Design of Slab Thickness and Joint Spacing for Jointed Plain Concrete Pavement

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A structural design procedure for jointed plain concrete pavement (JPCP) is presented. The design system considers directly the slab thickness, slab length, concrete strength, traffic volume and distribution, foundation support, and thermal gradients, using fundamental structural principles. The procedure was calibrated to actual field conditions by correlating the actual amount of transverse cracking and total computed fatigue damage in the slab. Field data from 11 agencies were used. The design system shows that, for a given traffic level, climate, and foundation support, there are definite combinations of slab thickness, strength, and length (joint spacing) that must be used to control slab cracking. A thicker slab permits an increase in slab length for the same amount of transverse cracking. As more transverse cracking is tolerated (as on lower-volume roads), a longer joint spacing is allowed. Decreasing the level of axle load distribution from a heavy to a moderate level would decrease the slab thickness or allow a longer slab to be used or both. The effect of foundation support (K) at a higher level of allowable cracking is appreciable compared with the effect at a lower level of cracking. The modulus of rupture (M_R) has a pronounced effect on both slab thickness and joint spacing.

The structural design of jointed plain concrete pavement (JPCP) has traditionally been performed by determining a required slab thickness from fatigue (1) or serviceability analysis (2) and independently selecting a maximum joint spacing to minimize jointing costs (particularly when dowels are used). This practice has led to a substantial amount of intermediate slab cracking over time and under traffic for the longer slabs.

For example, the 12-, 13-, 19-, 18-ft random spacing used by many agencies results in the 18- and 19-ft slabs cracking whereas the 12- and 13-ft slabs rarely crack. The 25- and 30-ft slabs constructed by several states have generally had substantial intermediate cracking over time under traffic. Most of the 12-, 13-, 19-, and 18-ft slabs have been 8 to 9 in. thick and the 30-ft slabs 10 in. thick. Many agencies have now reduced their joint spacing to minimize slab cracking. Some agencies are also beginning to construct thicker slabs (10 to 14 in.) for heavily trafficked routes while using the same joint spacing as for thinner slabs.

In this paper, a design procedure is presented that provides both a required slab thickness and a corresponding maximum joint spacing to limit slab cracking for given traffic, thermal gradients, portland cement concrete (PCC) strength, and foundation support. The procedure was developed from basic structural concepts and correlated with extensive field data from several agencies.

BASIC DESIGN CONCEPT

The basic concept in developing a design procedure based on fatigue analysis is to prevent cracking of the slabs, which is one of the most serious types of pavement distress requiring rehabilitation.

Finite-Element Model

An evaluation was conducted to determine the best structural analysis program for jointed concrete pavement. Several programs were evaluated (3), and the results show that the finite-element slab analysis program developed by Huang and Wang (4) has the desirable capabilities for analysis of JPCP slabs. This program has many important capabilities, including the determination of (a) stresses and deflections in concrete pavement slabs with full or partial subgrade contact, (b) variable load transfer of transverse and longitudinal joints, and (c) the effect of thermal gradients on curling stresses, both independently and in combination with traffic load. The method is based on the theory of minimum potential energy by dividing the slab into small elements, considered thin plates, interconnected only at a finite number of nodal points. Other major advantages of the finite-element method are that computed stresses agree well with experimental results (3), elements of varying sizes can be easily incorporated in the analysis, and no special treatment is needed at a free edge.

Critical Fatigue Location in Slab

The location of the critical point at which cracking initiates in the PCC slab is vital to the development of a fatigue analysis when the objective is to prevent slab cracking. The location of the critical point is approached by using both field studies and a comprehensive slab fatigue analysis. Results from highway field studies (5,6) indicate that in slabs of normal thickness (>8 in.) cracking usually initiates at the slab edge and propagates transversely across the slab. These cracks are usually located in the center third of the slab. Available data (6) also indicate that transverse cracking occurs much more often than longitudinal or corner cracking. However, where serious pumping has occurred at the transverse joint, corner breaks or diagonal cracks also occur. Longitudinal cracking in the wheel path or in the center of the slab is believed to be initiated by either large compressive stresses from joint infiltration or foundation settlement. However, some longitudinal cracks certainly are load caused and occur as second-stage slab breakup.

A comprehensive fatigue analysis was conducted by using the finite-element program and Miner's fatigue damage hypothesis to determine theoretically the critical point in the slab where cracking should initiate if caused by truck loadings. Two critical positions in the slab were evaluated based on the results from the field studies: (a) near the transverse joint in the wheel paths, where longitudinal cracking often initiates, and (b) along the outside edge at midslab between the transverse joints, where transverse cracking initiates. A fatigue analysis was conducted by considering typical variations in truck axle weights, axle types, and lateral displacement across the slab. Stresses in the slab were computed by using the finite-element program for different magnitudes and lateral positions of the load. Stresses were computed over a range of slab thickness (H) and modulus of foundation support (K). Fatigue damage (D) was then computed by using these stresses and Miner's cumulative damage hypothesis (7).

