Pavement Analysis and Design

TE-503 A/TE-503

Lecture-13
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DTEM

PORTLAND CEMENT ASSOCIATION METHOD

The Portland Cement Association's (PCA) thickness-design procedure for concrete highways and streets was published in 1984, superseding that published in 1966. The procedure can be applied to JPCP, JRCP, and CRCP. A finite element computer programme called JSLAB (Tayabji and Colley, 1986) was employed to compute the critical stresses and deflections, which were then used in conjunction with some design criteria to develop the design tables and charts. The design criteria are based on general pavement design, performance, and research experience, including relationships to performance of pavements in the AASHO Road Test and to studies of pavement faulting. Design problems can be worked out by hand with tables and charts presented herein or by a microcomputer programme available from PCA.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Criteria

One aspect of the new design procedure is the inclusion of an erosion analysis, in addition to the fatigue analysis.

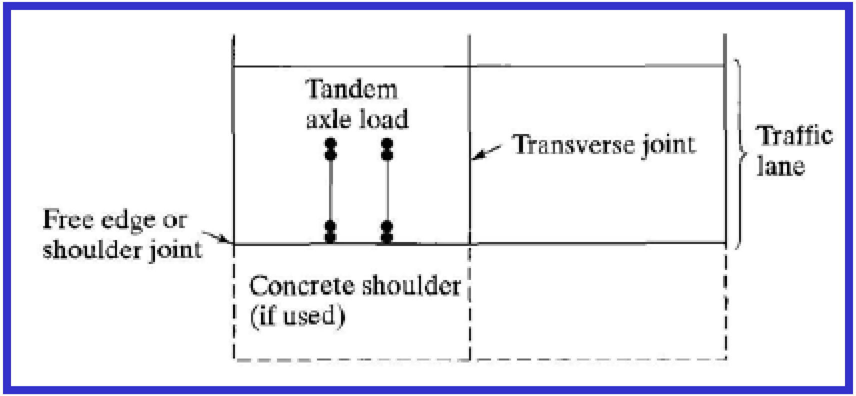
Fatigue analysis recognizes that pavements can fail by fatigue of concrete.

In erosion analysis, pavements fail by pumping, erosion of foundation and joint faulting.

PORTLAND CEMENT ASSOCIATION METHOD- Design Criteria

Fatigue Analysis

Fatigue analysis is based on the edge stress midway between the transverse joints, with the most critical loading position being shown in Figure. Because the load is near the midslab far away from the joints, the presence of the joints has practically no effect on the edge stress. When a concrete shoulder is tied onto the mainline pavement, the magnitude of the critical stress is reduced considerably.



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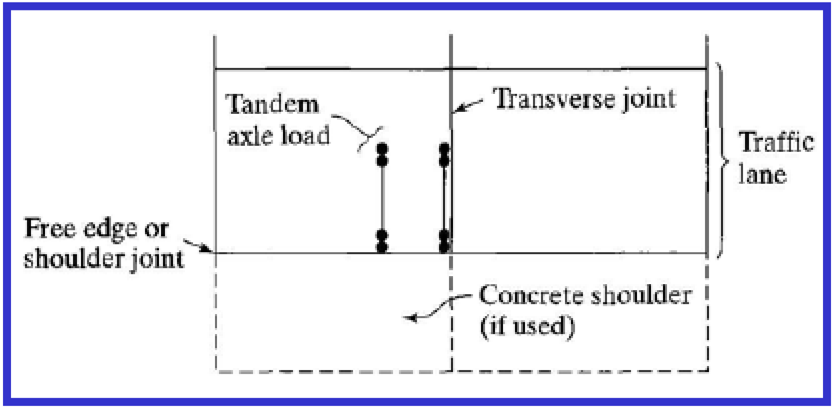
PORTLAND CEMENT ASSOCIATION METHOD- Design Criteria



Erosion Analysis

Pavement distresses such as pumping, erosion of foundation, and joint faulting are related more to pavement deflections than to flexural stresses. The most critical pavement deflection occurs at the slab corner when an axle load is placed at the joint near the corner.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

After deciding whether doweled joints and concrete shoulders are to be used, the thickness design is governed by four design factors:

1. **Concrete modulus of rupture**
2. **Subgrade and subbase support**
3. **Design period**
4. **Traffic**

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

1-Concrete Modulus of Rupture

The flexural strength of concrete is defined by the modulus of rupture, which is determined at 28 days by the method specified by AST M in "C78-84 Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third Point Loading."

The 28-day flexural strength is used as the design strength. The variability of strength and the gain in strength with age should be considered in the fatigue analysis.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

1-Concrete Modulus of Rupture

In view of the fact that the variations in modulus of rupture have far greater effect on thickness design than do the usual variations in other material properties, it is recommended that the modulus of rupture be reduced by one coefficient of variation.

A coefficient of variation of 15 %, which represents good to fair quality control, was assumed and was incorporated into the design charts and tables. Also incorporated was the effect of strength gain after 28 days.

PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

2-Subgrade and Subbase Support

Subgrade and subbase support is defined by the modulus of subgrade reaction, *k*. The PCA method does not consider the variation of *k* values over the year. The contention is that the reduced subgrade support during thaw periods has very little or no effect on the required thickness of concrete pavements, as evidenced by the results of AASHO Road Test. This is true because the brief periods when *k* values are low during spring thaws are more than offset by the longer freezing periods when *k* values are much higher than the design value. To avoid the tedious method of considering seasonal variations in *k* values, normal summer or fall *k* values can be used as reasonable mean values for design purposes.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

2-Subgrade and Subbase Support

TABLE 12.3 Effect of Untreated Subbase on k Values

Subgrade k value (pci)	Subbase k values (pci)			
	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

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

2-Subgrade and Subbase Support

TABLE 12.4 Design *k* Values for Cement-Treated Bases

Subgrade *k* value (pci)	Subbase *k* values (pci)			
	4 in.	6 in.	8 in.	10 in.
50	170	230	310	390
100	280	400	520	640
200	470	640	830	—

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

3-Design Period

The term "design period" should not be confused with the term "pavement life," which is not subject to precise definition. "Design period" is more nearly synonymous with the term "traffic analysis period."

Because traffic probably cannot be predicted with much accuracy for a longer period, a design period of 20 years has commonly been used in pavement design.

However, there are cases where the use of a shorter or longer design period is economically justified. For example, a special-haul road that will be used only a few years requires a much shorter design period; a premium facility that must provide a high level of performance for a long time with little or no pavement maintenance can require a design period of up to 40 years.

PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic

The information presented in Section 6.4, such as Eq. 6.26, can be used to determine the design traffic. The growth factor can be determined from Table 6.12 and the lane distribution factor for multilane highways from Figure 6.8.

$$n_i = (n_0)_i(G)(D)(L)(365)(Y) \tag{6.26}$$

Information on the average daily truck traffic (ADTT) and the axle-load distribution is needed in using the PCA design procedure. The ADTT includes only trucks with six tyres or more and does not include panel and pickup trucks or other vehicles with only four tyres.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic

TABLE 6.12 Traffic Growth Factors

Annual growth rate (%)	20-Year design period	40-Year design period
1.0	1.1	1.2
1.5	1.2	1.3
2.0	1.2	1.5
2.5	1.3	1.6
3.0	1.3	1.8
3.5	1.4	2.0
4.0	1.5	2.2
4.5	1.6	2.4
5.0	1.6	2.7
5.5	1.7	2.9
6.0	1.8	3.2

Source. After PCA (1984).

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic

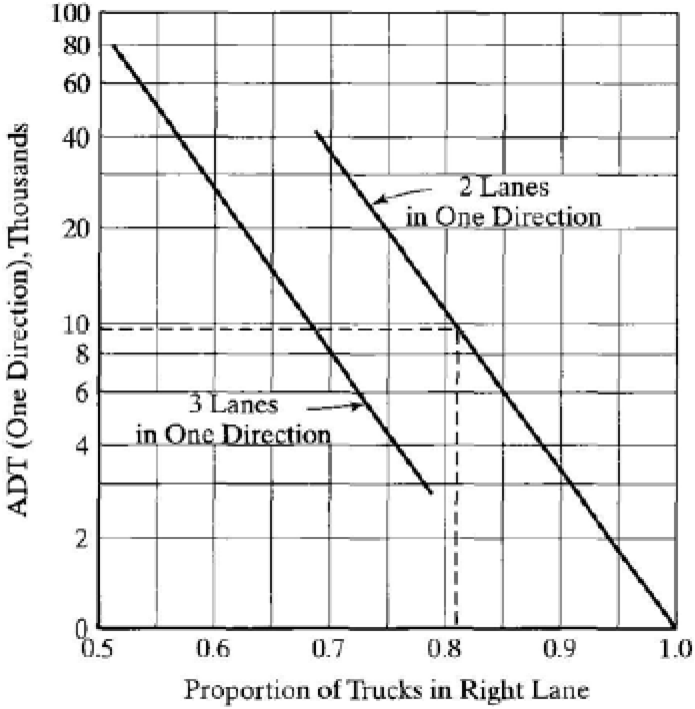

FIGURE 6.8

Proportion of trucks in design lane of multiple-lane highways. (After PCA (1984).)

PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic -Axle Load Distribution

Data on the axle load distribution of truck traffic is needed to compute the number of single and tandem axles of various weights expected during the design period. These data can be obtained from special traffic studies to establish the loadometer data for the specific project or from the W-4 table of a loadometer station representing truck weights and types that are expected to be similar to the project under design. If axle load distribution data are not available, the simplified design procedure described in Section 12.2.4 can be used.

Table 12.5 illustrates how the information in a W-4 table for a loadometer station can be used to determine the number of various axles based on the total number of trucks. In the W-4 table, axle loads are grouped by 2-kip increments for single axles and 4-kip increments for tandem axles, as shown in column 1.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic -Axle Load Distribution

TABLE 12.5 Axle Load Distribution for a Given Facility

Axle load kip (1)	Axles per 1000 trucks (2)	Adjusted axles per 1000 trucks (3)	Axles in design period (4)
Single axles			
28–30	0.28	0.58	6310
26–28	0.65	1.35	14,690
24–26	1.33	2.77	30,140
22–24	2.84	5.92	64,410
20–22	4.72	9.83	106,900
18–20	10.40	21.67	235,800
16–18	13.56	28.24	307,200
14–16	18.64	38.83	422,500
12–14	25.89	53.94	586,900
10–12	81.05	168.85	1,837,000
Tandem axles			
48–52	0.94	1.98	21,320
44–48	1.89	3.94	42,870
40–44	5.51	11.48	124,900
36–40	16.45	34.27	372,900
32–36	39.08	81.42	885,800
28–32	41.06	85.54	930,700
24–28	73.07	152.23	1,656,000
20–24	43.45	90.52	984,900
16–20	54.15	112.81	1,227,000
12–16	59.85	124.69	1,356,000

Note. 1 kip = 4.45 kN.
Source. After PCA (1984).

The axles per 1000 trucks shown in column 2 are obtained from the W-4 table. The total trucks counted = 13,215, with 6,918 two-axle, four-tyre trucks, constituting 52% of total trucks. Because the trucks in column 2 include two-axle, four-tyre trucks, which should be excluded from consideration, the data in column 2 must be divided by (1 - 0.52) to obtain the adjusted axles per 1000 trucks shown in column 3.

Trucks on design lane in design period = 10,880,000

Column 4 = Column 3 x (Trucks on design lane in design period)/1000.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Factors

4-Traffic -Load Safety Factor

In the design procedure, the axle load must be multiplied by a load-safety factor (LSF). The recommended load-safety factors are as follows:

1. For interstate highways and other multilane projects where there will be uninterrupted traffic flow and high volumes of truck traffic, LSF = 1.2.

2. For highways and arterial streets where there will be moderate volumes of truck traffic, LSF = 1.1.

3. For roads, residential streets and other streets that will carry small volumes o f truck traffic, LSF = 1.0.

In special cases, the use of a load safety factor as high as 1.3 might be justified for a premium facility to maintain a higher than normal level of pavement serviceability throughout the design period.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

The method presented in this section can be used when detailed axle-load distributions have been determined or estimated, as described in Section 12.2.2. If the axle load data are not available, the simplified method presented in Section 12.2.4 should be used.

Design Tables and Charts

Separate sets of tables and charts are used to evaluate fatigue and erosion damages. The following parameter values are used in their development:

Elastic modulus of concrete = 4 x 10^6 psi,

Poisson ratio of concrete = 0.15,

Diameter of dowels = 1/8 in./in. of slab,

Spacing of dowels = 12 in,

Modulus of dowel support = 2 x 10^6 pci,

Spring constant for aggregate interlock joints = 5000 psi,

Spring constant for tied concrete shoulder = 25,000 psi.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Fatigue Damage

Fatigue damage is based on the edge stress. Because the edge stress on mainline pavements without concrete shoulders is much greater than that on those with tied concrete shoulders, two different tables are needed: Table 12.6 for slabs without concrete shoulders, Table 12.7 for slabs with concrete shoulders.

The equivalent stresses shown in these tables are the edge stresses multiplied by a factor of 0.894. It is not known what axle load was used to generate these stresses. Based on the levels of stress, it appears that an 18-kip load was used for single axles and a 36-kip load was used for tandem axles. Both tables show that the equivalent stresses under 36-kip tandem-axle loads are smaller than those under 18-kip single-axle loads, which is as expected.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Fatigue Damage

TABLE 12.6 Equivalent Stresses for Slabs Without Concrete Shoulders

Slab thickness (in.)	k of Subgrade–subbase (pci)						
	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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem); 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Fatigue Damage

TABLE 12.7 Equivalent Stresses for Slabs with Concrete Shoulders

Slab thickness (in.)	*k* of Subgrade–subbase (pci)						
	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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem);
1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984)

PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Fatigue Damage

After the equivalent stress is determined, the stress ratio factor can be computed by dividing the equivalent stress by the design modulus of rupture, so that the allowable number of load repetitions can be obtained from Figure 12.12. Note that the reduction in the modulus of rupture by 15% and the increase in the modulus of rupture with age have been incorporated in the chart, so the user simply inputs the 28-day strength as the design modulus of rupture. Figure 12.12 can be applied to pavements both with and without concrete shoulders. If the allowable repetitions fall outside the range of the chart, the allowable number of repetitions is considered to be unlimited.

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Fatigue Damage

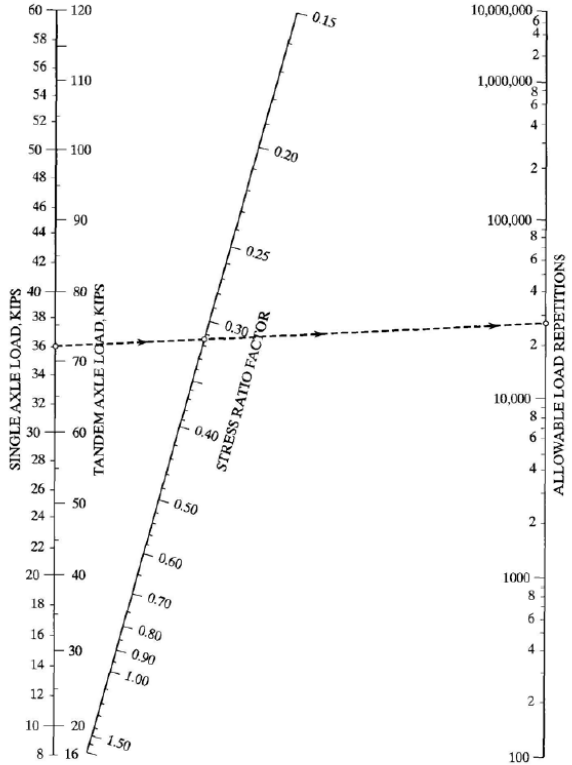

FIGURE 12.12

Stress ratio factors versus allowable load repetitions both with and without concrete shoulders (1 kip = 4.45 kN). (After PCA (1984).)

PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Erosion Damage

Because erosion damage occurs at the pavement corner and is affected by the type of joint, separate tables for doweled and aggregate interlock joints are needed. The erosion criteria also require two separate charts for slab with and without concrete shoulders. Table 12.8 shows the erosion factors for slabs with doweled joints and no concrete shoulders; Table 12.9 shows the erosion factors for slabs with aggregate interlock joints and no concrete shoulders. After the erosion factor is found, the allowable number of load repetitions can be obtained from Figure 12.13.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Erosion Damage

TABLE 12.8 Erosion Factors for Slabs with Doweled Joints and no Concrete Shoulders

Slab thickness (in.)	k of Subgrade-subbase (pci) 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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem);
1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

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PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Erosion Damage

TABLE 12.9 Erosion Factors for Slabs with Aggregate Interlock Joints and no Concrete Shoulders

Slab thickness (in.)	k of Subgrade–subbase (pci) 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	3.78/3.75	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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem); 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD- Design Procedure

Erosion Damage

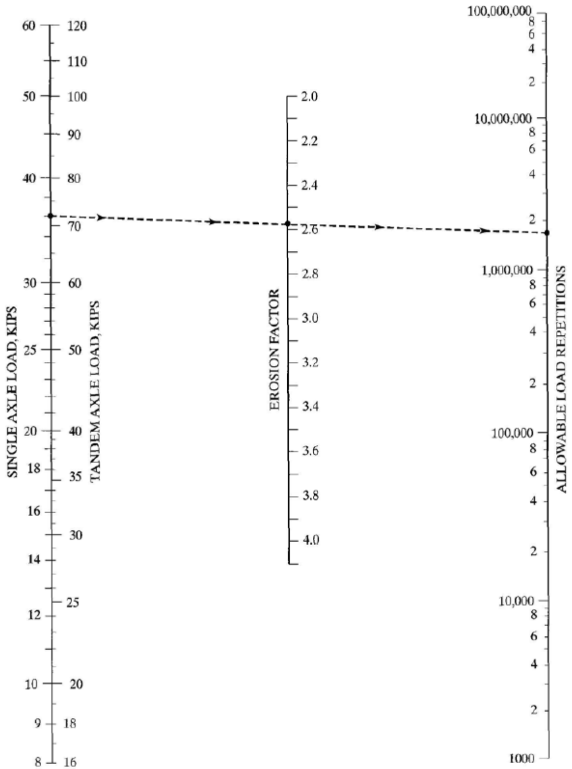


FIGURE 12.13

Erosion factors versus allowable load repetitions without concrete shoulders (1 kip = 4.45 kN). (After PCA (1984).)

