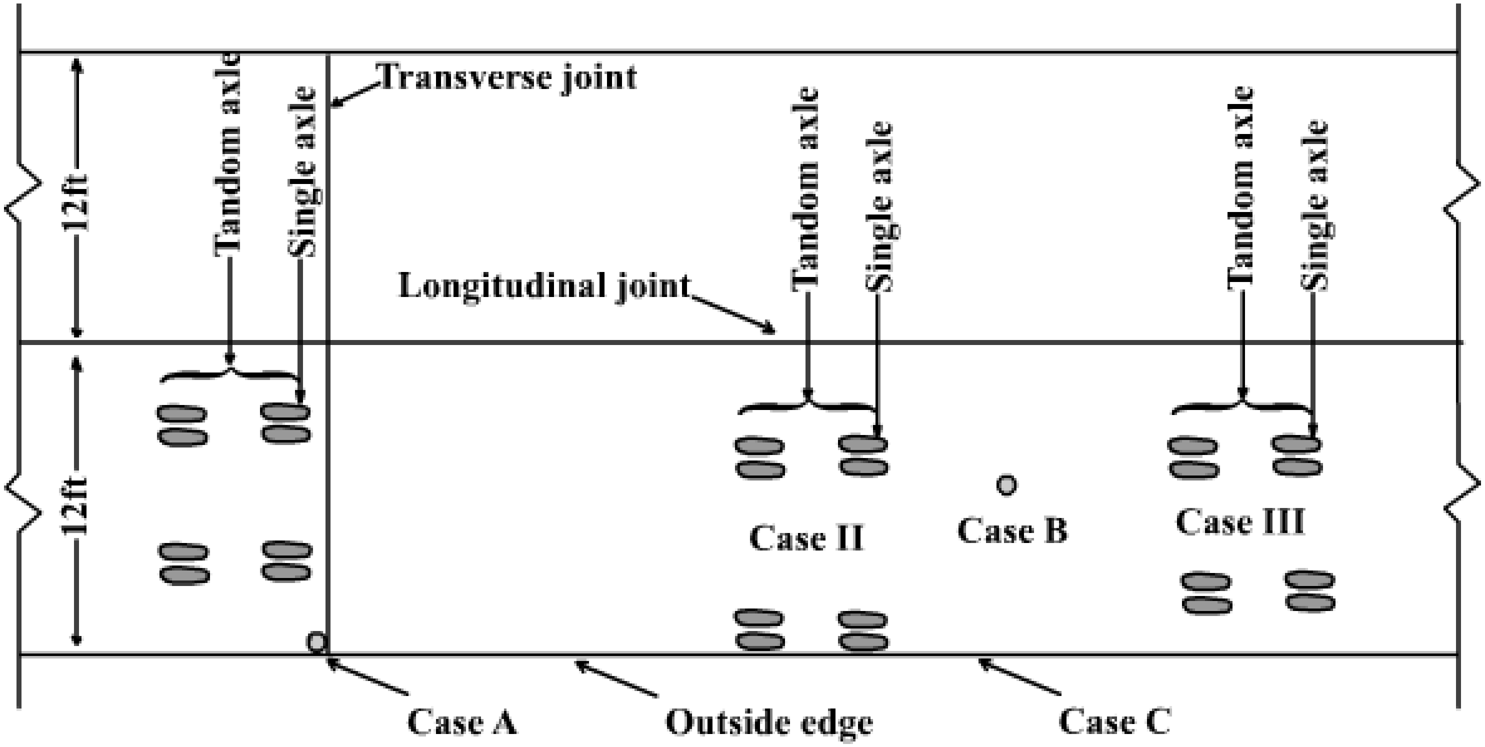


Figure 4.19 Curling of Slab due to Temprature Gradient

Stresses in Rigid Pavements

2. Stresses due to traffic wheel loads:

- Westergaard Equation
- There are three critical locations of the wheel load on the concrete pavement:



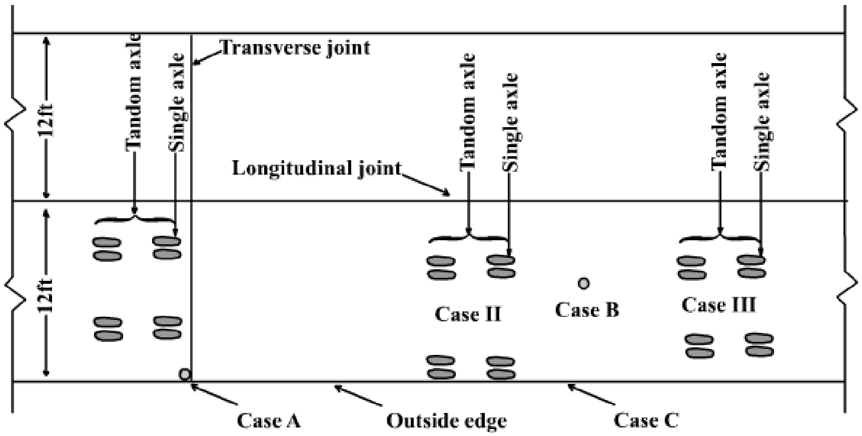
Stresses in Rigid Pavements

2. Stresses due to traffic wheel loads:

– **Case A**: the wheel load is applied at the intersection of the pavement edge and a transverse joint

– **Case B**: Load is applied at the interior of the slab

– **Case C**: Load is applied at the edge of the slab at considerable distance away from any corner



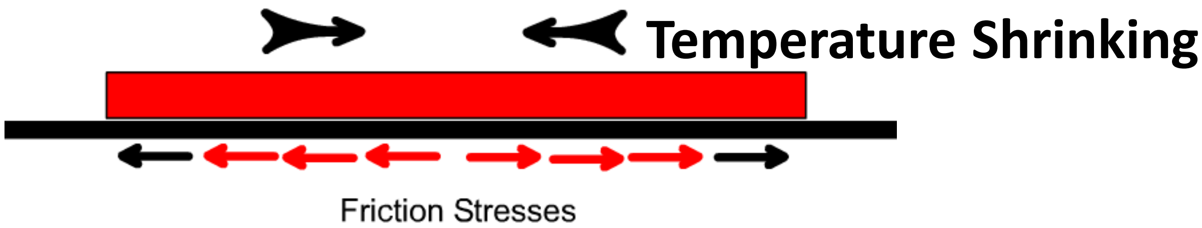
Stresses in Rigid Pavements

3. Stresses due to temperature effects:

– The tendency of the slab edges **to curl downward during the day** and **upward during the night** as a result of temperature gradients

» **This is resisted by the weight of the slab itself**

» This resistance tends to keep the slab in its original position, resulting in stresses being induced in the pavement



Stresses in Rigid Pavements

3. Stresses due to temperature effects:

- The curling stresses may be high enough to
  - » cause cracking of the pavement
  - » reduce the subgrade support beneath some sections
- Studies have shown **that curling stresses can be higher than 200 lb/in2 for 10 ft slabs and much higher for wider slabs**.