Results from the analysis for midslab show that, when the mean lateral placement is less than 36 in., the critical fatigue damage point is clearly at the slab edge (see Figure 1). In addition, the fatigue damage at the midslab edge loading is much greater than the fatigue damage near the transverse joint

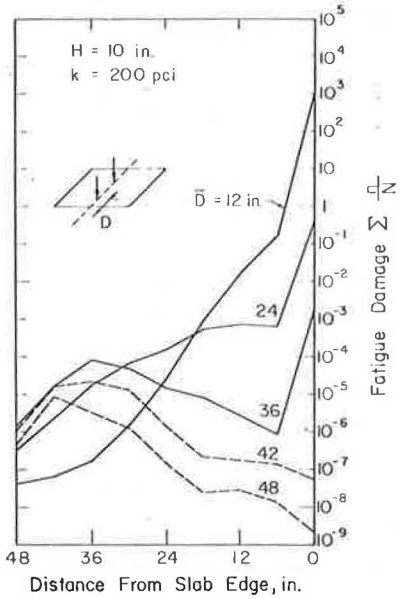


Figure 1. Computed fatigue damage across slab due to lateral distribution of trucks in lane (at midpoint between transverse joints).

for any lateral distance. These analytic results agree with the field studies mentioned earlier, in which extensive pumping has not occurred. Beams cut from slabs show that the fatigue cracks initiate at the bottom of the slabs and work their way toward the top with increasing load applications.

DEVELOPMENT OF FATIGUE DAMAGE ANALYSIS

A comprehensive fatigue damage analysis for PCC slabs was developed based on the following:

1. The critical fatigue damage location in the slab is at the longitudinal edge midway between transverse joints.
2. Critical edge stresses caused by both traffic loads and thermal gradient curl are considered to prevent transverse cracking.
3. Both load and thermal curl stresses are computed by using the finite-element program, which has been shown to provide accurate results.
4. The proportion of traffic occurring near the slab edge is used in the fatigue analysis.
5. Concrete strength changes with time and thus the fatigue analysis must be time-dependent.
6. Fatigue damage is computed according to the Miner hypothesis.
7. A correlation between computed fatigue damage and measured cracking was determined, and thus a limiting damage to control slab cracking can be selected.

PCC Fatigue

Several laboratory studies have shown that plain PCC beams experience fatigue failure when subjected to high repetitive flexural stresses (8-17). In addition, several road tests and many in-service PCC slabs have been observed to experience fatigue failure when subjected to many applications of heavy truck traffic (5,18). Fatigue damage is obvious on many multilane pavements where the outside truck lane has much more slab cracking than the inner lanes. However, no correlation between laboratory and field fatigue results has been attempted.

The results from laboratory studies provide significant information about the fatigue properties of PCC applicable to pavement fatigue conditions:

1. The number of repeated loads that PCC can sustain in flexure before fracture depends on the ratio of applied flexural stress to the ultimate static flexural strength or modulus of rupture.
2. PCC does not have a fatigue limit within 20 million load applications; hence, there is no limiting repeated stress below which the life will be infinite (8-10). The mean fatigue strength of PCC, which is the strength expressed as a percentage of the static ultimate strength, is approximately 55 percent at 10 million applications of load (11).
3. Application of varying flexural stress levels gives different fatigue results depending on the sequence of applied loads of varied intensity (10,11). Thus, Miner's damage hypothesis, which assumes linear accumulation of damage, does not give an exact prediction of PCC failure. However, data from recent tests indicate that the inaccuracy of Miner's hypothesis is not very significant compared with the large variability in strength and fatigue life that is typical of PCC (19). Hence, it was concluded that Miner's hypothesis represents the cumulative damage characteristics of concrete in a reasonable manner (19).
4. Fatigue life of PCC is highly variable; coefficients of variation range up to 100 percent.
5. Repeated rest periods during a fatigue test increase fatigue strength, and thus some recovery occurs during the rest periods (11).
6. The effect of moisture conditions of PCC under flexural fatigue has not been fully determined. Some limited tests indicate that high moisture content gives lower fatigue strength (10,20). A recent limited study tends to indicate that saturation affects fatigue life but does not significantly change fatigue strength (21); however, the results are not conclusive.
7. The increase in PCC modulus of rupture with time significantly affects the increase in fatigue life but not fatigue strength as long as the modulus of rupture at the specific time is used to compute the stress ratio (21).

Fatigue data were obtained for plain PCC beams from three studies (9,19,21). A plot of stress/strain versus number of load applications for 140 tests from these studies is shown in Figure 2. The data from the three studies generally overlap each other.

The applicability of these laboratory fatigue results from beam specimens to the fatigue of actual pavement slabs under field conditions has never been established. Many of the differences that exist between laboratory and field conditions probably result in different fatigue responses. Moreover, the uncertainty about many factors that might affect PCC fatigue life is so great and available information so limited that any laboratory curves used to estimate fatigue damage in field slabs must be calibrated based on field data, as done later in this paper.

A fatigue curve must be selected for design purposes. After consideration of a number of factors, the following curve was selected for design:

$$\text{Log}_{10}N = 16.61 - 17.61(R) \quad (1)$$

where N is the number of stress applications to failure and R is the ratio of repeated flexural stress to modulus of rupture. This expression, compared with the mean regression curve ($P_F = 0.5$), provides a safety margin of one decade of load application, as shown in Figure 2, and represents a failure probability of 24 percent.

Figure 2. Summary of PCC flexural fatigue data with curve used.