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

For a four-lane interstate rigid pavement with doweled joints and no concrete shoulders. A 4-in. untreated subbase will be placed on a clay subgrade with a k value of 100 pci. Other information include concrete modulus of rupture = 650 psi, design period = 20 years, current ADT = 12,900, annual growth rate = 4%, and ADTT = 19% of ADT. Determine the thickness of slab for the given loading.

Single Axles: 30, 28, 26, 24, 20, 18, 16, 14, 12 kips

Tandem axles: 52, 48, 44, 40, 36, 32, 28, 24, 20, 16 kips

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

On the worksheet, a trial thickness of 9.5 in. is selected. For a subgrade k value of 100 pci and a subbase thickness of 4 in., from Table 12.3, the k value for subbase-subgrade combination is 130 pci.

TABLE 12.3 Effect of Untreated Subbase on *k* Values

Subgrade *k* value (pci)	Subbase *k* values (pci)			
	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

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

1. For interstate highways and other multilane projects where there will be uninterrupted traffic flow and high volumes of truck traffic, LSF = 1.2.

Load safety factor of 1.2 is recommended (Column 2).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

TABLE 12.6 Equivalent Stresses for Slabs Without Concrete Shoulders

Slab thickness (in.)	k of Subgrade–subbase (pci)						
	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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem); 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

With a thickness of 9.5 in. and a k value of 130 pci, an equivalent stress of 206 psi for single axles and 192 psi for tandem axles (Table 12.6) and entered as items 8 and 11 on the worksheet.

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

The stress ratio factor is the ratio between the equivalent stress and the modulus of rupture, so ratios of (206/650) 0.317 for single axles and (192/650) 0.295 for tandem axles are entered as items 9 and 12.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

TABLE 12.8 Erosion Factors for Slabs with Doweled Joints and no Concrete Shoulders

Slab thickness (in.)	*k* of Subgrade-subbase (pci)					
	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

Note. Number at left is for single axle and number at right is for tandem axle (single/tandem);
1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

For D = 9.5 in and k= 130 pci, erosion factors of 2.59 for single axles and 2.79 for tandem axles are obtained from Table 12.8 and entered as items 10 and 13.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Calculation of Pavement Thickness

Project *Design 1A, four-lane Interstate, rural*

Trial thickness *9.5* in.

Subbase-subgrade *k* *130* pci

Modulus of rupture. MR *650* psi

Load safety factor. LSF *1.2*

Doweled joints: yes ✓ no

Concrete shoulder: yes no ✓

Design period 20 years

4 in. untreated subbase

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

8. Equivalent stress 206 10. Erosion factor 2.59
9. Stress ratio factor 0.317

Single Axles

30	36.0	6,310	27,000	23.3	1,500,000	0.4
28	33.6	14,690	77,000	19.1	2,200,000	0.7
26	31.2	30,140	230,000	13.1	3,500,000	0.9
24	28.8	64,410	1,200,000	5.4	5,900,000	1.1
22	26.4	106,900	Unlimited	0	11,000,000	1.0
20	24.0	235,800	”	0	23,000,000	1.0
18	21.6	307,200	”	0	64,000,000	0.5
16	19.2	422,500			Unlimited	0
14	16.8	586,900			”	0
12	14.4	1,837,000			”	0

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Column 3 for Single Axle

TABLE 12.5 Axle Load Distribution for a Given Facility

Axle load kip (1)	Axles per 1000 trucks (2)	Adjusted axles per 1000 trucks (3)	Axles in design period (4)
Single axles			
28–30	0.28	0.58	6310
26–28	0.65	1.35	14,690
24–26	1.33	2.77	30,140
22–24	2.84	5.92	64,410
20–22	4.72	9.83	106,900
18–20	10.40	21.67	235,800
16–18	13.56	28.24	307,200
14–16	18.64	38.83	422,500
12–14	25.89	53.94	586,900
10–12	81.05	168.85	1,837,000
Tandem axles			
48–52	0.94	1.98	21,320
44–48	1.89	3.94	42,870
40–44	5.51	11.48	124,900
36–40	16.45	34.27	372,900
32–36	39.08	81.42	885,800
28–32	41.06	85.54	930,700
24–28	73.07	152.23	1,656,000
20–24	43.45	90.52	984,900
16–20	54.15	112.81	1,227,000
12–16	59.85	124.69	1,356,000

Note. 1 kip = 4.45 kN.
Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

11. Equivalent stress *192* 13. Erosion factor *2.79*

12. Stress ratio factor *0.295*

Tandem Axles

52	*62.4*	*21,320*	*1,100,000*	*1.9*	*920,000*	*2.3*
48	*57.6*	*42,870*	*Unlimited*	*0*	*1,500,000*	*2.9*
44	*52.8*	*124,900*	,,	*0*	*2,500,000*	*5.0*
40	*48.0*	*372,900*	,,	*0*	*4,600,000*	*8.1*
36	*43.2*	*885,800*			*9,500,000*	*9.3*
32	*38.4*	*930,700*			*24,000,000*	*3.9*
28	*33.6*	*1,656,000*			*92,000,000*	*1.8*
24	*28.8*	*984,900*			*Unlimited*	*0*
20	*24.0*	*1,227,000*			,,	*0*
16	*19.2*	*1,356,000*				
			Total	*62.8*	Total	*38.9*

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Column 3 for Tandem Axle

TABLE 12.5 Axle Load Distribution for a Given Facility

Axle load kip (1)	Axles per 1000 trucks (2)	Adjusted axles per 1000 trucks (3)	Axles in design period (4)
Single axles			
28–30	0.28	0.58	6310
26–28	0.65	1.35	14,690
24–26	1.33	2.77	30,140
22–24	2.84	5.92	64,410
20–22	4.72	9.83	106,900
18–20	10.40	21.67	235,800
16–18	13.56	28.24	307,200
14–16	18.64	38.83	422,500
12–14	25.89	53.94	586,900
10–12	81.05	168.85	1,837,000
Tandem axles			
48–52	0.94	1.98	21,320
44–48	1.89	3.94	42,870
40–44	5.51	11.48	124,900
36–40	16.45	34.27	372,900
32–36	39.08	81.42	885,800
28–32	41.06	85.54	930,700
24–28	73.07	152.23	1,656,000
20–24	43.45	90.52	984,900
16–20	54.15	112.81	1,227,000
12–16	59.85	124.69	1,356,000

Note. 1 kip = 4.45 kN.
Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

8. Equivalent stress 206
9. Stress ratio factor 0.317
10. Erosion factor 2.59

Single Axles

30	36.0	6,310	27,000	23.3	1,500,000	0.4
28	33.6	14,690	77,000	19.1	2,200,000	0.7
26	31.2	30,140	230,000	13.1	3,500,000	0.9
24	28.8	64,410	1,200,000	5.4	5,900,000	1.1
22	26.4	106,900	Unlimited	0	11,000,000	1.0
20	24.0	235,800	,,	0	23,000,000	1.0
18	21.6	307,200	,,	0	64,000,000	0.5
16	19.2	422,500			Unlimited	0
14	16.8	586,900			,,	0
12	14.4	1,837,000			,,	0

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Column 4
For single axle load of 36 kips and stress ratio factor of 0.317, allowable load repetitions are 27,000.

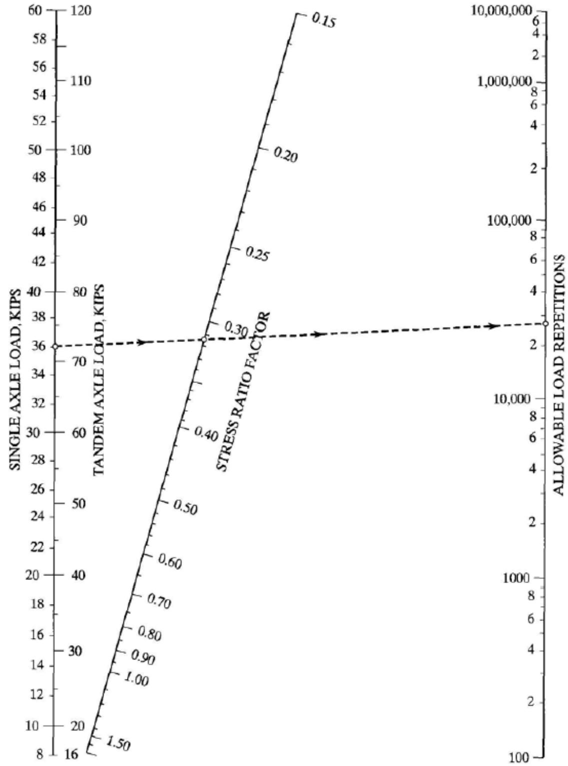


FIGURE 12.12

Stress ratio factors versus allowable load repetitions both with and without concrete shoulders (1 kip = 4.45 kN). (After PCA (1984).)

