

NEW PCA THICKNESS DESIGN PROCEDURE FOR CONCRETE HIGHWAY AND STREET PAVEMENTS

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The previous version of the Portland Cement Association's (PCA) thickness design procedure (1) for concrete highways and streets was first published in 1966. Since then, several new practices in pavement construction and performance experience have developed for which existing design procedures do not apply:

- pavements with undoweled (aggregate interlock) transverse joints
- lean concrete subbases under concrete pavements
- concrete shoulders
- modes of distress, primarily due to erosion of pavement foundations, that are unrelated to the traditional, existing design criteria
- triple axles (tridem)

To include these items, a revised design procedure (2) has been developed by the PCA. One new aspect of the procedure is the erosion criteria which recognizes that pavements can fail due to excessive pumping, erosion of foundation, and joint faulting. The stress criteria recognizes that pavements can crack in fatigue due to excessive load repetitions. The primary purpose of this paper is to explain the basis for the design criteria and the development of the design procedures. Secondary purposes are to present a few examples to show the mechanics of the design procedures and the effects of using, or not using, doweled joints, concrete shoulders, and special subbases.

Applications of Design Procedures

The design procedures apply to the following types of concrete pavements: plain, plain doweled, reinforced, and continuously reinforced.

Plain pavements are constructed without reinforcing steel or doweled joints. Load transfer at the joints is obtained by aggregate interlock between the cracked faces below the joint saw cut

or groove. For load transfer to be effective, it is necessary that short joint spacings be used.

Plain-doweled pavements are built without reinforcing steel; however, smooth steel dowel bars are installed as load transfer devices at each contraction joint and relatively short joint spacings are used to control cracking.

Reinforced pavements contain reinforcing steel and dowel bars for load transfer at the contraction joints. The pavements are constructed with longer joint spacings than used for plain pavements. Between the joints, one or more transverse cracks will usually develop; these are held tightly together by the reinforcing steel and good load transfer is provided.

Commonly used joint spacings that perform well are 15 ft for plain pavements, not more than 20 ft for plain-doweled pavements, and no more than about 40 ft for reinforced pavements. Joint spacings greater than these have been used but sometimes greater spacing causes pavement distress at joints and intermediate cracks between joints.

Continuously reinforced pavements are built without contraction joints. Due to the relatively heavy, continuous-steel reinforcement in the longitudinal direction, these pavements develop transverse cracks at close intervals. A high degree of load transfer is developed at these crack faces held tightly together by steel reinforcement.

An adequate pavement thickness is dependent upon the type of pavement selected from the list described above, and the type of shoulder and subbase selected by the designer.

Design problems can be worked out by hand with tables and charts provided in the PCA Manual (2) or by microcomputer program (3) available from PCA. A metric edition of the design manual is also available (4).

Basis For Design--General

The thickness design methods presented here are based on knowledge of pavement theory, performance, and research experience. The knowledge gained from performance of pavements is the most important. Accordingly, it is essential to examine the relationship between the roles that performance and theory play in a design procedure. Sophisticated theoretical methods developed in recent years

permit the responses of the pavement--stresses, deflections, pressures--to be more accurately modeled. This theoretical analysis is a necessary part of a mechanistic design procedure, for it allows consideration of a full range of design-variable combinations. An important second aspect of the design procedure is the criteria applied to the theoretically computed values--the limiting or allowable values of stress, deflection, or pressure. Defining the criteria so that design results are related to pavement performance experience and research data is critical in developing a design procedure.

The theoretical parts of the design procedures given here are based on a comprehensive analysis of concrete stresses and deflections by a finite-element computer program (5). The program models the conventional design factors of concrete properties, foundation support, and loading, plus joint load transfer by dowels or aggregate interlock and concrete shoulder, for axle-load placements at slab interior, edge, joint, and corner.

The criteria for the design procedures are based on general pavement design, performance, and research experience including relationships to performance of pavements at the AASHTO Road Test and to studies of the faulting of pavements.

The design criteria can be appropriately modified if regional or local specific performance experience becomes available for more favorable or adverse conditions. This could be the case for particular climate, soil, or drainage conditions and future design innovations.

Design Factors

After selection of the type of concrete pavement (plain pavement with or without dowels, reinforced pavement), type of subbase if needed, and type of shoulder (with or without concrete shoulder, curb and gutter or integral curb), thickness design is determined based on four design factors:

1. Flexural strength of the concrete (modulus of rupture, MR), by third-point loading test
2. Strength of the subgrade, or subgrade and subbase combination, (k)
3. The weights, frequencies, and types of truck axle loads that the pavement will carry
4. Design period, which in this and other pavement design procedures is usually taken at 20 years, but may be more or less.

Two methods of handling truck axle-load data are given in the PCA Manual:

- A full design procedure which assumes that detailed axle-load data have been predicted based on information from truck weigh stations, weigh-in-motion studies, or other sources.
- A simplified design procedure for use where detailed axle-load data are not available; here, a selection is made of one of several axle-load distributions representing different categories of road and street types.

In the full design procedure, the axle loads are multiplied by a load safety factor (LSF). These load safety factors are recommended:

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

- For highways and arterial streets where there will be moderate volumes of truck traffic, LSF = 1.1.
- For roads, residential streets, and other streets that will carry small volumes of truck traffic, LSF = 1.0.

Aside from the load safety factors, a degree of conservatism is provided in the design procedure to compensate for such things as unpredicted truck overloads and normal construction variations in material properties and layer thicknesses. Above this basic level of conservatism (LSF = 1.0), the load safety factors of 1.1 or 1.2 provide a greater allowance for the possibility of unpredicted heavy truck loads and volumes and a higher level of pavement serviceability appropriate for higher type pavement facilities.

