This paper represents our views and does not necessarily reflect those of the Pennsylvania Department of Transportation or the Federal Highway Administration.

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Structural Design of PCC Shoulders

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A structural design procedure for plain jointed portland cement concrete (PCC) highway shoulders has been developed. The procedure can be used to provide PCC shoulders either for rehabilitation of existing pavement or for new pavement construction. All major factors that are known to affect the behavior of PCC shoulders are considered in the mechanistic design approach, including encroaching moving trucks, parked trucks, foundation support, load transfer across the longitudinal joint, shoulder slab thickness and tapering, width of shoulder, and traffic lane slab. The finite-element structural analysis technique was used along with a model for concrete fatigue damage to sum damage for both moving encroaching trucks and parked trucks. A relation was established between accumulated fatigue damage and slab cracking. The shoulder can thus be designed for an allowable amount of cracking, which can vary depending on the performance level desired. Procedures for tying the PCC shoulder to the mainline PCC slab are recommended to provide adequate load transfer and avoid joint spalling. Long-term, low-maintenance performance of the PCC shoulder, as well as significant improvement in the performance of the traffic lane, can be obtained if the shoulder is properly designed.

Portland cement concrete (PCC) shoulders have been constructed for several years on urban expressways and rural highways. They were first constructed on an experimental basis but more recently as regular construction. Since no structural design procedure is available, design has been based on engineering judgment and the performance of a few experimental sections. The purpose of this study is to develop a structural design procedure that considers the major design variables that affect the behavior of PCC shoulders. The design includes the placement of PCC shoulders for the purpose of rehabilitating existing pavements and also for new pavement construction.

Shoulders are an integral part of today's major highways and are required to provide structural support to (a) encroaching traffic loads from the adjacent traffic lane, (b) emergency parking, and (c) regular traffic if the shoulder is used as a detour around a closed lane or as an additional lane during peak traffic hours. Field results of this study (1) have shown that the PCC shoulder contributes to the structural support of traffic in the adjacent lane so that distress in the lane is significantly reduced. The lack of adequate shoulder design in the past (usually attributable to minimizing construction costs) has often led to considerable distress and maintenance requirements.

The major design variables for PCC shoulders have been shown to include (a) slab thickness and tapering of thickness, (b) joint spacing, (c) foundation support and loss of support, (d) tie between shoulder and traffic lane (including load transfer of the longitudinal joint), (e) width of the shoulder slab, and (f) design and condition of the adjacent traffic lane (1). The shoulder must withstand both repeated moving loads and static loads from parked vehicles. Both of these conditions involve edge-loading conditions from heavy trucks. The edge-loading condition has been determined to be the most critical for fatigue damage (2) and the point at which cracking initiates.

The influence of these major design variables for PCC shoulders has been analyzed in a previous study (1), and the following conclusions have been drawn:

1. Two load positions must be considered to determine the required shoulder thickness—the inside edge near the lane-shoulder longitudinal joint (encroached traffic) and the outside "free" edge (parked traffic).
2. A minimum thickness of 15 cm (6 in) is recommended, since thinner slabs will have very high stresses when they are loaded by typical heavy trucks and tend to crack after only a few load applications.
3. Tapering of the shoulder thickness between the two edges is not recommended.
4. Tied-shoulder width should be at least 90-152 cm (3-5 ft) to provide maximum structural benefits to the traffic lane and shoulder. However, a wider shoulder of 3.0-3.6 m (10-12 ft) is mostly used for geometric and safety considerations.
5. Use of a tie system that provides at least 50 percent load transfer is a very effective way to reduce critical stresses near the longitudinal joint in both the traffic lane and the shoulder.
6. Provision of a "moderate" foundation support, i.e., $k = 54.2\ \text{N/cm}^3$ ($200\ \text{lbf/in}^3$), appears justified.
7. A maximum slab length of 3.6 m (15 ft) is recommended.

Finite-element models and procedures for slab stress-strain computation were used in the initial study. A comprehensive procedure for fatigue analysis is developed in this study that gives accumulated fatigue damage at both edges of the PCC shoulder. Therefore, fatigue damage produced by the encroachment of traffic from the mainline pavement at the inner edge of the shoulder can be compared with the fatigue damage from the parked traffic at the outer edge of the shoulder. This procedure is computerized. The computer program—called JCS-1—provides cumulative fatigue-damage data for selecting the structural design of the PCC shoulder and is written in FORTRAN.

DEVELOPMENT OF DESIGN PROCEDURE

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 controlling slab cracking. The location of the critical point is determined by using both field and slab fatigue analysis results (1, 3, 4). These results indicate that, for normal highway loadings and slab widths, the critical fatigue damage is in the center third of the slab at the edge.