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Col 5= [Col 3/Col 4] x 100

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

8. Equivalent stress 206
9. Stress ratio factor 0.317
10. Erosion factor 2.59

Single Axles

30	36.0	6,310	27,000	23.3	1,500,000	0.4
28	33.6	14,690	77,000	19.1	2,200,000	0.7
26	31.2	30,140	230,000	13.1	3,500,000	0.9
24	28.8	64,410	1,200,000	5.4	5,900,000	1.1
22	26.4	106,900	Unlimited	0	11,000,000	1.0
20	24.0	235,800	,,	0	23,000,000	1.0
18	21.6	307,200	,,	0	64,000,000	0.5
16	19.2	422,500			Unlimited	0
14	16.8	586,900			,,	0
12	14.4	1,837,000			,,	0

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

8. Equivalent stress 206   10. Erosion factor 2.59

9. Stress ratio factor 0.317

Single Axles

30	36.0	6,310	27,000	23.3	1,500,000	0.4
28	33.6	14,690	77,000	19.1	2,200,000	0.7
26	31.2	30,140	230,000	13.1	3,500,000	0.9
24	28.8	64,410	1,200,000	5.4	5,900,000	1.1
22	26.4	106,900	Unlimited	0	11,000,000	1.0
20	24.0	235,800	,,	0	23,000,000	1.0
18	21.6	307,200	,,	0	64,000,000	0.5
16	19.2	422,500			Unlimited	0
14	16.8	586,900			,,	0
12	14.4	1,837,000			,,	0

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Column 6
For single axle load of 36 kips and stress ratio factor of 2.59, allowable load repetitions are 1,500,000.

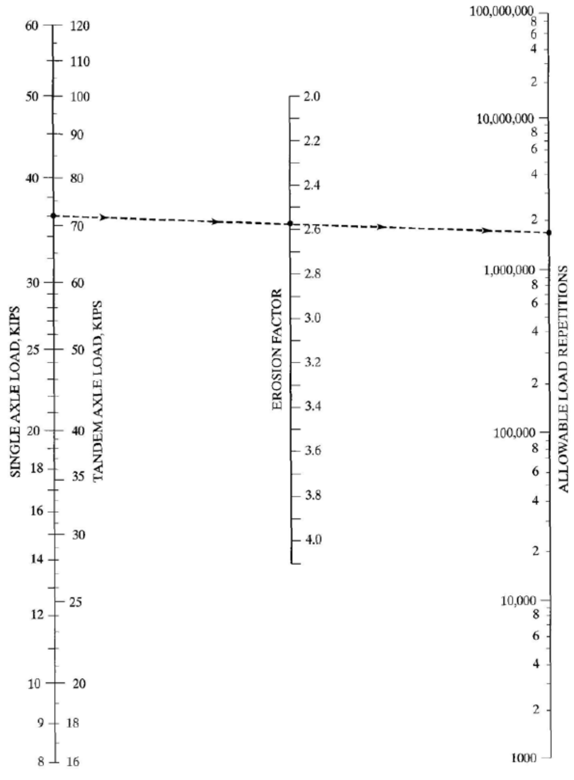


FIGURE 12.13

Erosion factors versus allowable load repetitions without concrete shoulders (1 kip = 4.45 kN). (After PCA (1984).)

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Col 7= [Col 3/Col 6] x 100

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

8. Equivalent stress 206   10. Erosion factor 2.59

9. Stress ratio factor 0.317

Single Axles

30	36.0	6,310	27,000	23.3	1,500,000	0.4
28	33.6	14,690	77,000	19.1	2,200,000	0.7
26	31.2	30,140	230,000	13.1	3,500,000	0.9
24	28.8	64,410	1,200,000	5.4	5,900,000	1.1
22	26.4	106,900	Unlimited	0	11,000,000	1.0
20	24.0	235,800	,,	0	23,000,000	1.0
18	21.6	307,200	,,	0	64,000,000	0.5
16	19.2	422,500			Unlimited	0
14	16.8	586,900			,,	0
12	14.4	1,837,000			,,	0

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

Axle load, kips	Multiplied by LSF %2	Expected repetitions	Fatigue analysis		Erosion analysis	
			Allowable repetitions	Fatigue percent	Allowable repetitions	Damage percent
1	2	3	4	5	6	7

11. Equivalent stress *192*
12. Stress ratio factor *0.295*
13. Erosion factor *2.79*

Tandem Axles

52	*62.4*	*21,320*	*1,100,000*	*1.9*	*920,000*	*2.3*
48	*57.6*	*42,870*	*Unlimited*	*0*	*1,500,000*	*2.9*
44	*52.8*	*124,900*	,,	*0*	*2,500,000*	*5.0*
40	*48.0*	*372,900*	,,	*0*	*4,600,000*	*8.1*
36	*43.2*	*885,800*			*9,500,000*	*9.3*
32	*38.4*	*930,700*			*24,000,000*	*3.9*
28	*33.6*	*1,656,000*			*92,000,000*	*1.8*
24	*28.8*	*984,900*			*Unlimited*	*0*
20	*24.0*	*1,227,000*			,,	*0*
16	*19.2*	*1,356,000*				
			Total	*62.8*	Total	*38.9*

PORTLAND CEMENT ASSOCIATION METHOD-Numerical Problem

The damages caused by fatigue and erosion are 62.8% and 38.9%, respectively. Both are less than 100%, so the use of a 9.5-in. slab is quite adequate.

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

A series of tables was developed by PCA to select the pavement thickness when specific axle load data are not available. The factors to be conidered are traffic, subgrade-subbase strength and the modulus of rupture of concrete.

Traffic Category

Traffic is divided into four axle load categories, as shown in Table 12.12. The ADT and ADTT values should not be used as the primary criteria for selecting the axle load category. More reliance should be placed on word descriptions of the expected maximum axle loads.

The axle load distributions used to prepare the simplified design tables for each traffic category are shown in Table 12.13. Each of these is the average of several W-4 tables representing pavement facilities in the appropriate category.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

TABLE 12.12 Axle Load Categories for Simplified Design Procedure

Axle-load category	Description	ADT	Traffic: ADTT %	Traffic: ADTT Per day	Traffic: Maximum axle loads (kips) Single axles	Traffic: Maximum axle loads (kips) Tandem axles
1	Residential streets Rural and secondary roads (low to medium)	200–800	1–3	Up to 25	22	36
2	Collector streets Rural and secondary roads (high) Arterial streets and primary roads (low)	700–5000	5–18	40–1000	26	44
3	Arterial streets and primary roads (medium) Expressways and urban and rural interstate highways (low to medium)	3000–12,000 2 lanes 3000–50,000+ 4 lanes or more	8–30	500–5000+	30	52
4	Arterial streets, primary roads expressways (high) Urban and rural interstate highways (medium to high)	3000–20,000 2 lanes 3000–150,000+ 4 lanes or more	8–30	1500–8000+	34	60

Note. The descriptors high, medium, or low refer to the relative weights of axle loads for the type of street or road; ADTT does not include two-axle, four-tire trucks; 1 kip = 4.45 kN.
Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

TABLE 12.13 Axle Load Distribution for Four Traffic Categories

Axle load (kips)	Axles per 1000 trucks			
	Category 1	Category 2	Category 3	Category 4
Single axles				
4	1693.31			
6	732.28			
8	483.10	233.60		
10	204.96	142.70		
12	124.00	116.76	182.02	
14	56.11	47.76	47.73	
16	38.02	23.88	31.82	57.07
18	15.81	16.61	25.15	68.27
20	4.23	6.63	16.33	41.82
22	0.96	2.60	7.85	9.69
24		1.60	5.21	4.16
26		0.07	1.78	3.52
28			0.85	1.78
30			0.45	0.63
32				0.54
34				0.19
Tandem axles				
4	31.90			
8	85.59	47.01		
12	139.30	91.15		
16	75.02	59.25	99.34	
20	57.10	45.00	85.94	
24	39.18	30.74	72.54	71.16
28	68.48	44.43	121.22	95.79
32	69.59	54.76	103.63	109.54
36	4.19	38.79	56.25	78.19
40		7.76	21.31	20.31
44		1.16	8.01	3.52
48			2.91	3.03
52			1.19	1.79
56				1.07
60				0.57

Note. 1 kip = 4.45 kN; all two-axle, four-tire trucks are excluded.
Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Subgrade-Subbase Strength

Subgrade-subbase strength is characterized by the descriptive terms low, medium, high, and very high. These terms are related to the modulus of subgrade reaction *k*, as shown in Table 12.14.