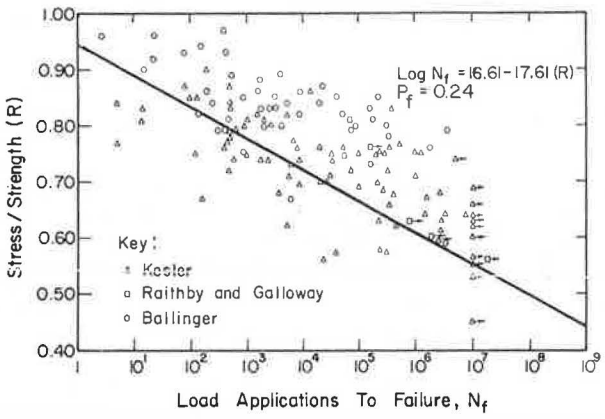
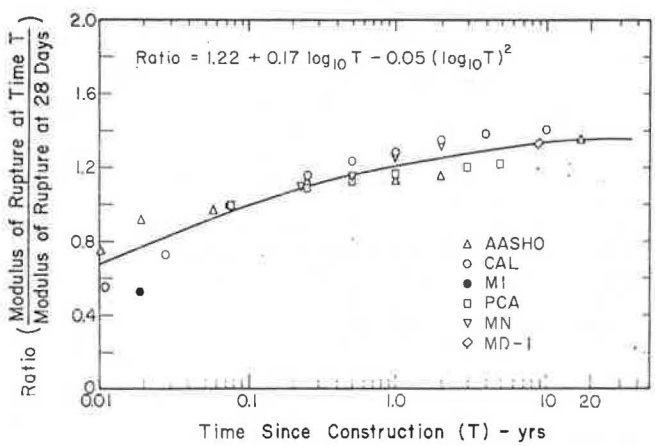


Figure 3. Change in PCC modulus of rupture with time.



PCC Strength Increase

PCC strength data were obtained from five projects located in as many states (22-25) and also from the Portland Cement Association (1). The modulus of rupture at times ranging from 3 days to 17 years was obtained from tests on beams cast during construction and then cured over time and beams cut from slabs over time (see Figure 3). The following equation was obtained by using multiple regression techniques:

$$F_A = 1.22 + 0.17 \log_{10}T - 0.05(\log_{10}T)^2 \quad (2)$$

where F_A is the ratio of the modulus of rupture at time T to the modulus of rupture at 28 days and T is the time since slab construction (years).

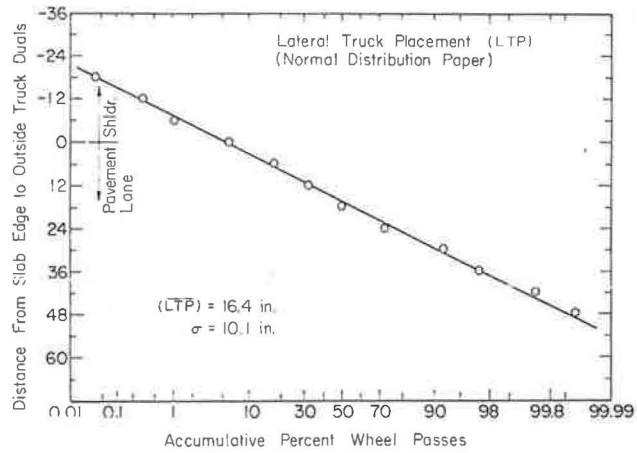
The modulus of rupture can be estimated at any time T by using the following expression:

$$F = F_A(F_{28}) \quad (3)$$

where F is the modulus of rupture at time T and F_{28} is the modulus of rupture at 28 days (third-point loading).

The above equations can be used to estimate the ultimate modulus of rupture at any time over the life of the pavement for use in the fatigue damage analysis.

Figure 4. Lateral distribution of trucks in outer lane on four-lane freeway.



Lateral Truck Distribution

The lateral placement of trucks in the traffic lane is crucial because of the high longitudinal edge stresses that develop when the wheel load is near the edge. The lateral distribution varies with several factors, such as the width of the traffic lane, the location of the edge stripe, paved or unpaved shoulders, any edge restraints such as retaining walls, and the existence of curb and gutter.

The lateral distribution should be measured for local conditions, and only general guidelines are given as to the typical range of the mean distance. If heavy trucks travel on the average down the center lane, the mean distance (for a 12-ft-wide lane and an 8-ft-wide truck) would be 24 in. However, available evidence indicates that when there is a paved shoulder and no lateral obstructions, there is a definite tendency for trucks to shift about 3 to 12 in. toward the slab edge, which gives a mean value for lateral distribution of approximately 12 to 21 in. Bureau of Public Roads measurements at 15 locations in 1956 for 12-ft concrete traffic lanes and paved shoulders on two-lane rural highways showed an average of 11 in. (26). Studies by Emery (27) in 1975 showed a mean of approximately 16 to 18 in. on rural four-lane Interstate highways. The lateral distribution obtained from Emery is approximately normal and the standard deviation is 10 in., as shown in Figure 4.

Results from the study by Emery (27) show that on rural Interstate highways with paved shoulders approximately 10 percent of loads were within 6 in. of the slab edge. Several of our own observations tend to confirm that there is a significant proportion of loads near the edge. Additional data are greatly needed to establish lateral placements of trucks for varying conditions.

Thermal Gradients

The thermal gradient in the PCC slab is defined as follows:

$$G = (T_{top} - T_{bottom})/H \quad (4)$$

where

G = thermal gradient (°F/in.),
T_{top} = temperature at the top of the slab (°F),
T_{bottom} = temperature at the bottom of the slab (°F), and
H = PCC slab thickness (in.).

A positive gradient indicates that the top of the slab is warmer than the bottom, which normally occurs during the daytime. A negative gradient indicates that the bottom is warmer than the top, which normally occurs during the nighttime. A positive gradient results in tensile stress at the bottom of the slab, and a negative gradient results in compressive stress at the bottom of the slab. During times when the gradient is positive (termed daytime), the total combined stress at the bottom of the slab edge midway between the joints under traffic load will be much greater than during the times when the gradient is negative (termed nighttime).

The temperature gradient varies continually throughout a 24-hr period and also varies from month to month. A mean monthly positive daytime gradient and mean nighttime gradient can be used in design.