In special cases, the use of a load safety factor as high as 1.3 may be justified to maintain a higher-than-normal level of pavement serviceability throughout the design period. An example is a very busy urban freeway with no alternate detour routes for the traffic. Here, it may be better to provide a premium facility to circumvent for a long time the need for any significant pavement maintenance that would disrupt traffic flow.

Design Examples

Full Design Procedure (Axle-Load Data Available)

Figure 1 is a worksheet showing the format for completing design problems. It requires as input data the following design factors:

- Type of joint and shoulder
- Concrete flexural strength (MR) at 28 days
- k value of the subgrade or subgrade and subbase combination
- Load safety factor (LSF)
- Axle-load distribution (Column 1)
- Expected number of axle-load repetitions during the design period (Column 3).

Both a fatigue analysis and an erosion analysis are shown on the design worksheet. The step-by-step design procedure is as follows: the design input data shown at the top of Fig. 1 are established and Columns 1 and 3 are filled out. The axle loads are multiplied by the load safety factor for Column 2.

Fatigue Analysis. Results of fatigue analysis, are the same for pavements with doweled and undoweled joints, and also for continuously reinforced pavements. The reasons for this are explained in a later section.

1. On Fig. 1, enter as items 8 and 11 the equivalent stress factors from Table 1 depending on trial thickness and k value.
2. Divide these by the concrete modulus of rupture and enter as items 9 and 12.
3. Fill in Column 4, "Allowable Repetitions," determined from Fig. 2.
4. Compute Column 5 by dividing Column 3 by Column 4, multiplying by 100, then total the fatigue at the bottom.

Figure 1. Example of design calculations.

Calculation of Pavement Thickness

Project Design 1A, four-lane Interstate, rural
 Trial thickness 9.5 in. Doweled joints: yes ☒ no ☐
 Subbase-subgrade k 130 pci Concrete shoulder: yes ☐ no ☒
 Modulus of rupture, MR 650 psi Design period 20 years
 Load safety factor, LSF 1.2
4 in. untreated subbase

Axle load, kips	Multiplied by LSF <u>1.2</u>	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 2.599. 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

11. Equivalent stress 192 13. Erosion factor 2.7912. 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	<u>62.8</u>	Total	<u>38.9</u>

Erosion Analysis.

1. Enter the erosion factors from Table 2 as items 10 and 13 in the worksheet.
2. Fill in Column 6, "Allowable Repetitions," determined from Fig. 3.

3. Compute Column 7 by dividing Column 3 by Column 6, multiplying by 100, then total the erosion damage at the bottom.

In the use of the charts, precise interpolation of allowable repetitions is not required. If the

Table 1. Equivalent stress-no concrete shoulder (single axle/tandem axle).

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

Table 2. Erosion factors--doweled joints, no concrete shoulder (single axle/tandem axle).

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

Figure 2. Fatigue analysis--allowable load repetitions based on stress ratio factor (with and without concrete shoulder).