TABLE 12.14 Subgrade Soil Types and Approximate *k* Values

Type of soil	Support	*k* Values (pci)
Fine-grained soils in which silt and clay-size particles predominate	Low	75–120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130–170
Sands and sand-gravel mixtures relatively free of plastic fines	High	180–220
Cement-treated subbases	Very high	250–400

Note. 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Subgrade-Subbase Strength

When a subbase is used, the increase in *k* value can be determined from Table 12.3 or 12.4, depending on whether the subbase is untreated or stabilized.

TABLE 12.3 Effect of Untreated Subbase on *k* Values

Subgrade *k* value (pci)	Subbase *k* values (pci)			
	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

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

TABLE 12.4 Design *k* Values for Cement-Treated Bases

Subgrade *k* value (pci)	Subbase *k* values (pci)			
	4 in.	6 in.	8 in.	10 in.
50	170	230	310	390
100	280	400	520	640
200	470	640	830	—

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Design Tables

The PCA design manual contains a series of tables showing the allowable ADTT for pavements with either doweled or aggregate interlock joints. Separate tables were developed for each axle load category. To illustrate the method, only the table for axle load category 3 with doweled joints is shown, as shown in Table 12.15.

Three different moduli of rupture can be specified. The values 650 and 600 psi (4.5 and 4.1 MPa) on the upper portion of the tables are for good concrete with normal aggregates and are recommended for general design use; the value 550 psi (3.8 MPa) on the bottom portion is for a special case where high-quality aggregates are not available.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Design Tables

TABLE 12.15 Allowable ADTT[a] for Axle Load Category 3 with Doweled Joints

No concrete shoulder or curb					Concrete shoulder or curb				
Slab thickness (in.)	Subgrade-subbase support				Slab thickness (in.)	Subgrade-subbase support			
	Low	Medium	High	Very high		Low	Medium	High	Very high
MR = 650 psi									
7.5				250	6.5			83	320
8		130	350	1300	7	52	220	550	1900
8.5	160	640	1600	6200	7.5	320	1200	2900	9800
9	700	2700	7000	11,500[b]	8	1600	5700	13,800	
9.5	2700	10,800			8.5	6900	23,700[b]		
10	9900								
MR = 600 psi									
					6.5				67
8			73	310	7			120	440
8.5		140	380	1500	7.5		270	680	2300
9	160	640	1700	6200	8	370	1300	3200	10,800
9.5	630	2500	6500		8.5	1600	5800	14,100	
10	2300	9300			9	6600			
10.5	7700								
MR = 550 psi									
					7				82
8.5			70	300	7.5			130	480
9		120	340	1300	8	67	270	670	2300
9.5	120	520	1300	5100	8.5	330	1200	2900	9700
10	460	1900	4900	19,100	9	1400	4900	11,700	
10.5	1600	6500	17,400		9.5	5100	18,600		
11	4900								

Note. [a]ADTT excludes two-axle, four-tire trucks.
[b]Erosion controls the design; otherwise fatigue controls. 1 in. = 25.4 mm, 1 psi = 6.9 kPa.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Design Tables

The allowable ADTT is based on a 20-year design period and does not include any two-axle, four-tyre trucks. If the design period is not 20 years, the predicted ADTT must be changed proportionately. Incorporated in the tables are the load safety factors 1.0, 1.1, 1.2 and 1.2 for axle load categories 1, 2, 3, and 4, respectively. The tables were developed by first assuming an ADTT and then determining the percentages of fatigue and erosion damage from the given slab thickness, concrete modulus of rupture, and subgrade-subbase *k* value. The allowable ADTT was then computed as:

$$\text{Allowable ADTT} = \frac{100 \times (\text{assumed ADTT})}{\%\ \text{fatigue or erosion damage}}$$

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

The following information is given for a concrete pavement: arterial street, doweled joints, curb and gutter, design ADT = 6200, total trucks per day = 1440, ADTT = 630, concrete modulus of rupture = 650 psi and 4 in. of untreated granular subbase on a subgrade with *k* = 150 pci. Determine slab thickness by the simplified method.

Solution: From Table 12.12, both ADT and ADTT fit well with axle-load category 3.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

TABLE 12.12 Axle Load Categories for Simplified Design Procedure

Axle-load category	Description	ADT	Traffic: ADTT %	Traffic: ADTT Per day	Traffic: Maximum axle loads (kips) Single axles	Traffic: Maximum axle loads (kips) Tandem axles
1	Residential streets Rural and secondary roads (low to medium)	200–800	1–3	Up to 25	22	36
2	Collector streets Rural and secondary roads (high) Arterial streets and primary roads (low)	700–5000	5–18	40–1000	26	44
3	Arterial streets and primary roads (medium) Expressways and urban and rural interstate highways (low to medium)	3000–12,000 2 lanes 3000–50,000+ 4 lanes or more	8–30	500–5000+	30	52
4	Arterial streets, primary roads expressways (high) Urban and rural interstate highways (medium to high)	3000–20,000 2 lanes 3000–150,000+ 4 lanes or more	8–30	1500–8000+	34	60

Note. The descriptors high, medium, or low refer to the relative weights of axle loads for the type of street or road; ADTT does not include two-axle, four-tire trucks; 1 kip = 4.45 kN.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

The following information is given for a concrete pavement: arterial street, doweled joints, curb and gutter, design ADT = 6200, total trucks per day = 1440, ADTT = 630, concrete modulus of rupture = 650 psi and 4 in. of untreated granular subbase on a subgrade with *k* = 150 pci. Determine slab thickness by the simplified method.

Solution: From Table 12.3, the *k* value of the subgrade and subbase combined is about 170 pci.

TABLE 12.3 Effect of Untreated Subbase on *k* Values

Subgrade *k* value (pci)	Subbase *k* values (pci)			
	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

Note. 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.

Source. After PCA (1984).

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

The following information is given for a concrete pavement: arterial street, doweled joints, curb and gutter, design ADT = 6200, total trucks per day = 1440, ADTT = 630, concrete modulus of rupture = 650 psi and 4 in. of untreated granular subbase on a subgrade with *k* = 150 pci. Determine slab thickness by the simplified method.

Solution: So the subgrade-subbase support is classified as medium according to Table 12.14.

TABLE 12.14 Subgrade Soil Types and Approximate *k* Values

Type of soil	Support	*k* Values (pci)
Fine-grained soils in which silt and clay-size particles predominate	Low	75–120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130–170
Sands and sand-gravel mixtures relatively free of plastic fines	High	180–220
Cement-treated subbases	Very high	250–400

Note. 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

The following information is given for a concrete pavement: arterial street, doweled joints, curb and gutter, design ADT = 6200, total trucks per day = 1440, ADTT = 630, concrete modulus of rupture = 650 psi and 4 in. of untreated granular subbase on a subgrade with *k* = 150 pci. Determine slab thickness by the simplified method.

Solution: From Table 12.15, a 7.5-in. slab gives an allowable ADTT of 1200; a 7-in. slab gives only 220.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

TABLE 12.15 Allowable ADTT[a] for Axle Load Category 3 with Doweled Joints

No concrete shoulder or curb					Concrete shoulder or curb				
Slab thickness (in.)	Subgrade-subbase support: Low	Medium	High	Very high	Slab thickness (in.)	Subgrade-subbase support: Low	Medium	High	Very high
MR = 650 psi									
7.5				250	6.5			83	320
8		130	350	1300	7	52	220	550	1900
8.5	160	640	1600	6200	7.5	320	1200	2900	9800
9	700	2700	7000	11,500[b]	8	1600	5700	13,800	
9.5	2700	10,800			8.5	6900	23,700[b]		
10	9900								
MR = 600 psi									
					6.5				67
8			73	310	7			120	440
8.5		140	380	1500	7.5		270	680	2300
9	160	640	1700	6200	8	370	1300	3200	10,800
9.5	630	2500	6500		8.5	1600	5800	14,100	
10	2300	9300			9	6600			
10.5	7700								
MR = 550 psi									
					7				82
8.5			70	300	7.5			130	480
9		120	340	1300	8	67	270	670	2300
9.5	120	520	1300	5100	8.5	330	1200	2900	9700
10	460	1900	4900	19,100	9	1400	4900	11,700	
10.5	1600	6500	17,400		9.5	5100	18,600		
11	4900								

Note. [a]ADTT excludes two-axle, four-tire trucks.
[b]Erosion controls the design; otherwise fatigue controls. 1 in. = 25.4 mm, 1 psi = 6.9 kPa.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD-Simplified Design Procedure

Numerical problem

The following information is given for a concrete pavement: arterial street, doweled joints, curb and gutter, design ADT = 6200, total trucks per day = 1440, ADTT = 630, concrete modulus of rupture = 650 psi and 4 in. of untreated granular subbase on a subgrade with *k* = 150 pci. Determine slab thickness by the simplified method.

Solution:

The predicted ADTT is 630, so the use of 7.5 in. is adequate.