Thickness Design of Rigid Pavements

- **Objective:** determine the thickness of the concrete slab that will be adequate to carry the projected traffic load for the design period
- Two design methods are used extensively:
  - **AASHTO Method**
  - **American Concrete Pavement method**
- **AASHTO Method**: based on the results obtained from the AASHTO road test
  - It provides the determination of the pavement thickness and the amount of steel reinforcement if used, as well as the design of joints

AASHTO Method

- **Design considerations**
  - Factors considered in the AASHTO procedure in the 1993 guide are:
    1. **Pavement performance**
    2. **Subbase strength**
    3. **Subgrade strength**
    4. **Traffic**
    5. **Concrete properties**
    6. **Drainage**
    7. **Reliability**

AASHTO Method

1. **Pavement performance**
   - The same as flexible pavement
   - P_i may be taken as 4.5, and P_t may also be selected by the designer
2. **Subbase strength**
   - Graded granular materials or suitably stabilized materials
   - If the pavement may be subjected to frost action, the percentage of fines should be reduced to a minimum.

AASHTO Method

2. Subbase strength

– Thickness is usually not less than 6 in

– It should be extended 1 to 3 ft outside the edge of the pavement structure

Table 20.4 Recommended Particle Size Distributions for Different Types of Subbase Materials

	Types of Subbase					
Sieve Designation	*Type A*	*Type B*	*Type C (Cement Treated)*	*Type D (Lime Treated)*	*Type E (Bituminous Treated)*	*Type F (Granular)*
Sieve analysis percent passing						
2 in.	100	100	—	—	—	—
1 in.	—	75–95	100	100	100	100
⅜ in.	30–65	40–75	50–85	60–100	—	—
No. 4	25–55	30–60	35–65	50–85	55–100	70–100
No. 10	15–40	20–45	25–50	40–70	40–100	55–100
No. 40	8–20	15–30	15–30	25–45	20–50	30–70
No. 200	2–8	5–20	5–15	5–20	6–20	8–25
(The minus No. 200 material should be held to a practical minimum.)						
Compressive strength lb/in^2 at 28 days			400–750	100		
Stability						
Hveem Stabilometer					20 min	
Hubbard field					1000 min	
Marshall stability					500 min	
Marshall flow					20 max	
Soil constants						
Liquid limit	25 max	25 max				25 max
Plasticity index[a]	N.P.	6 max	10 max[b]		6 max[b]	6 max

AASHTO Method

3. Subgrade strength

- It is given in terms of the **Westergaard modulus of subgrade reaction k**
  - ✓ The load in lb/in^2 on a loaded area, divided by the deformation in inches
  - ✓ Obtained by conducting a plate-bearing test
- **Figure 20.8** shows an approximate interrelationship of soil classification and bearing values

AASHTO Method

3. **Subgrade strength**
   - The **effective modulus of subgrade reaction** ***k*** is determined considering:
     a. **Seasonal effect on the resilient modulus of the subgrade**
     b. **Type and thickness of subbase material**
     c. **Whether bedrock lies within 10 ft of the subgrade surface**
     d. **Effect of potential erosion of subbase**

AASHTO Method

a. Seasonal effect on the resilient modulus of the subgrade

- Procedure is similar to flexible pavement
- Relative damage *u* from **Figure 20.12**

b. Type and thickness of subbase material

- The composite modulus of subgrade reaction (k_{∞})depends on:
  - » **Subbase elastic modulus E_{SB}**
  - » **Roadbed resilient modulus**
  - » **Subbase thickness**