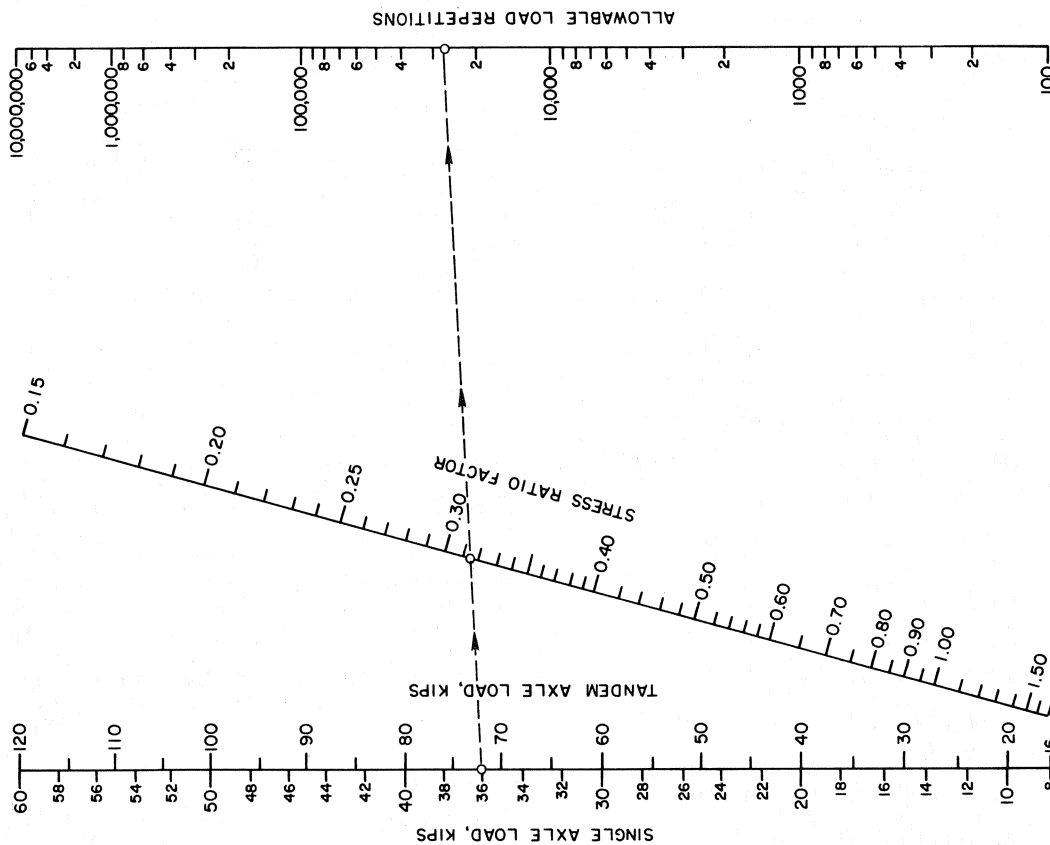
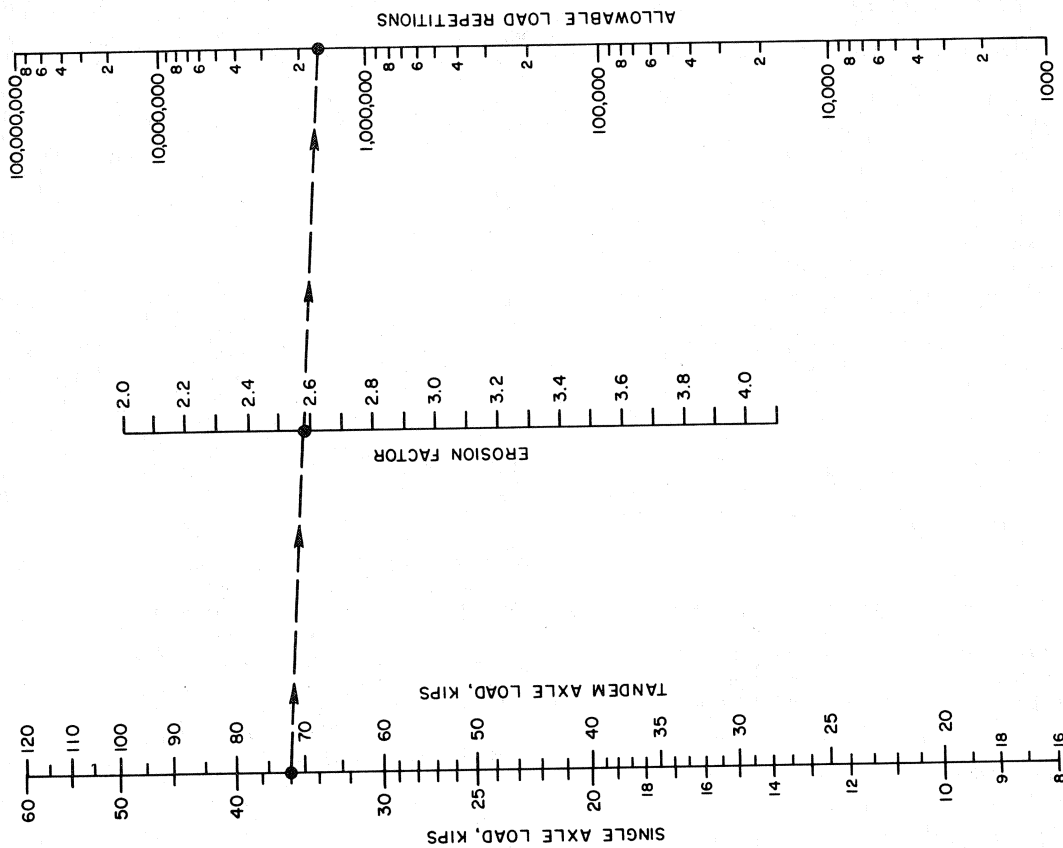


Figure 3. Erosion analysis--allowable load repetitions based on erosion factor (without concrete shoulder).



intersection line runs off the top of the chart, the allowable load repetitions are considered to be unlimited.

The trial thickness is not an adequate design if either of the totals of fatigue or erosion damage are greater than 100%. A greater trial thickness should be selected for another run. A lesser trial thickness is selected if the totals are much lower than 100%.

Comments For This Particular Example. (1) Totals of fatigue use and erosion damage of 63% and 39%, respectively, show that the 9.5-in. thickness is adequate for the design conditions, (2) this design has 37% reserve capacity available for heavy-axle loads in addition to those estimated for design purposes, (3) comments 1 and 2 raise the question of whether a 9.0-in. thickness would be adequate. Separate calculations showed that 9.0 in. is not adequate because of excessive fatigue consumptions (245%), and (4) the design is controlled by fatigue analysis in this case.

General Comments Not Necessarily Applicable to the Example Shown. (1) The fatigue analysis will usually control the design of light-traffic pavements (residential streets and secondary roads regardless of whether the joints are doweled) and medium traffic pavements with doweled joints, (2)

Table 3. Allowable ADTT,* axle-load Category 3--pavements with doweled joints.

Concrete Shoulder or Curb					
	Slab thickness, in.	Subgrade-subbase support			
		Low	Medium	High	Very high
MR = 650 psi	6.5			83	320
	7	52	220	550	1,900
	7.5	320	1,200	2,900	9,800
	8	1,600	5,700	13,800	
	8.5	6,900	23,700**		
MR = 600 psi	6.5				67
	7			120	440
	7.5		270	680	2,300
	8	370	1,300	3,200	10,800
	8.5	1,600	5,800	14,100	
MR = 550 psi	9	6,600			
	7				82
	7.5			130	480
	8	67	270	670	2,300
	8.5	330	1,200	2,900	9,700
	9	1,400	4,900	11,700	
	9.5	5,100	18,600		

*ADTT excludes two-axle, four-tire trucks; total number of trucks allowed will be greater--see Reference 2.