PORTLAND CEMENT ASSOCIATION METHOD

Lean-Concrete Subbase

The finite-element computer program can be used to analyze two layers of slab, either bonded or unbonded. If the bottom layer is a hardened lean concrete on which a layer of normal concrete is placed, the layers can be considered unbonded. If the two layers are built monolithically with the joints sawed deep enough to induce cracking through both layers, the case of two bonded layers applies. Design charts were developed by PCA for both bonded and unbonded cases. However, only the chart for the more popular unbonded case, which involves a normal concrete slab on a lean-concrete subbase, is presented here. In the finite-element analysis, the two layers of slab were assumed to have the same width. Because the lean-concrete subbase is usually built at least 2 ft (0.61 m) wider than the pavement on each side to support the tracks of the slipform paver, the assumption of equal width provides additional margin of safety to the design.

PORTLAND CEMENT ASSOCIATION METHOD

Lean-Concrete Subbase

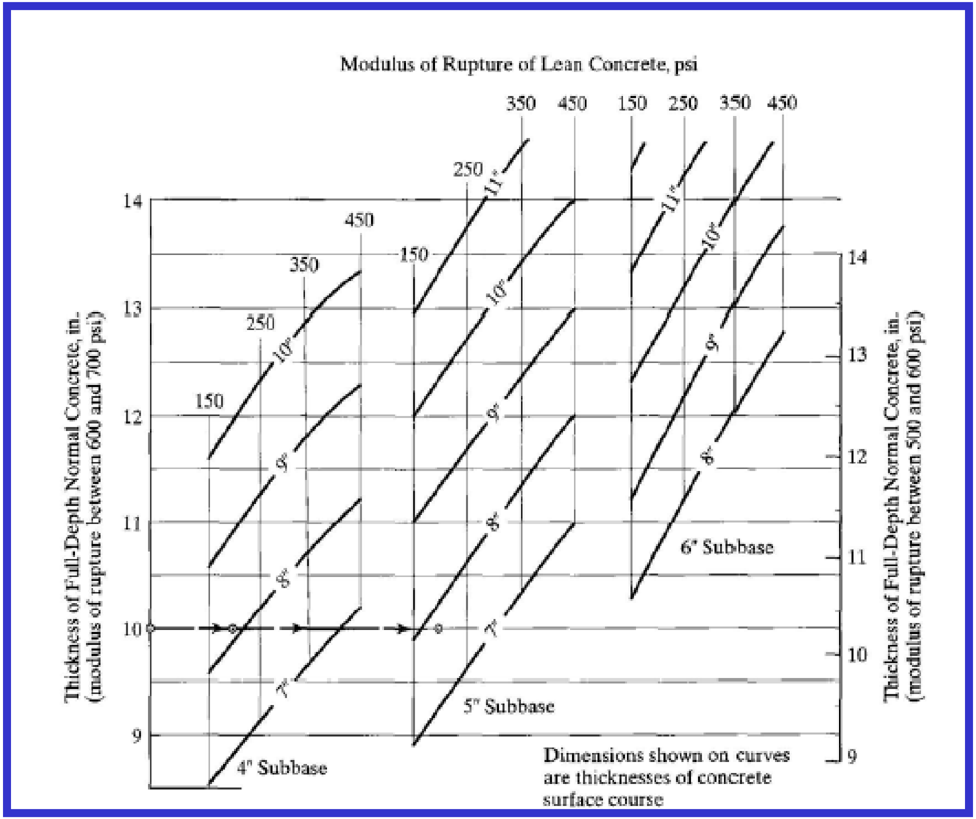
Figure is the design chart for concrete pavements with lean-concrete sub-bases. To use the design chart, the slab thickness required for a conventional pavement without a lean-concrete subbase must be determined by the procedure described previously.

For a given thickness of lean-concrete subbase, the thickness of concrete slab can be reduced, depending on the moduli of rupture of the two concrete materials. For example, if the moduli of rupture are 650 psi (4.5 MPa) for normal concrete and 200 psi (1.4 MPa) for lean concrete, the design equivalent to the 10-in. (254-mm) pavement can be either a 7.7-in. (196-mm) concrete slab on a 5-in. (127-mm) lean-concrete sub-base or an 8.5-in. (206-mm) concrete slab on a 4-in. (102-mm) lean-concrete subbase, as shown by the dashed line in Figure 12.16.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD

Lean-Concrete Subbase



Pavement Analysis and Design

PORTLAND CEMENT ASSOCIATION METHOD

Lean-Concrete Subbase

The normal practice has been to select a surface thickness about twice the sub-base thickness. Therefore, either an 8-in. (203-mm) slab on a 5-in. (127-mm) subbase or an 8.5-in. (216-mm) slab on a 4-in. (127-mm) subbase can be used for practical design.

The use of the design chart will ensure that the fatigue and erosion damage in the two layers of concrete does not exceed that in the conventional pavement. The use of a very low modulus of rupture, 200 psi (1.4 MPa), is recommended to minimize reflection cracking from the unjointed subbase through the concrete surface. If, contrary to current practice, joints are placed in the subbase at the same location as in the concrete surface, higher moduli of rupture for lean concrete may be used.

PORTLAND CEMENT ASSOCIATION METHOD

Lean-Concrete Subbase

The normal practice has been to select a surface thickness about twice the sub-base thickness. Therefore, either an 8-in. (203-mm) slab on a 5-in. (127-mm) subbase or an 8.5-in. (216-mm) slab on a 4-in. (127-mm) subbase can be used for practical design.

The use of the design chart will ensure that the fatigue and erosion damage in the two layers of concrete does not exceed that in the conventional pavement. The use of a very low modulus of rupture, 200 psi (1.4 MPa), is recommended to minimize reflection cracking from the unjointed subbase through the concrete surface. If, contrary to current practice, joints are placed in the subbase at the same location as in the concrete surface, higher moduli of rupture for lean concrete may be used.

PORTLAND CEMENT ASSOCIATION METHOD

Tridem-Axle Loads

Three more tables, one for equivalent stresses and two for erosion factors, were developed by PCA for tridem axles. One of the tables that can be used to determine erosion factors for slabs with doweled joints is shown in Table 12.16 for illustrative purposes. The procedure is similar to that for single and tandem axles. After the equivalent stress or erosion factor is obtained from the tables, Figure 12.12, 12.13, or 12.14 can be used to determine the allowable number of load repetitions. Although tridem-axle loads are not shown in these figures, the scale for single-axle loads can be used by dividing the tridem-axle load by three.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD

Tridem-Axle Loads

TABLE 12.16 Erosion Factors for Slabs with Doweled Joints Under Tridem Axles

Slab thickness (in.)	k of Subgrade-subbase (pci) 50	100	200	300	500	700
4	3.89/3.33	3.82/3.20	3.75/3.13	3.70/3.10	3.61/3.05	3.53/3.00
4.5	3.78/3.24	3.69/3.10	3.62/2.99	3.57/2.95	3.50/2.91	3.44/2.87
5	3.68/3.16	3.58/3.01	3.50/2.89	3.46/2.83	3.40/2.79	3.34/2.75
5.5	3.59/3.09	3.49/2.94	3.40/2.80	3.36/2.74	3.30/2.67	3.25/2.64
6	3.51/3.03	3.40/2.87	3.31/2.73	3.26/2.66	3.21/2.58	3.16/2.54
6.5	3.44/2.97	3.33/2.82	3.23/2.67	3.18/2.59	3.12/2.50	3.08/2.45
7	3.37/2.92	3.26/2.76	3.16/2.61	3.10/2.53	3.04/2.43	3.00/2.37
7.5	3.31/2.87	3.20/2.72	3.09/2.56	3.03/2.47	2.97/2.37	2.93/2.31
8	3.26/2.83	3.14/2.67	3.03/2.51	2.97/2.42	2.90/2.32	2.86/2.25
8.5	3.20/2.79	3.09/2.63	2.97/2.47	2.91/2.38	2.84/2.27	2.79/2.20
9	3.15/2.75	3.04/2.59	2.92/2.43	2.86/2.34	2.78/2.23	2.73/2.15
9.5	3.11/2.71	2.99/2.55	2.87/2.39	2.81/2.30	2.73/2.18	2.68/2.11
10	3.06/2.67	2.94/2.51	2.83/2.35	2.76/2.26	2.68/2.15	2.63/2.07
10.5	3.02/2.64	2.90/2.48	2.78/2.32	2.72/2.23	2.64/2.11	2.58/2.04
11	2.98/2.60	2.86/2.45	2.74/2.29	2.68/2.20	2.59/2.06	2.54/2.00
11.5	2.94/2.57	2.82/2.42	2.70/2.26	2.64/2.16	2.55/2.05	2.50/1.97
12	2.91/2.54	2.79/2.39	2.67/2.23	2.60/2.13	2.51/2.02	2.46/1.94
12.5	2.87/2.51	2.75/2.36	2.63/2.20	2.56/2.11	2.48/1.99	2.42/1.91
13	2.84/2.48	2.72/2.33	2.60/2.17	2.53/2.08	2.44/1.96	2.39/1.88
13.5	2.81/2.46	2.68/2.30	2.56/2.14	2.49/2.05	2.41/1.93	2.35/1.86
14	2.78/2.43	2.65/2.28	2.53/2.12	2.46/2.03	2.38/1.91	2.32/1.83

Note. Number at left is without concrete shoulder and number at right is with concrete shoulder (without concrete shoulder/with concrete shoulder); 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD

Tridem-Axle Loads-Numerical problem

Given a concrete pavement with a thickness of 8 in., a *k* value of 100 pci, doweled joints, and no concrete shoulders, determine the allowable repetitions under a 54-kip tridem-axle load based on erosion criteria.