Computation of PCC Fatigue

A fatigue analysis procedure was developed based on the results discussed previously to provide a method of estimating traffic damage that could result in slab cracking. The basic fatigue design philosophy for plain jointed pavements is that transverse cracking must be controlled. This is possible through direct consideration of traffic loadings, thermal gradients, joint spacing, and foundation support. The PCC slab is subjected to many applications of heavy traffic loads. At the same time, it also experiences stresses due to temperature gradients, which have been shown to have a significant effect. Curling of the slab also results in gaps between the slab and the subbase that increase the stress under load.

The major steps in the fatigue analysis are as follows:

1. Determine the number of axle applications in each single and tandem axle-load group;
2. Select the trial slab-subbase structure, transverse joint spacing, PCC strength, thermal gradients, and other required factors; and
3. Compute the fatigue damage occurring at the slab edge for a given month, both day and night, by using Miner's cumulative damage hypothesis (7) and sum the damage monthly over the entire design period:

$$\text{Damage} = \sum_{k=1}^{k=p} \sum_{j=1}^{j=2} \sum_{i=1}^{i=m} (\text{nijk}/\text{Nijk}) \quad (5)$$

where

Damage = total accumulated fatigue damage occurring at the slab edge over the design period;
nijk = number of applied axle-load applications of magnitude over day or night for the month;
Nijk = number of allowable axle-load applications of magnitude over day or night for the month determined from the PCC fatigue curve;
i = a counter for magnitude of axle load, both single and tandem axle;
j = a counter for day and night (j=1 is day and j=2 is night);
k = a counter for months over the design period;
m = total number of single and tandem axle-load groups; and
p = total number of months in the design period.

The fatigue damage is computed at the slab longitudinal edge midway between joints.

Applied Traffic

The applied traffic (nijk) is computed by using the traffic data for the month under consideration:

$$\text{nijk} = (\text{ADTm})(\text{T}/100)(\text{DD}/100)(\text{LD}/100)(\text{A})(30)(\text{P}/100)(\text{C}/100)(\text{DN}/100)(\text{TF}/100)(\text{CON}/100) \quad (6)$$

where

ADT = average daily traffic at the end of the specific month under consideration,
T = trucks in ADT (%),
DD = traffic in direction of design lane (%),
LD = land distribution factor (percentage of trucks in design lane in one direction),
A = mean number of axles per truck,
P = axles in ith load group (%),
C = total axles in the lane within 6 in. of the edge (%),
DN = trucks during day or night (%),
TF = factor to either increase or decrease truck volume for the specific month, and
CON = 1 for single axles, 2 for tandem axles.

Allowable Traffic

The allowable traffic (Nijk) is computed from the PCC fatigue model. First, the total stress occurring at the edge of the slab for a given axle load is computed by considering both traffic load and slab curling for the given month for either day or night conditions. The stress is computed for edge loading of both single and tandem axles by using models developed from the finite-element program, which realistically considers the combination of load stress and slab curling stresses. The stress equations were derived by using multiple stepwise regression techniques from a factorial of data obtained from the finite-element program over a wide range of design variables.

A computer program called JCP-1 was developed to compute the accumulated fatigue damage over the design life of the pavement. These data can be used to evaluate and design a JPCP with reference to fatigue damage.

LIMITING FATIGUE CONSUMPTION

The fatigue analysis that has been developed is quite comprehensive in that it considers directly the effects of traffic loadings, thermal gradient through the slab, joint spacing, loss of foundation support (pumping), and increase in PCC strength over time. However, several factors are not considered because of insufficient information. One of the most important of these factors may be the use of PCC fatigue curves obtained from small beams to estimate the fatigue life of large, fully supported pavement slabs. In addition, there are considerable differences between traffic loading conditions in the laboratory and in the field. Other inadequacies could be cited, but the point to be made is that the final accumulated fatigue damage based on the stress equations computed for a pavement slab must be correlated with measured slab cracking before a limiting fatigue consumption can be selected with confidence for design.

According to Miner's hypothesis, a material should fracture when the accumulated damage equals 1.0. Even if this hypothesis were exactly correct, the variability of material strengths, loads, and other properties would cause a variation in accumulated damage ranging from much less than 1.0 to much greater. For example, the PCC concrete laboratory data shown in Figure 2 indicate a computed damage

Figure 5. Effect of fatigue damage on cracking of plain jointed PCC pavements.