**Erosion analysis controls the design; otherwise fatigue analysis controls.

the erosion analysis will usually control the design of medium- and heavy-traffic pavements with undoweled joints, (3) for pavements carrying a normal mix of axle weights, single-axle loads are usually more severe in the fatigue analysis, and tandem-axle loads are more severe in the erosion analysis.

Simplified Design Procedure (Axle-Load Data Not Available)

The simplified procedure is for use when specific axle-load data are not available. Simple design tables have been generated based on composite axle-load distributions that represent different categories of road and street types. A fairly wide range of pavement facilities is covered by four categories shown in the PCA Manual.

The designer does not directly use the axle-load data because the designs have been presolved and the results are displayed conveniently in tables such as Table 3.

In these tables, subgrade-subbase strength is characterized by the words Low ($k = 75$ to 120 pci), Medium (130-170), High (180-220), and Very High (250-400), and three levels of concrete strength (MR) are shown. In addition to estimates of these design inputs, an estimate of the ADTT (average daily truck traffic, two directions) is needed; this excludes 2 axle-4 tire trucks.

A sample problem illustrates use of the simplified design procedure.

Arterial street, two lanes

Design ADT = 6200
Total trucks per day = 1440
ADTT = 630
Clay subgrade
4-in. untreated subbase
Subgrade-subbase support = low
Concrete MR = 650 psi
Doweled joints, curb and gutter

Since it is expected that axle-load magnitudes will be about the average carried by arterial streets, not unusually heavy or light, the appropriate table, reproduced here as Table 3, is selected from the design manual.

For a subgrade-subbase classed as low, Table 3 shows an allowable ADTT of 1600 for an 8-in. slab thickness and 320 for a 7.5-in. thickness. This indicates that, for a concrete strength of 650 psi, the 8-in. thickness is adequate to carry the required design ADTT of 630.

Comments. (1) Other tables similar to Table 3 provided in the PCA Manual (2) apply to doweled and undoweled joints and pavements with and without concrete shoulders, (2) a widened lane, concrete curb and gutter, or adjacent lane (parking lot) provide edge support similar to that of a concrete shoulder, and (3) the tables list the allowable ADTT for a 20-year design period; for other design periods an adjustment is required--for example, for 30 years, multiply the estimated ADTT by 1.5 for a value to use in the tables.

Tridem Axle Loads

A tridem or triple axle is a set of three axles each spaced at 48 to 54 in. apart. These are used on special heavy-duty haul trucks.

Tridem loads can be included along with single and tandem-axle loads in the design analysis by use of data given in an appendix of the design manual. Fatigue and erosion damage for tridems are added to those for single and tandem-axle loads.

Triple axles are more damaging from an erosion criteria (deflection) than from a bending stress and fatigue criteria.

Effects of Load Transfer, Shoulders, and Special Subbases

This section presents the comparative effects on slab thickness requirements of the options of using, or not using, concrete shoulders, doweled joints, cement-treated subbase, and lean concrete subbase.

Three levels of traffic situations are listed in Table 4 as follows:

- Axle Load Category 1 represents relatively light truck traffic volume and weights on a county road with a few legal axle loads per day.
- Axle Load Category 3 represents medium truck traffic on a rural Interstate route.
- Axle Load Category 4 represents a heavy truck weight and volume situation on a major urban route.

The thickness reduction effected by each of the items (doweled joints, concrete shoulder, and cement-treated subbase) is diminished somewhat when the other items are included in the pavement design.

Effect of Shoulders

Concrete shoulders reduce critical pavement stresses and deflections at slab edges and corners. They also enable the effective sealing of the joint between slab and shoulder and this prevents water from entering at the slab edge.

The benefits of concrete shoulders can be considered from two different viewpoints: To give an improved performance and longer service life, or to provide additional structural capacity that enables a reduction in thickness. Table 4 shows design thicknesses for pavements with and without shoulders. The thickness reduction is in the range of 1 to 1.8 inches depending on the design inputs; in this range the greatest thickness reductions are for pavements without doweled joints and stabilized subbases.

Effect of Dowels

Table 4 compares design thickness requirements for pavements with doweled joints and those with aggregate interlock joints. In the examples shown, the thickness differences vary from 0 in. for light traffic, to about 1 in. for medium traffic, and from about 1 to 2 in. for heavy traffic and thicker pavements. In this range, the greater thickness reductions apply to pavements without concrete shoulders and stabilized subbases.

Table 4. Examples of design thickness.

Axle Load Category	Doweled Joints	CTSB ^a	Slab Thickness, in.	
			No Concrete Shoulder	Concrete Shoulder
1 (ADTT = 40)	Yes	No	6.0	5.1
	Yes	Yes	NA ^b	NA
	No	No	6.0	5.1
	No	Yes	NA	NA
3 (ADTT = 2000)	Yes	No	8.9	7.7
	Yes	Yes	8.1	7.0
	No	No	9.9	8.6
	No	Yes	9.0	7.8
4 (ADTT = 5000)	Yes	No	9.8	8.5
	Yes	Yes	9.0	7.8
	No	No	11.7	9.9
	No	Yes	10.5	8.9

^aCement-treated subbase

^bNot applicable

Effect of Cement-Treated Subbases (CTSB)

Stabilized subbases provide higher support moduli (k-values), additional joint support, especially for undoweled joints, and are more erosion resistant than untreated subbases. Table 4 illustrates the effect of using or not using a cement-treated subbase. For pavements with doweled joints, fatigue criteria usually control the design and the benefit of CTSB is worth about 0.7 to 0.8 in. of concrete thickness. For pavements with undoweled joints and heavy traffic, erosion criteria control the design and CTSB is worth 0.8 to 1.2 in. for these thicker slabs. For Category 1, the effect of CTSB is not shown since a stabilized subbase would probably not be used.