Solution: From Table 12.16, erosion factor = 3.14.

Rigid Pavement Design

PORTLAND CEMENT ASSOCIATION METHOD

Tridem-Axle Loads-Numerical problem

TABLE 12.16 Erosion Factors for Slabs with Doweled Joints Under Tridem Axles

Slab thickness (in.)	k of Subgrade-subbase (pci) 50	100	200	300	500	700
4	3.89/3.33	3.82/3.20	3.75/3.13	3.70/3.10	3.61/3.05	3.53/3.00
4.5	3.78/3.24	3.69/3.10	3.62/2.99	3.57/2.95	3.50/2.91	3.44/2.87
5	3.68/3.16	3.58/3.01	3.50/2.89	3.46/2.83	3.40/2.79	3.34/2.75
5.5	3.59/3.09	3.49/2.94	3.40/2.80	3.36/2.74	3.30/2.67	3.25/2.64
6	3.51/3.03	3.40/2.87	3.31/2.73	3.26/2.66	3.21/2.58	3.16/2.54
6.5	3.44/2.97	3.33/2.82	3.23/2.67	3.18/2.59	3.12/2.50	3.08/2.45
7	3.37/2.92	3.26/2.76	3.16/2.61	3.10/2.53	3.04/2.43	3.00/2.37
7.5	3.31/2.87	3.20/2.72	3.09/2.56	3.03/2.47	2.97/2.37	2.93/2.31
8	3.26/2.83	3.14/2.67	3.03/2.51	2.97/2.42	2.90/2.32	2.86/2.25
8.5	3.20/2.79	3.09/2.63	2.97/2.47	2.91/2.38	2.84/2.27	2.79/2.20
9	3.15/2.75	3.04/2.59	2.92/2.43	2.86/2.34	2.78/2.23	2.73/2.15
9.5	3.11/2.71	2.99/2.55	2.87/2.39	2.81/2.30	2.73/2.18	2.68/2.11
10	3.06/2.67	2.94/2.51	2.83/2.35	2.76/2.26	2.68/2.15	2.63/2.07
10.5	3.02/2.64	2.90/2.48	2.78/2.32	2.72/2.23	2.64/2.11	2.58/2.04
11	2.98/2.60	2.86/2.45	2.74/2.29	2.68/2.20	2.59/2.06	2.54/2.00
11.5	2.94/2.57	2.82/2.42	2.70/2.26	2.64/2.16	2.55/2.05	2.50/1.97
12	2.91/2.54	2.79/2.39	2.67/2.23	2.60/2.13	2.51/2.02	2.46/1.94
12.5	2.87/2.51	2.75/2.36	2.63/2.20	2.56/2.11	2.48/1.99	2.42/1.91
13	2.84/2.48	2.72/2.33	2.60/2.17	2.53/2.08	2.44/1.96	2.39/1.88
13.5	2.81/2.46	2.68/2.30	2.56/2.14	2.49/2.05	2.41/1.93	2.35/1.86
14	2.78/2.43	2.65/2.28	2.53/2.12	2.46/2.03	2.38/1.91	2.32/1.83

Note. Number at left is without concrete shoulder and number at right is with concrete shoulder (without concrete shoulder/with concrete shoulder); 1 in. = 25.4 mm, 1 pci = 271.3 kN/m^3.
Source. After PCA (1984).

PORTLAND CEMENT ASSOCIATION METHOD

Tridem-Axle Loads-Numerical problem

Given a concrete pavement with a thickness of 8 in., a *k* value of 100 pci, doweled joints, and no concrete shoulders, determine the allowable repetitions under a 54-kip tridem-axle load based on erosion criteria.

Solution: With a tridem-axle load of 54 kip, or a single-axle load of 18 kip, from Figure 12.13, the allowable number of repetitions is 2.3 x 10^6.

PORTLAND CEMENT ASSOCIATION METHOD

Numerical problem

Determine the thickness of a concrete pavement for a two-lane highway by the PCA method. The pavement has doweled joints and no concrete shoulders. The modulus of subgrade reaction is 200 pci and the concrete modulus of rupture is 650 psi. Assume a load safety factor of 1.1 and a design period of 20 years. The average daily traffic during the design period is 2500, of which 35% are trucks. Truck weight distribution data for single (S) and tandem (T) loads are tabulated in Table P12.3.

TABLE P12.3

Axle loads (kip)	No. axles per 1000 trucks	Axle loads (kip)	No. axles per 1000 trucks
16 S	130.9	24 T	80.2
18 S	110.8	28 T	34.4
20 S	65.4	32 T	24.0
22 S	15.6	36 T	17.2
24 S	2.3	40 T	16.8
26 S	1.9	44 T	10.5
28 S	0.9	48 T	9.6

DSIGN OF RIGID PAVEMENT SHOULDERS

Most of the information presented in Section 11.4 on the design of flexible pavement shoulders is also applicable to the design of rigid pavement shoulders. Some of the features of rigid pavement shoulders that are different from those of flexible pavement shoulders will be discussed here.

PCC shoulders have been used in urban expressways for many years, but their use on rural highways began only in the mid 1960s. The good performance of these pavements has made it the standard practice of many agencies to utilize PCC shoulders for rigid pavements.

DSIGN OF RIGID PAVEMENT SHOULDERS

Advantages of Tied Concrete Shoulders

Concrete shoulders must be tied to the mainline concrete pavements. The advantages of tied concrete shoulders are as follows:

1.The placement of a tied concrete shoulder next to the mainline pavement can substantially increase the load-carrying capacity of the pavement. The tied concrete shoulder provides support to the edge of the pavement and reduces stresses and deflections in the mainline slab. The shoulder is also benefited by receiving support from the mainline slab, so the damage due to encroaching traffic can be greatly reduced.

2.A tied longitudinal joint between mainline and shoulder pavements can be easily sealed to reduce the amount of surface runoff infiltrating into the pavement structure. Field studies conducted in Georgia and Illinois showed that sealing the longitudinal joint greatly reduced the amount of inflow from rainfall into the pavement structure (Dempseyet al.,1982).

DSIGN OF RIGID PAVEMENT SHOULDERS

Advantages of Tied Concrete Shoulders

3.Pumping beneath the mainline slab is reduced through the reduction of edge and corner deflections, the reduction of water infiltration through the longitudinal joint, and the draining of water far away from the traffic lane.

4.Tied concrete shoulders can reduce differential movements at the longitudinal shoulder joint and do not experience the lane/shoulder drop off type of distress that occurs so frequently in flexible shoulders.

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Types of Rigid Pavement Shoulders

As with mainline pavements, three types of shoulder pavements are available: jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuous reinforced concrete pavement (CRCP).

Generally, the type of shoulder should match the type of mainline pavement. However, some exceptions may be accepted:

1.For mainline JPCP, only JPCP shoulders with the same joint spacings as the mainline pavement are recommended, because of their low cost. If JRCP shoulders with longer joint spacings are used, the excessive joint movements may cause problems in the adjacent mainline slabs. All transverse joints should be provided with an adequate reservoir and sealed similarly to the mainline joints.

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Types of Rigid Pavement Shoulders

2.For mainline JRCP, either JRCP shoulders that match the mainline pavement in design or JPCP shoulders with closer joint spacings may be used. The use of JPCP shoulders is more cost effective, because no steel reinforcement is needed. They can be placed at the same time as the JRCP mainline pavement by leaving out the reinforcing steel and cutting transverse joints at shorter intervals.

3.For mainline CRCP, either CRCP shoulders that match the mainline pavement in design or JPCP shoulders with short joint spacings may be used. The use of short joint spacing for JPCP shoulders will reduce potential movements of the joints that might cause cracking in the mainline CRCP. The elimination of steel reinforcement in the JPCP shoulders can save construction cost.

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Design of Longitudinal Shoulder Joint

Adequate load transfer across the longitudinal shoulder joint must be provided to reduce the stresses and deflections in both mainline and shoulder slabs. Tied and keyed joints have been used most frequently to ensure a high degree of load transfer. Colley et al.(1978) investigated load transfers in laboratory slabs constructed with keyed, tied and keyed, and tied butt joints and concluded that all three were equally effective in reducing load-induced strains and deflections. However, the use of a keyed joint without tie bars was not recommended, because of the possibility of shoulder joint separation. The excellent performance of the tied butt joint suggests that this type of construction is feasible and can reduce costs. Malleable tie bars of No. 4 or No. 5 size spaced at 18 to 24 in. (457 to 610 mm) are preferable to stiffer short bars spaced at larger intervals.