Development of Analysis of Fatigue Damage

A comprehensive analysis of fatigue damage in PCC shoulders was developed based on the following factors:

1. The location of critical fatigue damage in the shoulder is at the longitudinal edge of the slab midway between the transverse joints.
2. Critical edge stresses caused by traffic loads are considered to prevent transverse cracking.
3. Load stresses are computed by using a finite-element program that has been shown to provide good results.
4. The proportion of mainline traffic encroaching on the inner edge of the shoulder and/or parking on the shoulder is used in the fatigue analysis.
5. Fatigue damage is computed and accumulated according to Miner's hypothesis (5).
6. A correlation between computed fatigue damage and measured cracking is determined, and a limiting damage criterion for PCC shoulder design is selected.

PCC Fatigue

Several laboratory studies have shown that plain PCC beams experience fatigue failure when they are subjected to high repetitive flexural stresses (6-8). In addition, in several road tests and in many slabs in service, PCC slabs have been observed to experience fatigue cracking when they were subjected to many applications of heavy truck traffic (3, 9).

Results from laboratory studies have shown that the number of repeated loads that PCC can sustain in flexure before fracture depends on the ratio of applied flexural stress to ultimate static flexural strength or modulus of rupture. In this study, Miner's hypothesis (5) is used to represent the cumulative-damage characteristics of concrete.

Fatigue data were obtained for plain PCC beams from three studies (10-12). An S-N plot of 140 tests from these studies, presented by Darter (1), shows a considerable scatter of data. A design curve was fit through the data that provides for a safety factor (the curve was moved back one decade of load applications from the average regression line):

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

where N = number of stress applications to failure of beam and R = ratio of repeated flexural stress to modulus of rupture. This equation represents a failure probability of 0.24 or 24 percent.

Truck Traffic on Shoulders

Truck traffic on shoulders includes moving encroachments near the longitudinal joint, parked trucks with wheel loads near the outside edge, and the use of shoulders as an additional traffic lane. One of the most important factors that affects the lateral distribution of truck traffic in the outside traffic lane is the existence of shoulders and whether or not they are paved. The encroachment of truck traffic onto the shoulders depends mainly on lateral placement in the adjacent traffic lane. Available evidence (1) indicates that, when there is a paved shoulder and there are no lateral obstructions, trucks traveling on the outer lane show a definite tendency to shift several centimeters toward the slab edge. Data collected by Taragin (13) for 3.6-m (12-ft) concrete traffic lanes show the mean lateral distance of mainline trucks from the slab edge to be 28 cm (11 in) when paved shoulders are used and 63.5 cm (25 in) when gravel or grass shoulders are used. This lateral shift toward the slab edge increases the number of truck encroachments onto the shoulder accordingly.

Another aspect to be considered is the number of parked trucks along a given highway section. Some of the main factors that affect this factor are the geometric layout of the section, its location relative to a weighing station, and, most important, its proximity to an interchange. In addition, PCC shoulders are sometimes used for regular traffic as a detour around a closed lane or as an additional lane during peak traffic hours. These conditions will thus have an effect on the structural and geometric adequacy of PCC shoulders and must be considered in design.

If a PCC shoulder is to perform its functions, it is crucial that the truck traffic used in design be based on the actual future uses of the shoulder under local conditions along the project.

Computation of PCC Fatigue

A procedure of fatigue analysis was developed based on previous results to provide a method of estimating the traffic damage that would result in cracking of the PCC slab. The basic purpose in fatigue design for plain jointed concrete shoulders is to control linear cracking. This is possible through direct consideration of traffic loading, joint spacing, lane-shoulder tie, shoulder width, and foundation support and loss of support. Fatigue damage is investigated at two critical locations in the concrete shoulder: the inner and outer edges. As discussed earlier, these two locations are very important in design and must therefore be analyzed separately in the design procedure.

The major steps in the fatigue analysis are as follows:

1. Determine axle applications, at each of the two critical edge locations, in each single- and tandem-axle load group.
2. Select the trial slab-subbase structure, lane-shoulder load transfer, PCC strength and variability, PCC shoulder width, and other required factors.
3. Compute the fatigue damage at each of the shoulder edges for a given year by using Miner's cumulative damage hypothesis (5) and sum yearly over the entire design period:

$$\text{Damage} = \sum_{j=1}^{j=p} \sum_{i=1}^{i=m} (n_{ij}/N_{ij}) \qquad (2)$$

where

Damage = total accumulated fatigue damage over the design period at either of the slab edges;
j = a counter for years beyond the design period;
p = total number of years in the design period;
i = a counter for axle-load magnitude, both single and tandem axle;
m = total number of single- and tandem-axle load groups;
n_{ij} = number of applied axle-load applications of the ith magnitude for the jth year; and
N_{ij} = number of allowable axle-load applications of the ith magnitude for the jth year, determined from the PCC fatigue curve.

The fatigue damage is computed at each of the shoulder-slab longitudinal edges because results from field observations of many jointed concrete pavements (both traffic lanes and shoulders) and analytical fatigue analysis (1) have shown the midpoint between the transverse joints at the slab edge to be the critical point at which cracking initiates.