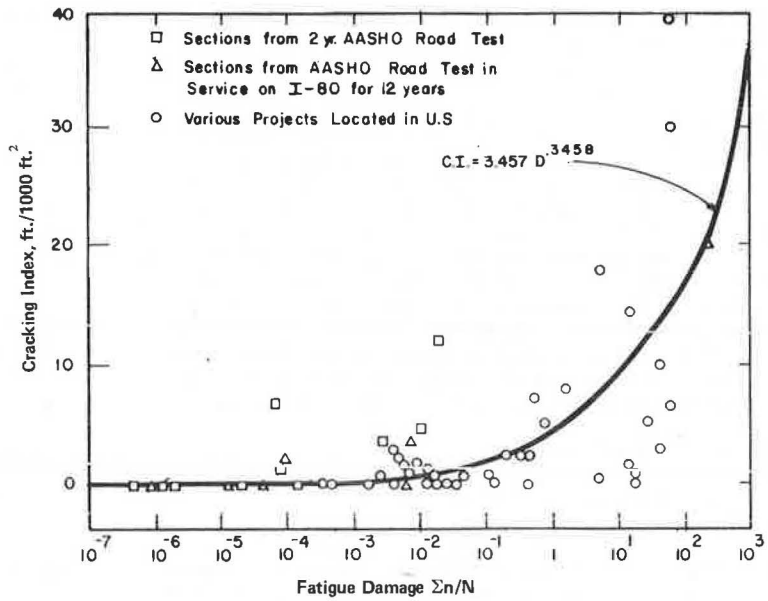
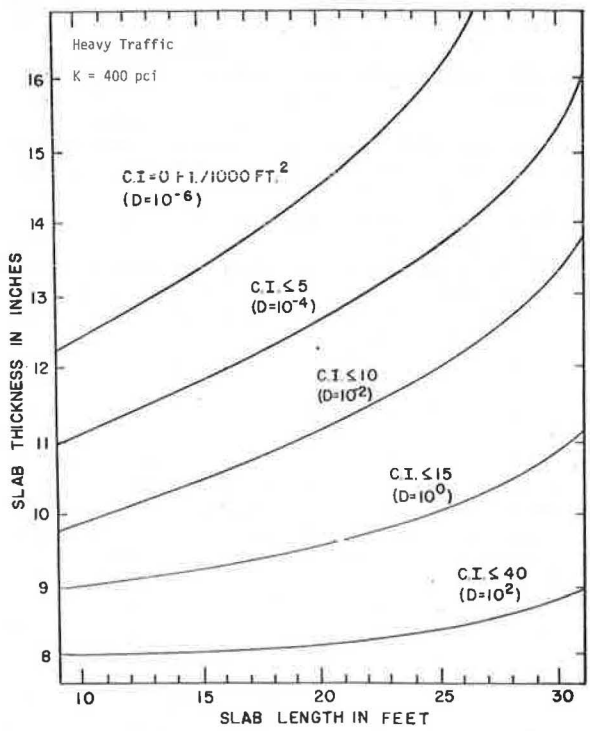


Figure 6. Effect of cracking index on slab thickness and slab length for heavy axle-load distribution.



ranging from roughly 5×10^{-4} to more than 1,000 based on the mean fatigue curve.

Assuming that Miner's hypothesis is exactly correct, the use of a computed damage value of 1.0 (or 100 percent) in design would result in a 50 percent chance of fatigue failure if no safety factors were applied to any of the input parameters. Hence, a design damage value of much less than 1.0 is essential to provide for a low probability of fatigue cracking (or high design reliability). This limiting value may vary depending on the type of pavement under design (i.e., low-volume or expressway).

The appropriate limiting value of accumulated fatigue damage for use in JPCP design was determined as follows:

1. Field data were collected from three sources. The first source was AASHO Road Test sections on loops 4, 5, and 6, which were under traffic for 2 years (1958 to 1960). Sections with excessive pumping were excluded. For the 28 sections that were included, slab thickness ranged from 8 to 12.5 in. The second source was AASHO Road Test sections that were left in service after the end of the test and became incorporated as part of I-80. These sections were under regular mixed traffic from 1962 to 1974. Extensive measurements of distress were made periodically by the Illinois Department of Transportation. Twenty-five sections were included, and the range of slab thickness was again from 8 to 12.5 in. The third source was 37 in-service projects located in the United States and Canada: New Jersey, Arizona, California (11), Michigan, Utah (9), Georgia (9), Colorado (2), Washington, Texas, and Ontario. These projects were mostly heavily trafficked highways ranging in age from 6 to 34 years.
2. The total accumulated fatigue damage from the opening of each project to traffic to the date of the survey was computed by using the JCP-1 computer program. The truck lane with the heaviest traffic was always used in the computations.
3. A plot of cracking index versus total accumulated fatigue damage is shown in Figure 5. This curve gives a 50 percent probability that for a certain value of fatigue damage the corresponding cracking index will be higher than the value read on the curve. With all the uncertainties involved in measuring the cracking index in the field and in computing fatigue damage, a more conservative curve that envelopes most of the data points plotted in the figure is needed for design.

The relation between slab cracking and computed fatigue damage indicates the following:

1. A correlation exists between transverse slab cracking and computed fatigue damage in the slab. Fatigue damage is computed at the longitudinal edge and hence should relate directly to transverse cracking. This correlation provides reasonable

verification of certain aspects of the fatigue computation procedure.

2. A limiting fatigue damage value can be selected for design based on how much cracking is acceptable in the pavement. The fatigue damage design limit must be chosen so that it corresponds to a specific tolerable level of transverse cracking. All projects that have less than 10^{-6} damage either exhibited no cracking or only a very minor amount. The amounts of probable transverse cracking for various accumulated damage values determined from an envelope fit above most of the data are as follows:

Fatigue Damage	Cracking Index (ft/1,000 ft²)
10^{-6}	0
10^{-4}	≤5
10^{-2}	≤10
10	≤15
10^{2}	≤40

Figure 7. Effect of cracking index on slab thickness and slab length for moderate axle-load distribution.