Effect of Lean Concrete Subbases (LCB)

Lean concrete subbases provide substantial slab and joint support and are considered to be highly erosion resistant. The effects of LCB depend on the thickness of lean concrete and its strength. Thickness reductions, not shown in Table 4, have been worked out for a 4-in. lean concrete subbase (non-monolithic) with a 28-day flexural strength of 200 psi. For the axle load Category 4 data shown in Table 4, the reductions vary from 1.6 to 2.0 in.

Development of Design Procedure

This section describes details of the analysis of concrete pavements and how the critical, computed stresses and deflections were related to design criteria so that results compare favorably with pavement performance studies.

Analysis of Concrete Pavements

The design procedure is based on a comprehensive analysis of concrete stresses and deflections at pavement joints, corners, and edges by a finite-element computer program, JSLAB (5). It allows considerations of slabs with finite dimensions, variable axle-load placement, and the modeling of load transfer at transverse joints or cracks and load transfer at the joint between pavement and concrete shoulder. For doweled joints, dowel properties such as diameter and modulus of dowel-concrete reaction are used directly. For aggregate interlock, keyway joints, and cracks in continuously reinforced pavements, a spring stiffness value is used to represent the load-deflection characteristics of such joints based on field and laboratory tests. The values used were: dowel bar size--1/8 in. per inch of slab thickness; dowel-concrete reaction--2,000,000 psi; spring constant for aggregate interlock joints--5000 lb/in./in. (average of about 35% joint efficiency); tied concrete shoulder--25,000 lb/in./in. (average about 65% joint efficiency). Actual joint efficiencies depend on slab thickness and support conditions.

Jointed Pavements. After analysis of different axle-load positions on the slab, the critical placements shown in Fig. 4 were established with the following conclusions:

1. The most critical pavement stresses occur when the truck wheels are placed at or near the pavement edge and midway between the joints, Fig. 4a. Since the joints are at some distance from this location, transverse joint spacing and type of load transfer have very little effect on the magnitude of stress. In the design procedure, therefore, the analysis based on flexural stresses and fatigue yield the same values for different joint spacings and different types of load transfer mechanisms (dowels or aggregate interlock) at transverse joints. When a concrete shoulder is

tied on to the mainline pavement, the magnitude of the critical stresses is considerably reduced.

2. The most critical pavement deflections occur at the slab corner when an axle load is placed at the joint with the wheels at or near the corner, Fig. 4b. (The greatest deflections for tridems occur when two axles are placed at one side of the joint and one axle at the other side.) In this situation, transverse joint spacing has no effect on the magnitude of corner deflections but the type of load transfer mechanism has a substantial effect. This means that design results based on the erosion criteria (deflections) may be substantially affected by the type of load transfer selected.

Continuously Reinforced Pavements. A continuously reinforced concrete pavement (CRCP) is one with no transverse joints and, due to the heavy, continuous steel reinforcement in the longitudinal direction, the pavement develops cracks at close intervals. These crack spacings on a given project are variable, running generally from 3 to 10 ft with averages of 4 to 5 ft.

In the finite-element computer analysis, a high degree of load transfer was assigned at the cracks of CRCP and the crack spacing was varied. The critical load positions established were the same as those for jointed pavements.

For the longer crack spacings, edge stresses for loads placed midway between cracks are of about the same magnitude as those for jointed pavements. For the average and shorter crack spacings, the edge stresses are less than those for jointed pavements, because there is not enough length of uncracked pavement to develop as much bending moment.

For the longer crack spacings, corner deflections are somewhat less than those for jointed pavements with doweled transverse joints. For average-to-long crack spacings, corner deflections are about the same as those for jointed, doweled pavements. For short crack spacings of 3 or 4 ft, corner deflections are somewhat greater than those for jointed, doweled pavements, especially for tandem-axle loads.

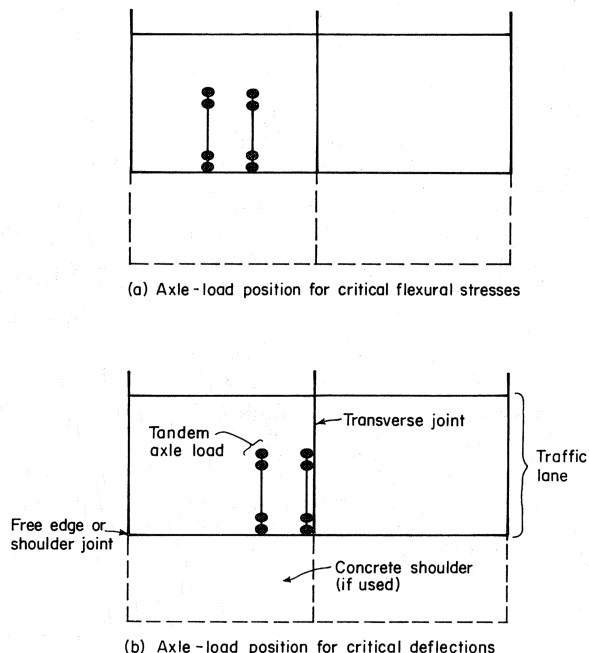
Considering natural variations in crack spacing that occur in one stretch of pavement, the following comparison of continuously reinforced pavements with jointed, doweled pavements is made. Edge stresses will sometimes be the same and sometimes less, while corner deflections will sometimes be less, the same, and greater at different areas of the pavement depending on crack spacing.