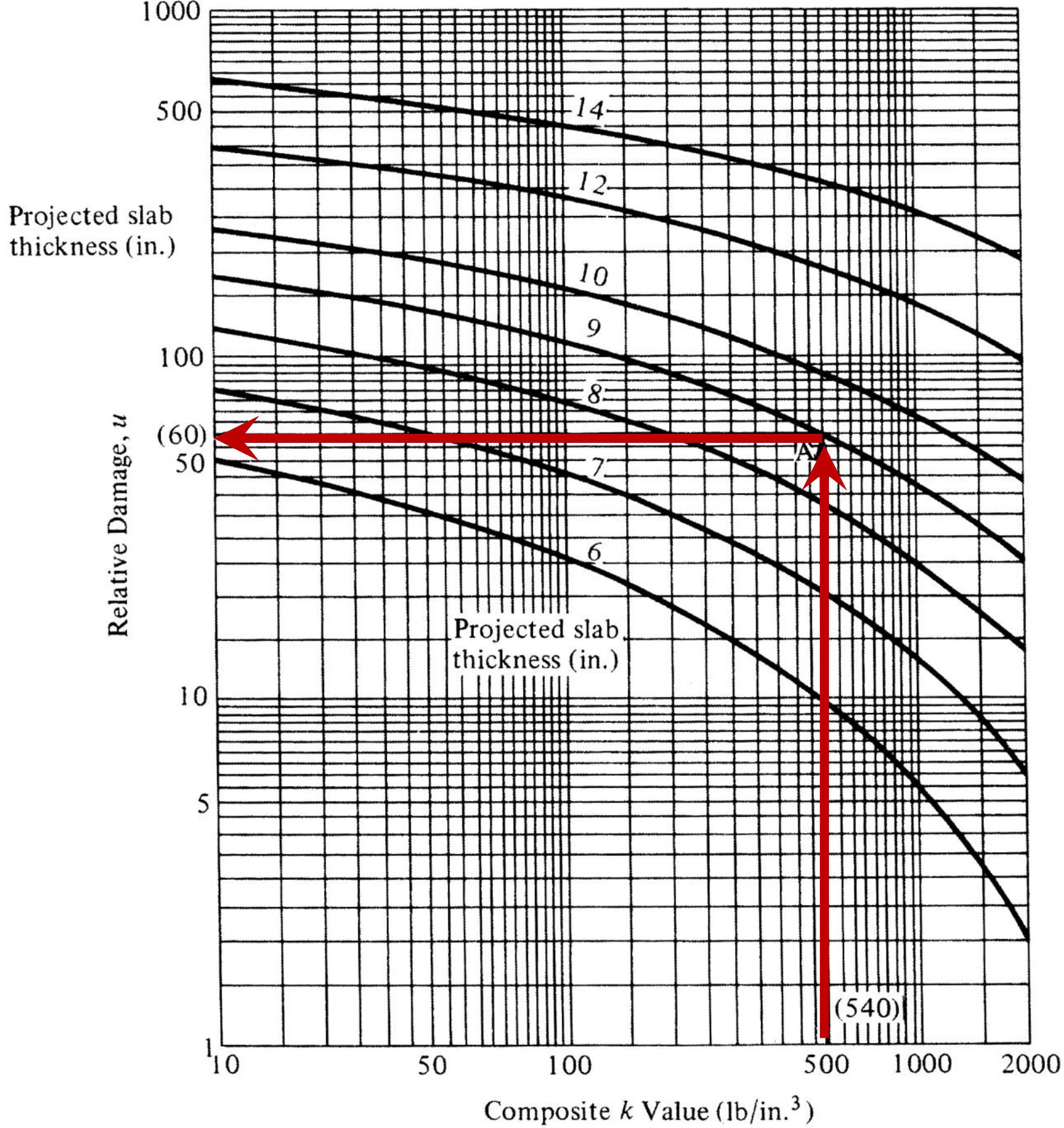


Figure 20.12 Chart for Estimating Relative Damage to Rigid Pavements Based on Slab Thickness and Underlying Support [1 lb/in^2 = 6.9 kN/m^2 1 lb/in^3 = 270 kN/m^3 1 inch = 254 cm]

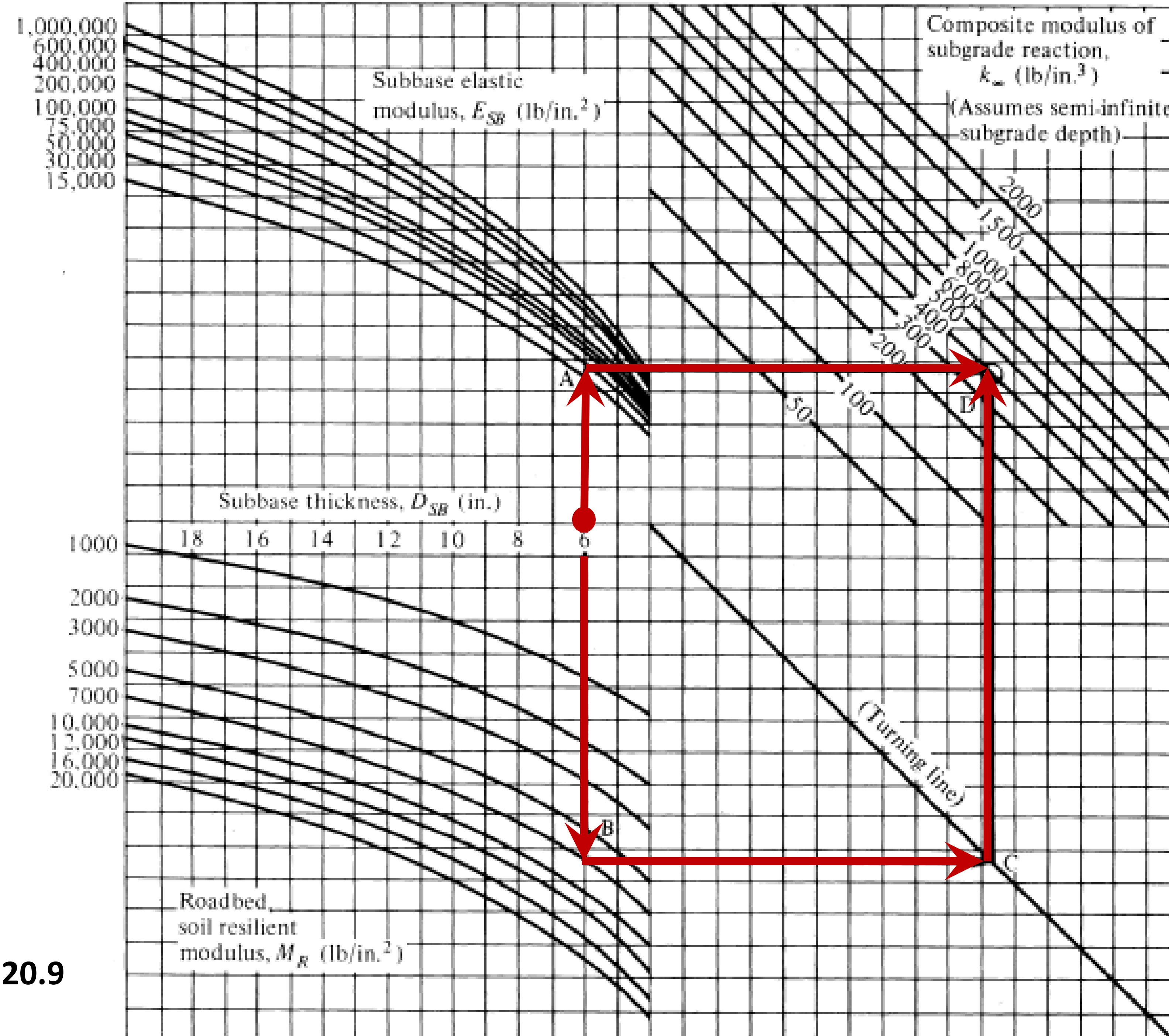

Composite modulus of subgrade reaction, k_∞ (lb/in.^{3})
(Assumes semi-infinite subgrade depth)
2000
1500
1000
800
600
500
400
300
200
100
50
Subbase elastic modulus, E_{SB} (lb/in.^{2})
1,000,000
600,000
400,000
200,000
100,000
75,000
50,000
30,000
15,000
Subbase thickness, D_{SB} (in.)
18
16
14
12
10
8
6
1000
2000
3000
5000
7000
10,000
12,000
16,000
20,000
Roadbed, soil resilient modulus, M_R (lb/in.^{2})
(Turning line)
A
B
C
D