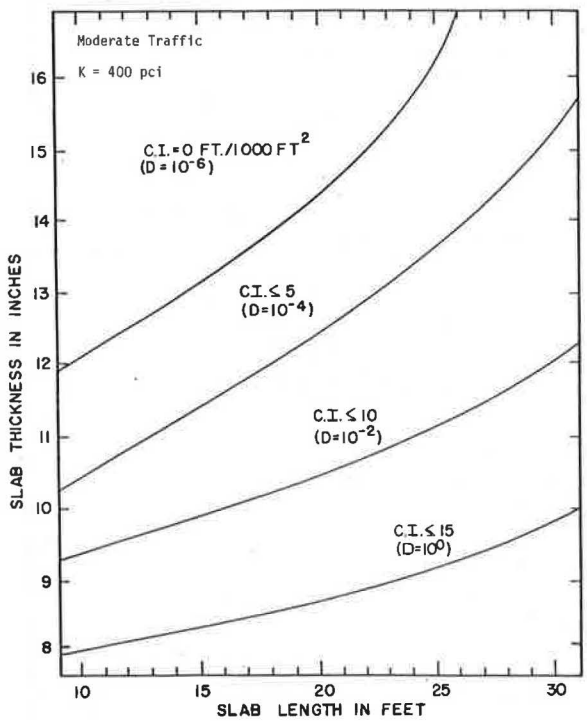
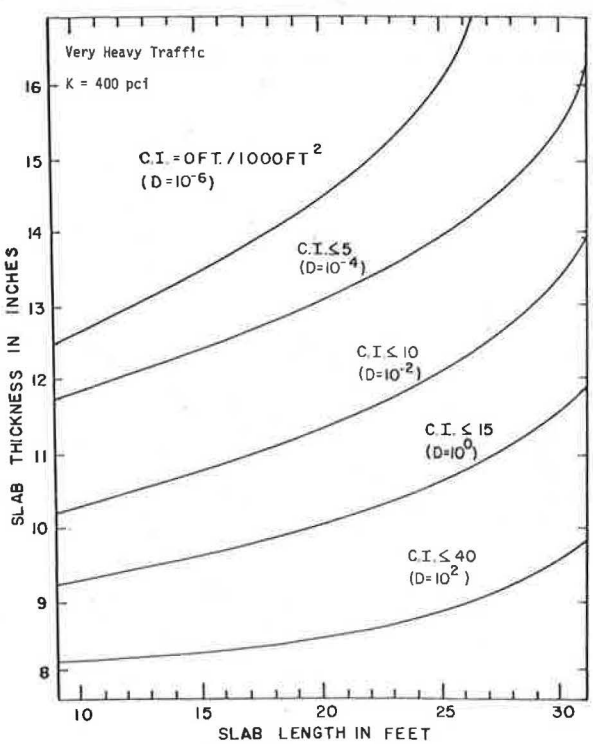


Figure 8. Effect of cracking index on slab thickness and slab length for very heavy axle-load distribution.



APPLICATION TO DESIGN

The proposed JPCP design method provides a comprehensive procedure for determining concrete slab thickness and strength and the maximum joint spacing needed to carry the expected traffic and climatic loading conditions throughout the entire design life of the pavement. The procedure specifically considers slab cracking. The faulting of joints must also be prevented through adequate load transfer (3).

The design procedures show that, for a specific slab thickness and other design factors held constant, the amount of slab cracking increases with the joint spacing. If more cracking is to be tolerated, then either the slab thickness should be decreased or the joint spacing should be increased (or the PCC strength decreased). The design method is unique in this respect. All other design methods for rigid pavement design only for the slab thickness. The joint spacing is usually decided on irrespective of the slab thickness. The dependence of slab thickness and joint spacing on each other, with its effects on different important design variables and their applications to the design process, is discussed below.

Cracking Level

As discussed earlier, this design method provides for designing the concrete slab for different levels of cracking. It has been shown in Figure 5 that, the higher the total fatigue damage in the concrete slab, the higher will be the cracking index. Therefore, the design engineer has flexibility in deciding on the amount of cracking to be tolerated, depending on the site conditions that will exist during the pavement design life.

Figure 6 shows the effect of the level of cracking on slab thickness and joint spacing for a highway with a heavy axle-load distribution. As the amount of cracking increases, the slab thickness decreases for a constant joint spacing. On the other hand, if the slab thickness is held constant, longer joint spacing is allowed. For example, if a slab thickness of 12 in. is obtained and a zero cracking index is chosen, a joint spacing of about 10 ft is needed. However, if a higher cracking index is tolerated (CI ≤10 ft/1,000 ft²), a joint spacing fo 25.0 ft is needed. On the other hand, if a joint spacing of 13 ft is fixed, a slab thickness of 11.4 in. can be used. This cracking index effect is also shown in Figures 7 and 8 for a traffic level with moderate and very heavy axle-load distributions.

Traffic Level

The effect of the level of traffic on slab thickness and joint spacing is shown in Figures 6 to 8. Three levels of traffic were analyzed: moderate, heavy,

Table 1. Determination of axle-load distribution for use in design.

Axle-Load Group	Weight (kips)	Design Axle-Load Distribution (%)		
		Moderate	Heavy	Very Heavy
Single axle	0-3	7.87	7.28	7.28
	3-7	17.59	16.28	16.28
	7-8	8.37	7.75	7.75
	8-12	16.22	15.01	15.01
	12-16	5.13	4.75	4.75
	16-18	2.10	1.94	1.94
	18-20	0.44	1.32	1.2
	20-22	0.34	1.02	0.81
	22-24	0.14	0.42	0.55
	24-26	0.05	0.14	0.3
	26-28	0.02	0.06	0.05
	28-30	0.01	0.02	0.03
	30-32		0.01	0.02
	32-34		0.01	0.02
	34-36			0.01
	36-38			0.01
Tandem axle	0-6	0.04	0.37	0.37
	6-12	10.54	9.76	9.76
	12-18	4.71	4.36	4.36
	18-24	6.14	5.68	5.68
	24-30	9.64	8.92	8.92
	30-32	5.29	4.90	4.90
	32-34	2.15	4.30	4.01
	34-36	1.70	3.40	1.92
	36-38	0.70	1.40	1.06
	38-40	0.24	0.48	0.83
	40-42	0.09	0.19	0.60
	42-44	0.04	0.08	0.35
	44-46	0.03	0.06	0.29
	46-48	0.02	0.03	0.31
	48-50	0.01	0.02	0.27
	50-52	0.01	0.02	0.16
	52-54	0.01	0.01	0.08
	54-56		0.01	0.05
	56-58			0.02
	58-60			0.02
	60-62			0.01
	62-64			0.01
	64-66			0.01
Total		100.00	100.00	100.00

and very heavy axle-load distributions with the same overall ADT volume. These axle-load distributions are given in Table 1.