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Design of Longitudinal Shoulder Joint

This will substantially reduce stress concentration and the possibility of joint spall in the vicinity of the bar. When a PCC shoulder is to be constructed adjacent to an existing pavement, tie bars can be installed by drilling holes in the edge of the existing slab. This can be done by using a tractor-mounted drill that can drill several holes at one time. Tie bars are installed in the holes by using epoxy or cement grout. The bar should be inserted into the slab over such a length as to develop sufficient bond. To avoid spalling over the base, a minimum insertion of 9 in. (229 mm) is required. In the case of new construction, tie bars can be inserted into the plastic concrete near the rear of the slip form paver. Bent bars can be installed manually or by mechanical means. The bent portion can be straightened later to tie the shoulder to the main-line pavement.

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Design of Longitudinal Shoulder Joint

In addition to tie bars, a keyway can be formed to provide additional load transfer capability. The longitudinal joint between the traffic lane and the shoulder should be provided with a sealant reservoir and sealed with an effective sealant. This will minimize the possibility of foreign materials collecting inside the joint to cause joint spall and reduce the amount of water and deicing salts entering into the joint and corroding the tiebars.

DSIGN OF RIGID PAVEMENT SHOULDERS

Shoulder Thickness Design

The thickness design concepts presented in Section 11.4.3 for flexible pavement shoulders are also applicable to rigid pavement shoulders. One major difference is that the inner edge is always more critical for flexible shoulders, because of encroaching traffic, but the outer edge can be more critical for rigid shoulders, because of parking traffic. There is also some question about whether a separately designed shoulder is really needed. Lokken (1973) reviewed the performance of 16 projects located in 12 states and recommended the use of a 6-in. (152-mm) slab with an alternative tapered slab varying from roadway pavement depth at the longitudinal joint to 6 in. (152 mm) at the outside edge of the shoulder. Slavis (1981) reported on the performance review of these same projects in 1980 and indicated that the vast majority performed extremely well.

DSIGN OF RIGID PAVEMENT SHOULDERS

Shoulder Thickness Design

The only notable deficiency identified in the field investigation was some faulting in one project due to inadequately covered tie bars. It is impossible to place the tie bars at the mid depth both of a 6-in. (152-mm) shoulder and of a thicker mainline pavement, so it was recommended in the 1980 review that the shoulder thickness be equal to the mainline slab at the longitudinal joint. This thickness can be used for the entire width of the shoulder or tapered to 6 in. (152 mm) at the outside edge. The use of the same thickness for both mainline and shoulder pavements is not only easier to construct, especially in installing the longitudinal joint, but has the further advantages of improving drainage by the elimination of bath tub trench and reducing differential frost heave.

DSIGN OF RIGID PAVEMENT SHOULDERS

Shoulder Thickness Design

If it is necessary to use thinner shoulder sections, for economic or other reasons, the thickness of the inner edge can be based on the encroaching and parking traffic combined, that of the outer edge on the parking traffic alone. The design method used for the mainline pavement can also be used for the shoulder, except that the traffic on the shoulder is much lighter. The following example illustrates how the PCA method can be used for determining the thickness of shoulder. In applying the PCA method to real situations, various weights of single- and tandem-axle loads must be analyzed separately, because each has a different effect on the mode of failure. However, for simplicity, only the 18-kip (80-kN) single-axle loads will be used in the example.

DSIGN OF RIGID PAVEMENT SHOULDERS

Shoulder Thickness Design-Numerical problem

The outside lane on a heavily traveled highway is subjected to 10 million applications of an 18-kip (80-kN) single-axle load during the design life. A JPCP shoulder with aggregate interlock transverse joints is tied onto the traffic lane. Assuming an encroaching traffic of 3.5%, a parking traffic of 0.02%, a load safety factor of 1.2, a concrete modulus of rupture of 650 psi (4.5 MPa), and a modulus of subgrade reaction of 100 pci (27.1 MN/m^3), determine the thickness of tied concrete shoulder by the PCA design method.

Solution:The outer edge of shoulder slab should be designed as aggregate interlock joints with no concrete shoulder, and the inner edge as aggregate interlock joints with concrete shoulder.

Parking traffic on the outer edge = 10,000,000 x 0.0002 = 2000.

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Shoulder Thickness Design-Numerical problem

The outside lane on a heavily traveled highway is subjected to 10 million applications of an 18-kip (80-kN) single-axle load during the design life. A JPCP shoulder with aggregate interlock transverse joints is tied onto the traffic lane. Assuming an encroaching traffic of 3.5%, a parking traffic of 0.02%, a load safety factor of 1.2, a concrete modulus of rupture of 650 psi (4.5 MPa), and a modulus of subgrade reaction of 100 pci (27.1 MN/m^3), determine the thickness of tied concrete shoulder by the PCA design method.

Total traffic on the inner edge including both encroaching and parking traffic = 10,000,000 x 0.0352 = 352,000.

Based on both fatigue and erosion analyses, the allowable repetitions for several assumed thicknesses are tabulated in Table 12.26. In the fatigue analysis, the equivalent stress was found from Table 12.6 for the outer edge with no concrete shoulder and Table 12.7 for the inner edge with concrete shoulder. The stress ratio was computed by dividing the equivalent stress with 650, which is the concrete modulus of rupture.

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Shoulder Thickness Design-Numerical problem

The outside lane on a heavily traveled highway is subjected to 10 million applications of an 18-kip (80-kN) single-axle load during the design life. A JPCP shoulder with aggregate interlock transverse joints is tied onto the traffic lane. Assuming an encroaching traffic of 3.5%, a parking traffic of 0.02%, a load safety factor of 1.2, a concrete modulus of rupture of 650 psi (4.5 MPa), and a modulus of subgrade reaction of 100 pci (27.1 MN/m^3), determine the thickness of tied concrete shoulder by the PCA design method.

The allowable number of repetitions was obtained from Figure 12.12. In the erosion analysis, the erosion factor was found from Table 12.9 for the outer edge and Table 12.11 for the inner edge.

The allowable number of repetitions was obtained from Figure 12.13 for the outer edge and from Figure 12.14 for the inner edge. The single-axle load to be used with the charts is 1.2x18, or 21.6 kip (96 kN).

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Shoulder Thickness Design-Numerical problem

TABLE 12.26 Computation of Allowable Load Repetitions by PCA Method

Assumed thickness (in.)	Fatigue analysis			Erosion analysis	
	Equivalent stress	Stress ratio	Allowable repetitions	Erosion sfactor	Allowable repetitions
Outer edge					
6.0	411	0.63	640	3.40	120,000
6.5	367	0.56	5000	3.30	240,000
Inner edge					
6.0	327	0.50	52,000	2.95	160,000
6.5	294	0.45	200,000	2.86	320,000
7.0	266	0.41	1,500,000	2.77	650,000

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Shoulder Thickness Design-Numerical problem

The outside lane on a heavily traveled highway is subjected to 10 million applications of an 18-kip (80-kN) single-axle load during the design life. A JPCP shoulder with aggregate interlock transverse joints is tied onto the traffic lane. Assuming an encroaching traffic of 3.5%, a parking traffic of 0.02%, a load safety factor of 1.2, a concrete modulus of rupture of 650 psi (4.5 MPa), and a modulus of subgrade reaction of 100 pci (27.1 MN/m^3), determine the thickness of tied concrete shoulder by the PCA design method.

It can be seen from Table 12.26 that fatigue is more critical for 6 and 6.5 in. (152 and 165 mm) slabs, as indicated by the smaller allowable load repetitions compared with the erosion analysis, but erosion is more critical for the 7-in. (178-mm) slab. The required thickness is 6.5 in. (165 mm) for the outer edge and 7.0 in. (178 mm) for the inner edge. That fatigue prevails in thin pavements and erosion in thick pavements can be explained by the fact that the edge stress decreases more rapidly than the corner deflection as the thickness increases.

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Shoulder Thickness Design-Numerical problem

The outside lane on a heavily traveled highway is subjected to 10 million applications of an 18-kip (80-kN) single-axle load during the design life. A JPCP shoulder with aggregate interlock transverse joints is tied onto the traffic lane. Assuming an encroaching traffic of 3.5%, a parking traffic of 0.02%, a load safety factor of 1.2, a concrete modulus of rupture of 650 psi (4.5 MPa), and a modulus of subgrade reaction of 100 pci (27.1 MN/m^3), determine the thickness of tied concrete shoulder by the PCA design method.

Separate calculations also indicate that the thickness for the mainline slab with aggregate interlock joints is 8 in. (203 mm) based on fatigue analysis, but 9 in. (229 mm) based on erosion analysis. The thickness of shoulder can be designed in several ways. The best, but most expensive, method is to use a uniform slab of 9 in. (229 mm). Another method is to use 9 in. (229 mm) at the longitudinal joint and taper to 6.5 in. (165 mm) at the outer edge. The last resort is to use a uniform thickness of 7 in. (178 mm). It is not worth the effort to taper the section from 7 to 6.5 in.(18 to 165 mm) because the saving is too small.

Assignment

Problems: 12.1 to 12.12

Date of submission: End Term