Figure 20.9

AASHTO Method

c. **Whether bedrock lies within 10 ft of the subgrade surface**

- If this bedrock extends over a significant length along the highway alignment
  - Overall modulus of subgrade reaction may increase
- This effect is taken into consideration by adjusting **the effective modulus subgrade using the chart in Figure 20.11**

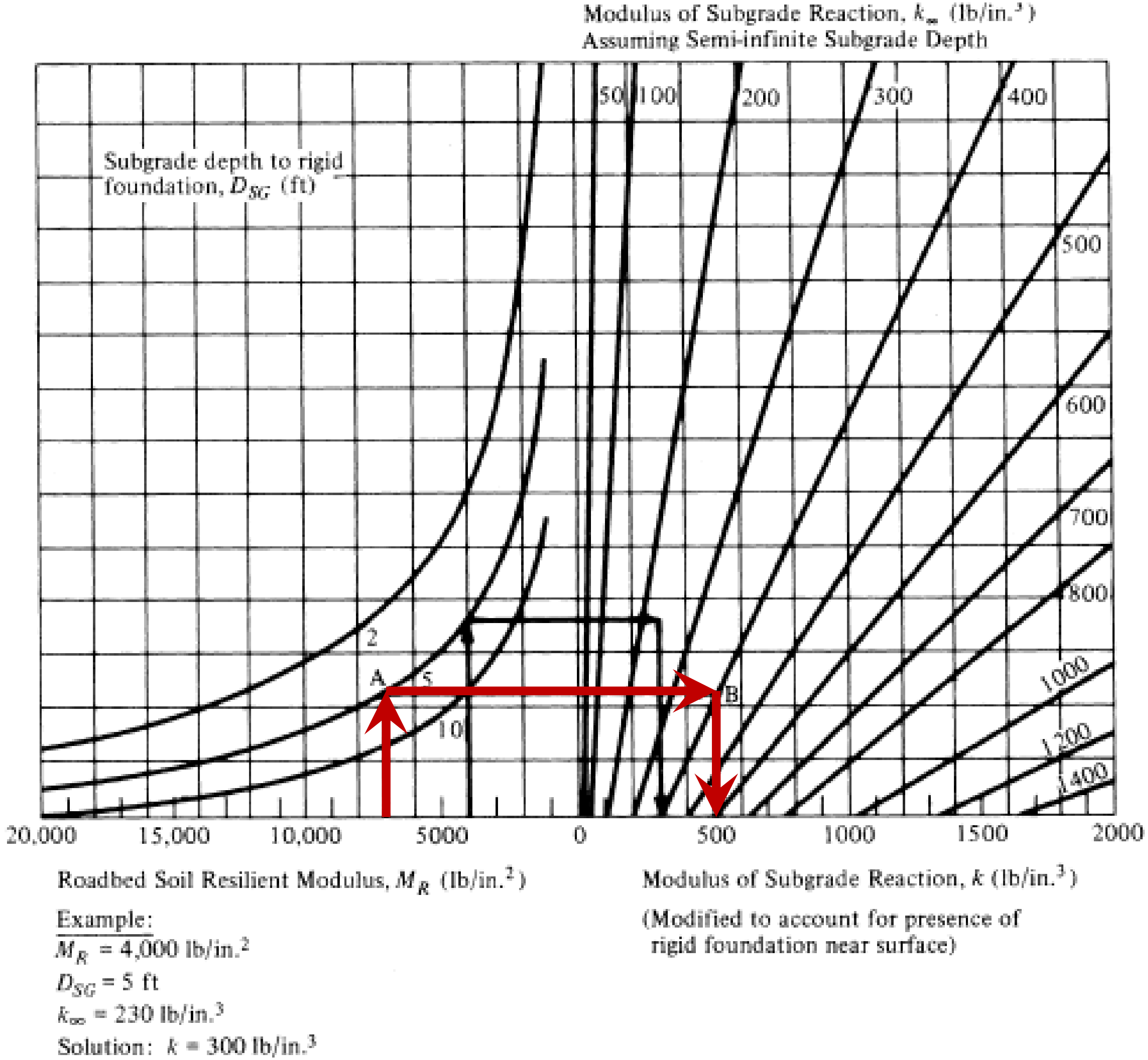


Figure 20.11 Chart to Modify Modulus of Subgrade Reaction to Consider Effects of Rigid Foundation Near Surface (within 10 ft) [1 lb/in^2 = 6.9 kN/m^2 1 lb/in^3 = 270 kN/m^3 1 ft = 0.3 m]

AASHTO Method

d. Effect of potential erosion of subbase

- This effect is included by the use the factor **loss of support (LS)**
- Using Table 20.5 and Figure 20.10

Table 20.5 Typical Ranges of Loss of Support Factors for Various Types of Materials

Type of Material	*Loss of Support (LS)*
Cement-treated granular base (E = 1,000,000 to 2,000,000 lb/in^2)	0.0 to 1.0
Cement aggregate mixtures (E = 500,000 to 1,000,000 lb/in^2)	0.0 to 1.0
Asphalt-treated base (E = 350,000 to 1,000,000 lb/in^2)	0.0 to 1.0
Bituminous stabilized mixtures (E = 40,000 to 300,000 lb/in^2)	0.0 to 1.0
Lime-stabilized mixtures (E = 20,000 to 70,000 lb/in^2)	1.0 to 3.0
Unbound granular materials (E = 15,000 to 45,000 lb/in^2)	1.0 to 3.0
Fine-grained or natural subgrade materials (E = 3,000 to 40,000 lb/in^2)	2.0 to 3.0