The figures show that as the axle-load distribution gets heavier the slab thickness increases or the joint spacing is decreased for the same cracking index. A cracking index of up to 5 ft/1,000 ft^2 is used to plot Figure 9 which shows the effect of different axle-load distribution levels on both slab thickness and joint spacing. Decreasing the traffic from a very heavy to a moderate axle-load distribution level decreases the slab thickness by approximately 1 in. for a constant slab length or increases the joint spacing by 3 ft for the same slab thickness.

Foundation Support

The effect of the pavement foundation support system (K) on slab thickness and joint spacing is shown in Figure 10. Different levels of cracking index are also shown in this figure. With the high cracking index (CI $\leq$40), using a stabilized base will decrease the slab thickness by 1 to 2 in. or (for the same slab thickness) will allow the use of a much longer slab. As the level of cracking index decreases (CI $\leq$10 or CI $\leq$5), a thicker slab is required (12 to 16 in.). Using a stabilized base will decrease the slab thickness requirement within the shorter slab range, but it will increase the thickness requirement within the longer slab range. This is due to the greater effect of curling conditions on the longer slabs than on the shorter slabs. Higher curling stresses are also expected in longer slabs with a stabilized base than in slabs with a less stiff foundation. These conditions require a thicker slab or shorter joint spacing.

Figure 9. Effect of axle-load distribution level on slab thickness and joint spacing.

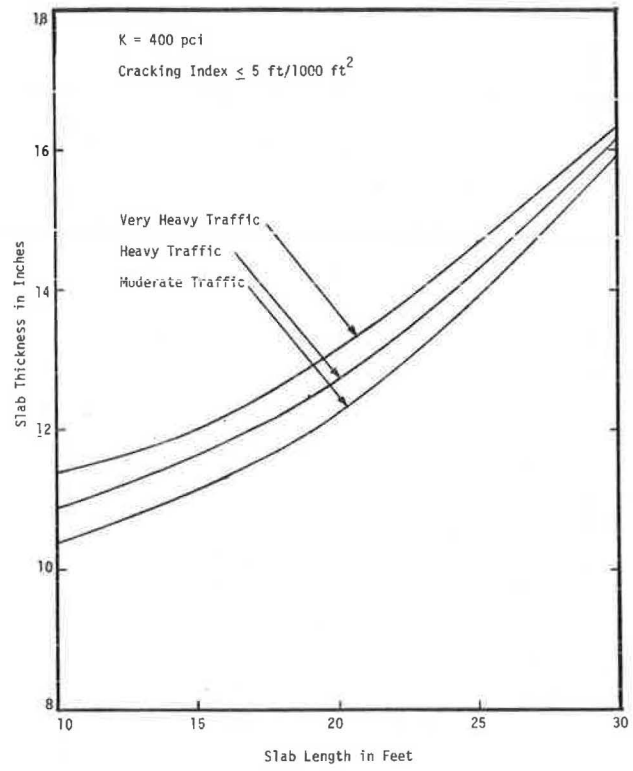


Figure 10. Effect of foundation support on slab thickness and joint spacing for different levels of cracking index and heavy traffic.

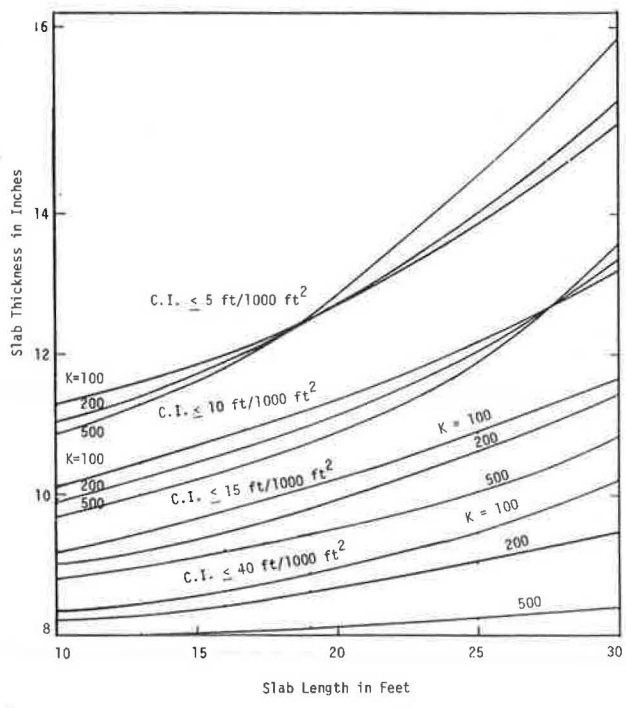


Figure 11. Effect of modulus of rupture on slab thickness and joint spacing for heavy traffic.