The average of these pavement responses is neither substantially better nor worse than those for jointed, doweled pavements. As a result, in this design procedure, the same pavement responses and criteria are applied to continuously reinforced pavements as those used with jointed, doweled pavements. This recommendation is consistent with pavement performance experience. Most design agencies suggest that the thickness of continuously reinforced pavements should be about the same as the thickness of doweled-jointed pavements.

Truck Load Placement

Truck wheel loads placed at the outside pavement edge create more severe conditions than any other load position. As the truck placement moves inward a few inches from the edge, the effects decrease substantially.

Figure 4. Critical axle load positions.



Only a small fraction of all the trucks run with their outside wheels placed at the edge. Most of the trucks are driven with their outside wheel placed about 2 ft from the edge. Taragin's (6) studies showed very little truck encroachment at pavement edge for 12-ft lanes for pavements with unpaved shoulders. More recent studies by Emery (7) showed more trucks at edge. Other recent studies (8) showed fewer trucks at edge than Emery. For this design procedure, the most severe condition, 6% of trucks at edge, is assumed so as to be on the safe side and to take account of recent changes in United States law permitting wider trucks.

At increasing distances inward from the pavement edge, the frequency of load applications increases while the magnitudes of stress and deflection decrease. Truck placement distribution and distribution of stress and deflection due to loads placed at and near the pavement edge are difficult to use directly in a design procedure. As a result, these distributions were analyzed and more easily applied techniques were prepared for design purposes.

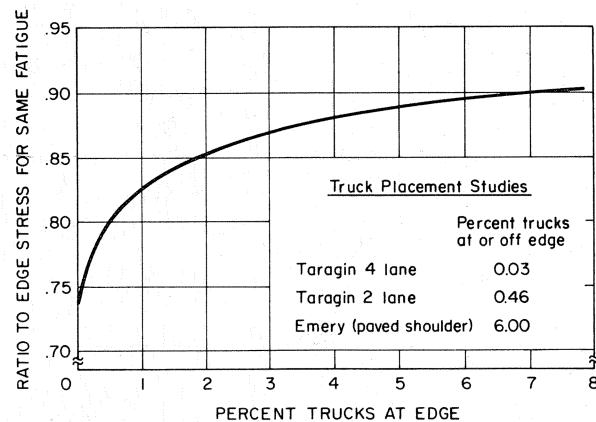
For stress-fatigue analysis, fatigue was computed incrementally at fractions of inches inward from the slab edge for different truck-placement distributions; this gave the equivalent edge-stress factors shown in Fig. 5. (This factor, when multiplied by edge-load stress, gives the same degree of fatigue consumption that would result from a given truck placement distribution.) The most severe condition, 6% truck encroachment, has been incorporated in the design procedures.

For erosion analysis, which involves deflection at the slab corner, the most severe case (6% of trucks at edge) is again assumed. Where there is no concrete shoulder, corner loadings (6% of trucks) are critical; and where there is a concrete shoulder, the greater number of loadings inward from the pavement corner (94% of trucks) are critical. These factors are incorporated into the design charts and computer programs as follows:

$$\text{Percent erosion damage} = 100 \Sigma n_i (C/N_i) \quad (1)$$

where n_i = expected number of axle-load repetitions for axle-group i .
 N_i = Allowable number of repetitions for axle-group i
 C = 0.06 for pavements without shoulder, and 0.94 for pavements with shoulder.

Figure 5. Equivalent edge stress factor depends on percent of trucks at edge.



Variation in Concrete Strength

Recognition of the variations in concrete strength is considered a realistic addition to the design procedure. Expected ranges of variations in the concrete's modulus of rupture have far greater effect than the usual variations in the properties of other materials, such as subgrade and subbase strength, and layer thicknesses. Variation in concrete strength is introduced by reducing the modulus of rupture by one coefficient of variation.

For design purposes, a coefficient of variation of 15% is assumed and is incorporated into the design charts, tables, and computer programs. The user does not directly apply this effect. The value of 15% represents fair-to-good quality control, and, combined with other effects discussed elsewhere in this section, was selected as being realistic and giving reasonable design results.

Concrete Strength Gain With Age

The 28-day flexural strength (modulus of rupture) is used as the design strength. This design procedure, however, incorporates the effect of concrete strength gain after 28 days. This modification is based on an analysis that incremented strength gain and load repetitions month by month for a 20-year design period. The effect is included in the design charts and tables so the user simply inputs the 28-day value as the design strength.

Warping and Curling of Concrete

In addition to traffic loading, concrete slabs are also subjected to warping and curling. Warping is the upward concave deformation of the slab due to variations in moisture content with slab depth. The effect of warping is twofold: It results in loss of support along the slab edges and also in residual compressive stresses in the slab bottom. Curling refers to slab behavior due to variations of temperature. During the day, when the top surface is warmer than the bottom, tensile-restraint stresses develop at the slab bottom. During the night, the temperature distribution is reversed and tensile restraint stresses develop at the slab surface. Temperature distribution is usually nonlinear and constantly changing. Also, maximum daytime and nighttime temperature differentials exist for short durations.

Usually the combined effect of curling and warping stresses are subtractive from load stresses because the moisture content and temperature at the bottom of the slab exceed that at the top more than the reverse.

The complex situation of differential conditions at a slab's top and bottom plus the uncertainty of the zero-stress position make it difficult to compute or measure the restraint stresses with any degree of confidence or verification. At present, the information available on actual magnitudes of restraint stresses does not warrant incorporation of the items in the procedure.