AASHTO Method

d. Effect of potential erosion of subbase

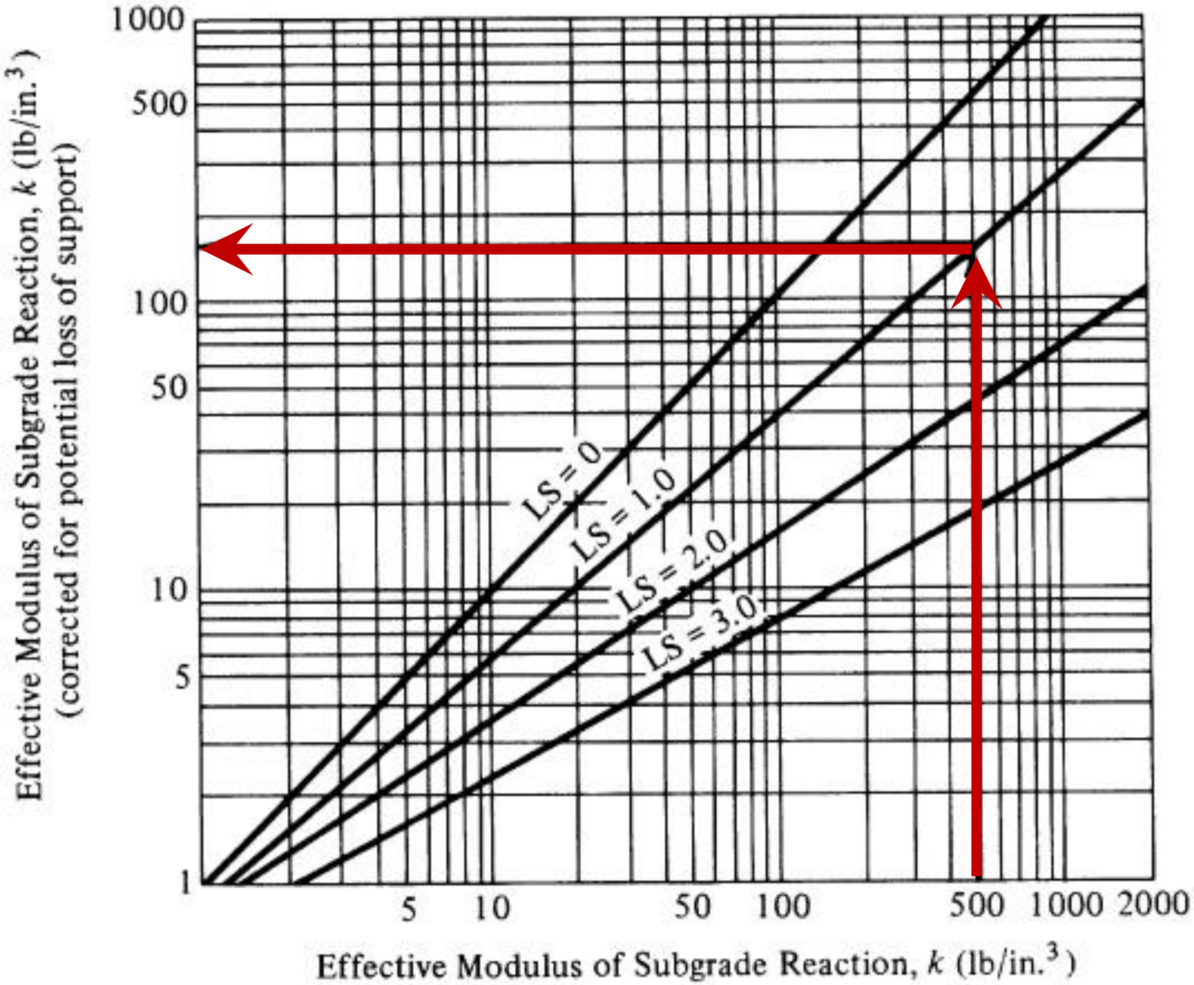


Figure 20.10 Correction of Effective Modulus of Subgrade Reaction for Potential Loss of Subbase Support

AASHTO Method

3. Subgrade strength

Example 20.2 Computing Effective Modulus of Subgrade Reaction for a Rigid Pavement Using AASHTO Method

A 6 in. layer of cement-treated granular material is to be used as subbase for a rigid pavement. The monthly values for the roadbed soil resilient modulus and the subbase elastic (resilient) modulus are given in columns 2 and 3 of Table 20.6 on the following page. If the rock depth is located 5 ft below the subgrade surface and the projected slab thickness is 9 in., estimate the effective modulus of subgrade reaction, using the AASHTO method.

Note that this is the example given in the 1993 AASHTO guide. Also note that the values for the modulus of the roadbed and subbase materials should be determined as discussed in Chapter 19, and the corresponding values shown in columns 2 and 3 of Table 20.6 should be for the same seasonal period.

AASHTO Method

3. Subgrade strength

Table 20.6 Data for and Solution to Example 20.2

(1) Month	(2) Roadbed Modulus M_R (lb/in^2)	(3) Subbase Modulus E_{SB} (lb/in^2)	(4) Composite k Value (lb/in^2) (Fig. 20.9)	(5) k Value (E_{SB}) on Rigid Foundation (Fig. 20.11)	(6) Relative Damage, u_r (Fig. 20.12)
January	20,000	50,000	1100	1350	0.35
February	20,000	50,000	1100	1350	0.35
March	2,500	15,000	160	230	0.86
April	4,000	15,000	230	300	0.78
May	4,000	15,000	230	300	0.78
June	7,000	20,000	400	500	0.60
July	7,000	20,000	400	500	0.60
August	7,000	20,000	400	500	0.60
September	7,000	20,000	400	500	0.60
October	7,000	20,000	400	500	0.60
November	4,000	15,000	230	300	0.78
December	20,000	50,000	1100	1350	0.35
					$\Sigma u_r = 7.25$