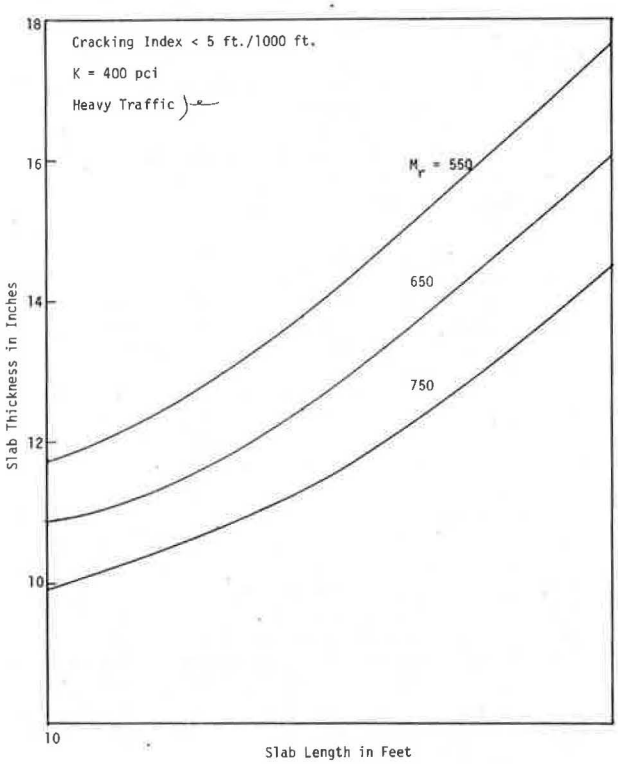
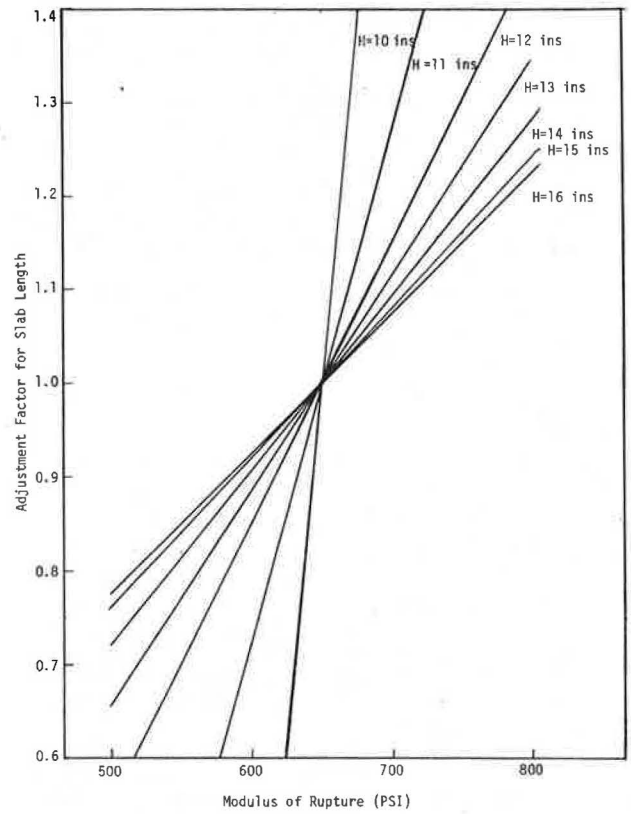


Figure 12. Effect of PCC modulus of rupture on adjustment factor for joint spacing for different slab thicknesses.



Modulus of Rupture

The effect of modulus of rupture (M_R) on slab thickness and joint spacing is shown in Figures 11 and 12. A concrete pavement with a stabilized base under typical traffic and environmental loading conditions is analyzed. The effect of three levels of modulus of rupture on slab thickness and length is shown in Figure 11. As modulus of rupture changes by ±100 psi, slab thickness changes by about ±1 -1.5 in. for the same joint spacing. If slab thickness is held constant, the joint spacing would be changed by about ±5 ft.

Figure 12 provides an adjustment factor that could be used to account for the change in modulus of rupture. For example, the slab length obtained for a pavement under typical conditions [a heavy axle-load distribution, a foundation support of 400 pci, a modulus of rupture of 650 psi, a cracking index of $\leq$5 ft/1,000 ft^2, and a slab thickness of 12 in. (Figure 6)] would be 16 ft. If M_R is 750 psi, then the slab length is 16 * 1.3 = 21 ft. On the other hand, if M_R is 550 psi, the slab length is 16 * 0.7 = 11 ft.

SUMMARY

The structural design procedure for JPCP described in this paper takes into direct consideration major design factors such as slab thickness, slab length, slab strength, traffic volume and distribution, foundation support, and climatic conditions throughout the pavement design life. A comprehensive set of 76 in-service pavements was used to determine a correlation between the amount of transverse cracking, measured on site, versus the total fatigue damage accumulated by each section throughout its in-service life and computed by the JCP-1 computer program.

In this paper different applications of the method to concrete pavement design have been shown and a new concrete pavement design concept of considering slab thickness and strength with transverse joint spacing has been developed. It was found that if a thicker slab were used a longer joint spacing could be allowed for the same level of cracking. This has long been known in airfield pavement design but is now quantified analytically.

The effect of the amount of cracking, traffic axle-load distribution level, foundation support (K) and modulus of rupture (M_R) were also studied. As more cracking is tolerated in the concrete pavement, a longer joint spacing is allowed. The effect of different axle-load distribution levels on both slab thickness and joint spacing is such that decreasing the axle-load distribution level from very heavy to moderate would decrease the slab thickness by approximately 1 in. or would increase the slab length by about 3 ft.

Foundation support has a greater effect on slab thickness and length if a higher cracking index is tolerated (15-40 ft/1,000 ft^2). A decrease of up to 1.5 in. is noted in the slab thickness if a stabilized base is used and a high cracking index is allowed. The modulus of rupture has an appreciable effect on both slab thickness and length. A change of ±100 psi in M_R will change the slab thickness by ±1 - 1.5 in. or will change the slab length by about ±5 ft.

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