As for the loss of support, this is considered in the erodability criterion, which is derived from actual field performance and therefore incorporates normal loss of support conditions.

Calculated stress increase due to loss of support varies from about 5% to 15%. This theoretical stress increase is counteracted in the real case because a portion of the load is dissipated in

bringing the slab edge back in contact with the support before the maximum stress is reached. Thus, the incremental load stress due to a warping-type loss of support is not incorporated in this design procedure.

In addition to the analysis of stresses and deflections for flat slabs, the finite-element analysis included data for slabs without support for 20 inches around their periphery. For the reasons discussed above, the data for these curled slabs and for restraint stresses were not selected for use in the design procedure. This was an arbitrary decision made to simplify a very complex situation. However, it should be noted that if the curled slab data had been selected for design purposes, a different set of criteria (allowable values of stress and deflection) would have been selected so that design results would agree with pavement performance studies.

Fatigue

The flexural fatigue criterion used in the procedure is similar to that used in the previous PCA method (1) except that it is applied to edge-load stresses that are of higher magnitude. It is based conservatively on studies of fatigue research (9-13). A modification in the high load-repetition range has been made to eliminate the discontinuity in the previous curve that sometimes caused unrealistic effects.

The allowable number of load repetitions for a given axle load is determined based on the stress ratio, SR (flexural stress divided by the 28-day modulus of rupture). The fatigue curve is incorporated into the design charts for use by the designer. Equations for the new fatigue curve are (N equals allowable number of load repetitions):

Stress Ratio	Equation
> 0.55	$\log_{10} N = (0.9718 - SR)/0.0828$
0.45 to 0.55	$N = (4.2577/(SR - 0.4325))^{**3.268}$ (2)
< 0.45	N = unlimited

Use of the fatigue criterion is made on the Miner hypothesis that fatigue resistance not consumed by repetitions of one load is available for repetitions of other loads. In a design problem, the total fatigue consumed should not exceed 100%.

Combined with the effect of reducing the design modulus of rupture by one coefficient of variation, the fatigue criterion is considered to be conservative for thickness design purposes.

Erosion

It has been apparent that there is an important mode of distress in addition to fatigue cracking that needs to be addressed in the design process. This is the erosion of material beneath and beside the slab. Many repetitions of heavy axle loads at slab corners and edges cause pumping; erosion of subgrade, subbase, and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints, especially in pavements with undoweled joints.

These particular pavement distresses are considered to be more closely related to pavement deflections than to flexural stresses.

Correlations of deflections computed from the finite-element analysis (5) with AASHO Road Test (14) performance data were not completely satisfactory for design purposes. (The principal mode

of failure of concrete pavements at the AASHO Road Test, all with doweled joints, was pumping or erosion of the granular subbase from under the slabs.) It was found that to be able to predict the AASHO Road Test performance, different values of deflection criteria would have to be applied to different slab thicknesses, and to a small extent, different foundation moduli (k values). More useful correlation was obtained by multiplying the computed corner deflection values (w) by computed pressure values (p) at the slab-foundation interface. These values were computed without the use of load safety factors. Power, or rate of work, with which an axle load deflects the slab is the parameter used for the erosion criterion—for a unit area, the product of pressure and deflection divided by a measure of the length of the deflection basin (l_e —radius of relative stiffness, in inches). The concept is that a thin pavement with its shorter deflection basin receives a faster load punch than a thicker slab. That is, at equal pw's and equal truck speed, the thinner slab is subjected to a faster rate of work or power (inch-pound per second).

Successful correlation to road test performance, conservatively set at a terminal PSI of 3.0, was obtained with the following expression in which the allowable number of load repetitions decreases with:

$$P = \text{power} = \frac{p (\text{unit area}) w}{l_e / (\text{truck speed})} (\text{a constant}) / k^{0.0633} \quad (3)$$

$$= \frac{pw}{h} k^{0.27} 268.7 = 268.7 p^2 / h / k^{0.73}$$

where: p and w have been defined above, and

h = slab thickness, in.

l_e = radius of relative stiffness, elastic subgrade, in.

k = modulus of subgrade reaction, pci.

Truck speed is not a design variable; it is used to introduce length of deflection basin in time units.

This produced a single criteria that explained the performance of slabs of different thicknesses and foundation strengths at the test road.

Included in the development of the erosion criteria, were correlation of the design results with studies on joint faulting by Brokaw (15) and Packard (16). In these studies, the degree of joint faulting and serviceability of pavements was related to pavement thickness, heavy truck count, and other factors. These studies included pavements in Wisconsin, Minnesota, North Dakota, Georgia, and California, and included a range of variables not found at the AASHO Road Test. These include: a greater number of trucks, undoweled pavements, a wide range of years of pavement service, and stabilized subbases. It was intended that the erosion criteria be developed to fit the road test data and the results of these faulting studies. The expression for the erosion criteria resulting from the above considerations is:

$$\log N = 14.524 - 6.777 (C_1 P - 9.0) 0.103 \quad (4)$$

where: N = allowable load repetitions to end of design period

P = power as defined above in terms of h and k

The constants in the equation were selected to make the expression fitting the road test data also fit the faulting studies; C_1 is an adjustment that has a value close to 1.00 for normal, untreated subbases and decreases to about 0.90 for stabilized subbases. The equation for erosion damage is:

$$\text{Percent Erosion Damage} = 100 \sum n_i (C_2/N_i) \quad (5)$$

where: n_i = expected number of axle load repetitions in axle group i

N_i = allowable number of repetitions in axle group i

C_2 = (for 6 percent trucks at edge)
0.06 for pavements without shoulder,
and 0.94 for pavements with concrete shoulder.