Total Subbase

Type: Granular

Thickness (in): 6

Loss of Support, LS: 1.0

Depth to Rigid Foundation (ft): 5

Projected Slab Thickness (in): 9

Average: $\bar{u}_r = \frac{\Sigma u_r}{n} = \frac{7.25}{12} = 0.60$

Effective modulus of subgrade reaction, k (lb/in^3) = 500

Corrected for loss of support: k (lb/in^3) = 170

AASHTO Method

4. Traffic

- It is similar to that presented for flexible pavements

$$\text{ESAL}_i = f_d \times G_{rn} \times \text{AADT}_i \times 365 \times N_i \times F_{Ei}$$

Table 20.7 and Table 20.8

$$G_{rn} = [(1 + r)^n - 1]/r$$

- It is necessary to assume the thickness of the slab at the start of the computation
  - » **Trial and error**

AASHTO Method

Table 20.7 ESAL Factors for Rigid Pavements, Single Axles, and P_t of 2.5 [1 kip = 4.44 kN 1 inch = 2.54 cm]

Axle Load (kip)	*Slab Thickness, D (in.)* 6	7	8	9	10	11	12	13	14
2	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002	.0002
4	.003	.002	.002	.002	.002	.002	.002	.002	.002
6	.012	.011	.010	.010	.010	.010	.010	.010	.010
8	.039	.035	.033	.032	.032	.032	.032	.032	.032
10	.097	.089	.084	.082	.081	.080	.080	.080	.080
12	.203	.189	.181	.176	.175	.174	.174	.173	.173
14	.376	.360	.347	.341	.338	.337	.336	.336	.336
16	.634	.623	.610	.604	.601	.599	.599	.599	.598
18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.51	1.52	1.55	1.57	1.58	1.58	1.59	1.59	1.59
22	2.21	2.20	2.28	2.34	2.38	2.40	2.41	2.41	2.41
24	3.16	3.10	3.22	3.36	3.45	3.50	3.53	3.54	3.55
26	4.41	4.26	4.42	4.67	4.85	4.95	5.01	5.04	5.05
28	6.05	5.76	5.92	6.29	6.61	6.81	6.92	6.98	7.01
30	8.16	7.67	7.79	8.28	8.79	9.14	9.35	9.46	9.52
32	10.8	10.1	10.1	10.7	11.4	12.0	12.3	12.6	12.7
34	14.1	13.0	12.9	13.6	14.6	15.4	16.0	16.4	16.5
36	18.2	16.7	16.4	17.1	18.3	19.5	20.4	21.0	21.3
38	23.1	21.1	20.6	21.3	22.7	24.3	25.6	26.4	27.0
40	29.1	26.5	25.7	26.3	27.9	29.9	31.6	32.9	33.7
42	36.2	32.9	31.7	32.2	34.0	36.3	38.7	40.4	41.6
44	44.6	40.4	38.8	39.2	41.0	43.8	46.7	49.1	50.8
46	54.5	49.3	47.1	47.3	49.2	52.3	55.9	59.0	61.4
48	66.1	59.7	56.9	56.8	58.7	62.1	66.3	70.3	73.4
50	79.4	71.7	68.2	67.8	69.6	73.3	78.1	83.0	87.1

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

AASHTO Method

Table 20.8 ESAL Factors for Rigid Pavements, Tandem Axles, and p_t of 2.5 [1 kip = 4.45 kN 1 inch = 2.54 cm]

	Slab Thickness, D (in.)								
Axle Load (kip)	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
2	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
4	.0006	.0006	.0005	.0005	.0005	.0005	.0005	.0005	.0005
6	.002	.002	.002	.002	.002	.002	.002	.002	.002
8	.007	.006	.006	.005	.005	.005	.005	.005	.005
10	.015	.014	.013	.013	.012	.012	.012	.012	.012
12	.031	.028	.026	.026	.025	.025	.025	.025	.025
14	.057	.052	.049	.048	.047	.047	.047	.047	.047
16	.097	.089	.084	.082	.081	.081	.080	.080	.080
18	.155	.143	.136	.133	.132	.131	.131	.131	.131
20	.234	.220	.211	.206	.204	.203	.203	.203	.203
22	.340	.325	.313	.308	.305	.304	.303	.303	.303
24	.475	.462	.450	.444	.441	.440	.439	.439	.439

(Continued)

AASHTO Method

Table 4.5 Percentage of Total Truck Traffic on Design Lane

Number of Traffic Lanes (Tow Directions)	Percentage of Trucks in Design Lane
2	50
4	45 (35-48)*
6 or more	40 (25-48)*

* Probable range

AASHTO Method

5. **Concrete properties**
   – Concrete property is given in terms of its **flexural strength (modulus of rupture)** at 28 days

6. **Drainage**
   – Drainage quality of the pavement is considered by using C_d factor
   – Use **Table 19.5 and Table 20.9**

6. Drainage

Table 19.5 Definition of Drainage Quality

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

Table 20.9 Recommended Values for Drainage Coefficient, C_d, for Rigid Pavements

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

AASHTO Method

7. Reliability

– Reliability considerations for rigid pavement are similar to those for flexible pavement.

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.

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

AASHTO Method / Design Procedure

- The basic equation developed in the 1986 AASHTO design guide for the pavement thickness is:

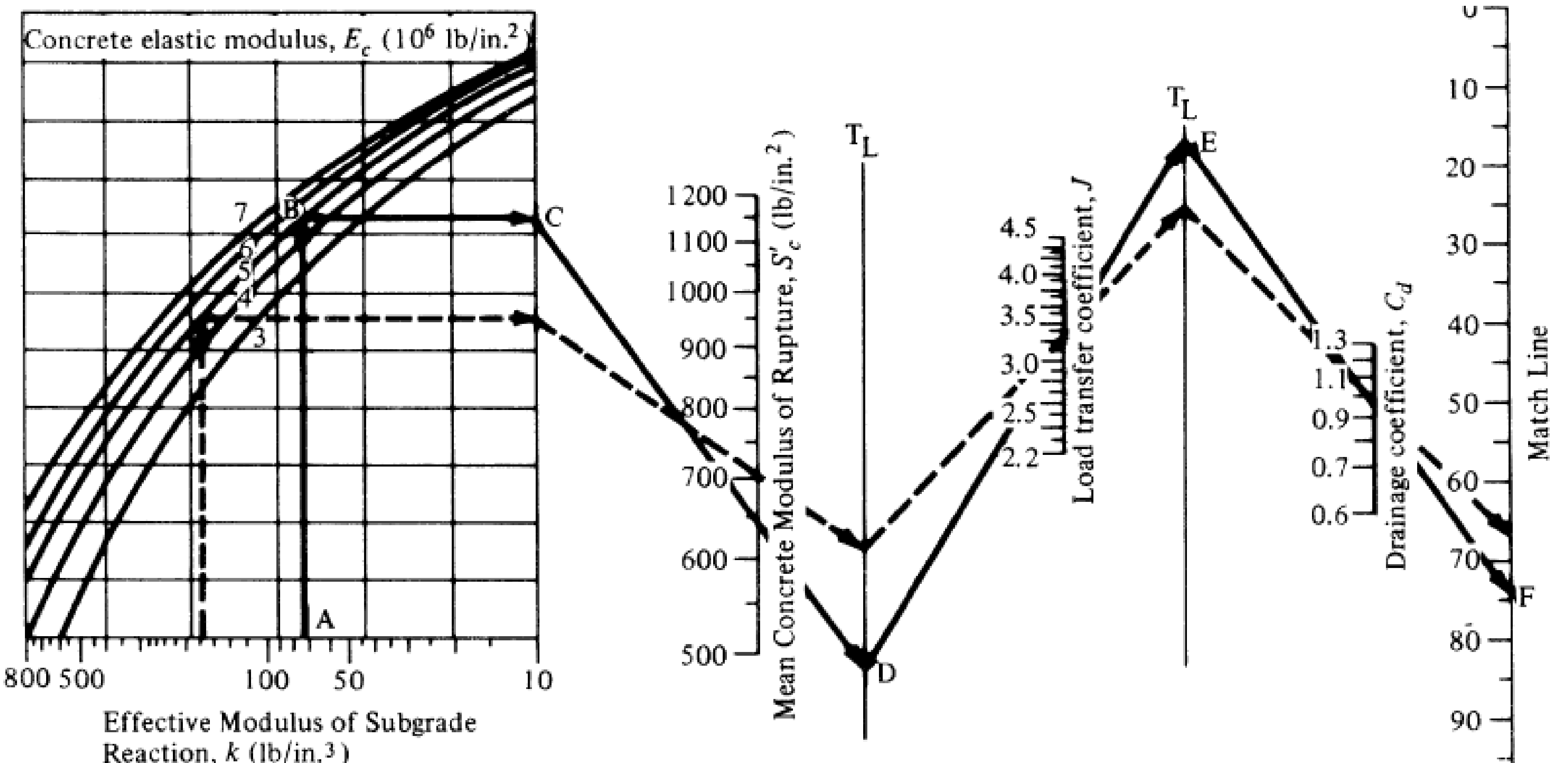
$$\log_{10} W_{18} = Z_R S_o + 7.35 \log_{10}(D + 1) - 0.06 + \frac{\log_{10}[\Delta PSI/(4.5 - 1.5)]}{1 + [(1.624 \times 10^7)/(D + 1)^{8.46}]}$$
$$+ (4.22 - 0.32P_t) \log_{10} \left\{ \frac{S'_c C_d}{215.63J} \left(\frac{D^{.75} - 1.132}{D^{.75} - [18.42/(E_c/k)^{.25}]} \right) \right\} \quad (20.21)$$

Z_R = standard normal variant corresponding to the selected level of reliability
S_o = overall standard deviation (see Chapter 19)
W_{18} = predicted number of 18 kip ESAL applications that can be carried by the pavement structure after construction
D = thickness of concrete pavement to the nearest half-inch
ΔPSI = design serviceability loss = $p_i - p_t$
p_i = initial serviceability index
p_t = terminal serviceability index
E_c = elastic modulus of the concrete to be used in construction (lb/in^2)
S'_c = modulus of rupture of the concrete to be used in construction (lb/in^2)
J = load transfer coefficient = 3.2 (assumed)
C_d = drainage coefficient

AASHTO Method / Design Procedure

- The design equation can be solved by using either a computer program or the two charts in **Figures 20.13 and 20.14**

AASHTO Method / Design Procedure

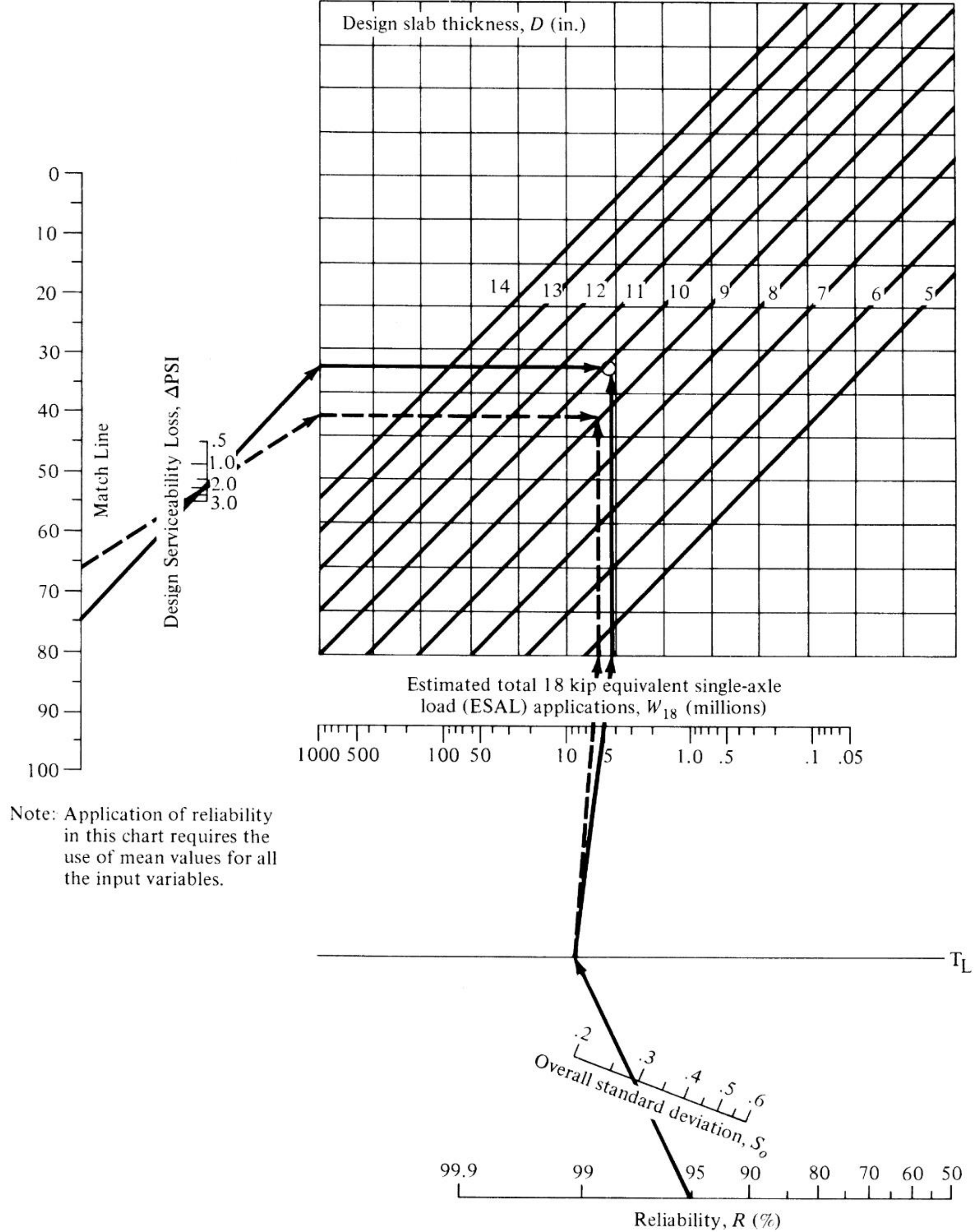


Example:

k = 72 lb/in.^{3}	S_o = 0.29
E_c = 5 × 10^6 lb/in.^{2}	R = 95% (Z_R = −1.645)
S'_c = 650 lb/in.^{2}	ΔPSI = 4.2 − 2.5 = 1.7
J = 3.2	W_{18} = 5.1 × 10^6 (18 kip ESAL)
C_d = 1.0	Solution: D = 10.0 in. (nearest half-in., from segment 2)

Figure 20.13 Design Chart for Rigid Pavements Based on Using Values for Each Input Variable (Segment 1)

Figure 20.14


Design slab thickness, D (in.)
14
13
12
11
10
9
8
7
6
5
0
10
20
30
40
50
60
70
80
90
100
Match Line
Design Serviceability Loss, ΔPSI
.5
1.0
2.0
3.0
Estimated total 18 kip equivalent single-axle load (ESAL) applications, W_{18} (millions)
1000 500
100 50
10
5
1.0 .5
.1 .05
Note: Application of reliability in this chart requires the use of mean values for all the input variables.
T_L
.2
.3
.4
.5
.6
Overall standard deviation, S_o
99.9
99
95
90
80
70
60
50
Reliability, R (%)

Example 20.3 Designing a Rigid Pavement Using the AASHTO Method

The use of the charts is demonstrated with the example given in Figure 20.13. In this case, input values for Segment 1 of the chart (Figure 20.13) are

Effective modulus of subgrade reaction, $k = 72\ \text{lb/in}^3$
Mean concrete modulus of rupture, $S'_c = 650\ \text{lb/in}^2$
Load transfer coefficient, $J = 3.2$
Drainage coefficient, $C_d = 1.0$

These values are used to determine a value on the match line as shown in Figure 20.13 (solid line ABCDEF). Input parameters for Segment 2 (Figure 20.14) of the chart are

Match line value determined in segment 1 (74)
Design serviceability loss, $\Delta PSI = 4.5 - 2.5 = 2.0$
Reliability, $R\% = 95\%$ ($Z_R = 1.645$)
Overall standard deviation, $S_o = 0.29$
Cumulative 18 kip ESAL = (5×10^6)

Solution: The required thickness of the concrete slab is then obtained, as shown in Figure 20.14, as 10 in. (nearest half-inch).

Note that when the thickness obtained from solving Eq. 20.21 analytically or by use of Figures 20.13 and 20.14 is significantly different from that originally assumed to determine the effective subgrade modulus and to select the ESAL factors, the whole procedure has to be repeated until the assumed and designed values are approximately the same, emphasizing the importance of using a computer program to facilitate the necessary iteration.

AASHTO Method / Design Procedure

Example 20.4 Evaluating the Adequacy of a Rigid Pavement Using the AASHTO Method

Using the data and effective subgrade modulus obtained in Example 20.2, determine whether the 9 in. pavement design of Example 20.2 will be adequate on a rural expressway for a 20-year analysis period and the following design criteria

$P_i = 4.5$
$P_t = 2.5$
ESAL on design lane during first year of operation $= 0.2 \times 10^6$
Traffic growth rate $= 4\%$
Concrete elastic modulus, $E_c = 5 \times 10^6$ lb/in^2
Mean concrete modulus of rupture $= 700$ lb/in^2
Drainage conditions are such that $C_d = 1.0$
$R = 0.95$ $(Z_R = 1.645)$
$S_o = 0.30$ (for rigid pavements $S_o = 0.3 - 0.4$)
Growth factor $= 29.78$ (from Table 19.6)
$k = 170$ (from Example 20.2)
Assume $D = 9$ in. (from Example 20.2)
ESAL over design period $= 0.2 \times 10^6 = 29.78 = 6 \times 10^6$

Solution: The depth of concrete required is obtained from Figures 20.13 and 20.14. The dashed lines represent the solution, and a depth of 9 in. is obtained. The pavement is therefore adequate.

Chapter 7
Pavement Design

Good Luck