Design charts show allowable N values as N_i/C_2 , to save a calculation step.

Table 5 shows pavement thicknesses derived from the erosion criteria compared with terminal roughness due to faulting (SVF), terminal serviceability (PSI), and terminal joint faulting; the latter three items were determined from the two faulting studies. Generally accepted terminal values are: SVF 11 to 14, PSI 2.0 to 3.0, and faulting of 4 to 7 thirty-seconds of an inch. It can be seen that the design thicknesses, when incorporated as inputs to the equations from the other studies, do approximately predict appropriate terminal conditions.

Brokaw's studies of undoweled pavements suggest that climate or drainage is a significant factor in pavement performance. The effects are illustrated in Table 5 where the terms, Good and Poor, refer to whether the pavement foundation is predominantly in a free-draining, or dry, condition or in a poorly drained wet condition. So far, this aspect of design has not been included in the design procedure, but it deserves further study. Investigations of the effects of climate on design and performance of concrete pavements have also been reported by Darter (17).

The erosion criterion is suggested for use as a guideline. It can be modified according to local experience since climate, drainage, local factors, and design innovations may have an influence. Accordingly, the 100% erosion-damage criterion, an

index number correlated with general performance experience, can be increased or decreased based on specific performance data gathered in the future for more favorable or more adverse conditions.

Effect of Tire Size and Spacing

Tire sizes and dual wheel spacings are greater for larger trucks and heavier axle loads. As tire contact areas and wheel spacings increase for heavier loads, stresses do not increase quite proportionally to load. To recognize this, stresses are taken proportional to load to the exponent 0.94 (18). Deflections are not so affected.

Subgrade Support Beyond Pavement Edge

Conventional theories on layered systems and their computer programs assume that subgrade-subbase layers do not exist beyond the pavement edge. Since it is obvious that the subgrade very near the edge responds to edge loading, the effect of this support was studied by use of the MATS computer program (19). For different k -values and slab thicknesses, the slab responses were equal to, or slightly less than, 89.6 percent and 96.7 percent of deflections and stresses respectively, of those determined without outside support. These factors are incorporated into the procedure only for pavements without concrete shoulders. With a concrete shoulder, the support outside the shoulder edge is too far away from truck loads to have any effect.

Lean Concrete Lower Course

An appendix in the PCA Manual describes the thickness design procedure for composite concrete pavements incorporating a lower layer of lean concrete, either as a subbase constructed separately or as a lower layer in monolithic construction. Lean concrete is stronger than conventional subbase materials and is considered to be nonerodable. Recognition of its superior structural properties can be taken by a reduction in thickness design requirements.

The design procedure indicates a thickness for a two-layer concrete pavement equivalent to a given thickness of normal concrete. The equivalence is

Table 5. Comparison of new design procedure to studies of pavement performance, undoweled pavements.

Data from New Design Procedure				Data from Other Sources				
Axle Load Category	TST ^a Per Day (30 years)	Design Thickness, in.	Subbase	Reference 15			Reference 16	
				Drainage	SVF ^b	PSI ^c	Fault ^d	
							15 ft ^e	20 ft ^e
4	1600	11.0	Granular	Good	6	3.0	3.8	4.8
		11.0	Granular	Poor	26	2.3	5.1	6.7
		10.0	Cement tr.	Good	NA ^f	NA	4.6	4.8
		10.0	Cement tr.	Poor	NA	NA	6.3	6.6
3	356	9.0	Granular	Good	4	3.0	4.0	5.1
		9.0	Granular	Poor	15	2.5	5.4	7.1
		8.3	Cement tr.	Good	NA	NA	4.7	4.9
		8.3	Cement tr.	Poor	NA	NA	6.4	6.8

^aTractor-semi-trailer trucks

^bPavement roughness due to faulting (slope variance)

^cPresent serviceability index

^dJoint faulting, 32nds of an inch

^eJoint spacing

^fNot applicable

based on providing thickness for a two-layer concrete pavement that will have the same margin of safety for fatigue and erosion as a single-layer normal concrete pavement. The criteria are that (1) stress ratios in either of the two concrete layers not exceed that of the reference pavement; and (2) erosion values at the subbase-subgrade interface not exceed those of the reference pavement. Rationale for the criteria is given in Reference 20 plus two additional considerations: (1) erosion criteria is included in addition to the fatigue approach given in the reference; and (2) for nonmonolithic construction, some structural benefit (21) is added because the subbase is constructed wider than the pavement.

Summary

The new thickness design procedure developed by the Portland Cement Association is reviewed. Design criteria include the erosion of subbase materials and faulting of pavements as well as the traditional fatigue cracking mechanism. The procedure applies to both jointed pavements, plain and reinforced, and continuously-reinforced pavements. Special topics include analysis of tridem axles and lean concrete subbases.

The design is based on pavement stress and deflection data determined with a finite-element computer program that models doweled and aggregate interlock joints, and pavements with and without concrete shoulders.

Details of the development of the design method include the setting of criteria for fatigue and erosion damage, based on pavement performance at the AASHO Road Test and pavement faulting studies. The effects of truck load placement, variation of concrete strength, warping and curling of slabs, and other factors are discussed.

The effects of doweled and aggregate interlock joints, concrete shoulders, cement-treated subbases, and lean concrete subbases are illustrated with examples of slab thickness requirements.

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