Applied traffic n_{ij} is computed from traffic data for the year under consideration by using the following expression:

$$n_{ij} = (ADT_y)(T/100)(DD/100)(LD/100)(A)(365)(P/100) \times (C/100)(CON) \qquad (3)$$

where

ADT_y = average daily traffic at the end of the specific year under consideration;
T = percentage trucks in ADT;
DD = percentage trucks in the direction of the traffic lane adjacent to the shoulder;
LD = lane distribution factor (percentage trucks in the design lane in one direction);
A = mean number of axles per truck;
P = percentage axles in the ith load group;
C = percentage total axles in the truck traffic lane that park on or otherwise use the adjacent PCC shoulder (used for computing fatigue damage at the outer edge) or percentage total axles in the traffic lane that encroach on or otherwise use the adjacent PCC shoulder (used for computing fatigue damage at the inner edge); and
CON = 1 for single axles, 2 for tandem axles.

Allowable traffic N_{ij} is computed from PCC fatigue considerations. The loading stress is computed at either of the two edges of the shoulder for a given axle load (single or tandem) by using a finite-element model.

The JCS-1 computer program was developed to compute accumulated fatigue damage over the design life of the PCC shoulder. These data can be used to incorporate consideration of fatigue damage in the evaluation and design of a plain jointed concrete shoulder.

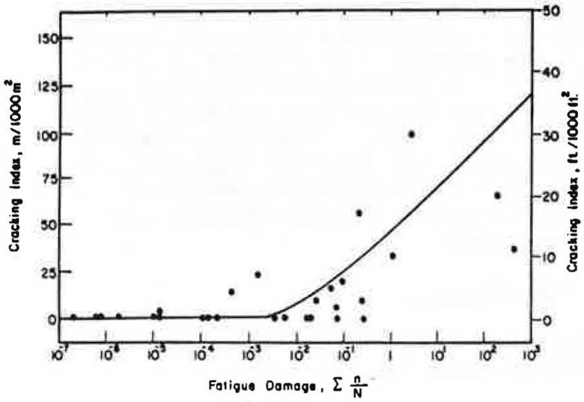
Limiting Fatigue Consumption

The fatigue analysis that has been developed considers directly the effects of traffic loadings, shoulder width, lane-shoulder tie, and loss of foundation support (i.e., pumping). There are several factors, however, that are not considered because of insufficient information. One of the most important factors may be the use of PCC fatigue curves for small beams in estimating the fatigue life of large, fully supported pavement slabs. Traffic loading conditions also differ considerably between the laboratory and the field. Other inadequacies could be cited, but the point to be made is that the final accumulated fatigue damage computed for a pavement slab based on Equation 2 must be correlated with measured slab cracking before a limiting fatigue consumption can be selected for design.

According to Miner's hypothesis (5), a material should fracture when the accumulated damage equals 1.0. Even if Miner's hypothesis were exact, the variability in material strengths along a concrete pavement would cause a variation in accumulated computed damage in the various slabs that would range from much less than to much greater than 1.0, since an average strength that represents all of the slabs is used.

To determine a limiting value of fatigue damage for use in the design procedure, Equation 2 was used in fatigue analysis of many in-service pavements. The

Figure 1. Cracking index versus computed fatigue damage developed for in-service pavements.



field data from 27 projects needed for the analysis were obtained from the zero-maintenance design project (2). The cracking index of each pavement project was measured. The curve shown in Figure 1 was developed from the analysis of sections that had joint spacing of 4.6-6.1 m (15-20 ft). The data for the curve were taken from plain jointed concrete pavements located in various states. By using this curve, the designer can select a limiting design value of fatigue damage to limit the cracking of the pavement slabs or, once the value of fatigue damage is computed for a given design, estimate the cracking index over the design period.

During the field survey conducted on I-74 (1), it was found that about 60 percent of the 7.6-m (25-ft) shoulder slabs showed transverse cracking. The severity of these cracks, however, is low to medium and therefore has not affected the performance of the PCC shoulder so far and is tolerated by highway users. The cracking index for this amount of cracking is 83 m/1000 m^2 (25 ft/1000 ft^2). According to Figure 1, the corresponding fatigue damage is between 10^1 and 10^2. Even with this amount of cracking, the PCC shoulder is still relatively smooth to drive on and provides adequate structural support to the traffic lane. It is believed, therefore, that the highway user will tolerate a higher level of cracking index when driving on the shoulder and that additional cracking can be tolerated without significantly reducing the amount of support provided to the traffic lane. Therefore, a fatigue damage of 10^3 [cracking index = 116 m/1000 m^2 (35 ft/1000 ft^2)] is recommended for use as a design limiting criterion for PCC shoulders on heavily trafficked highways. Recommended fatigue-damage values for pavement shoulders for high, medium, and low traffic volumes are as follows: Low traffic volume = 10^5 (ADT of the mainline = <2000), medium traffic volume = 10^4 (2000 < ADT < 20 000), and high traffic volume = 10^3 (ADT = >20 000).

JCS-1 COMPUTER PROGRAM

The JCS-1 (Jointed Concrete Shoulders-1) computer program was written to provide fatigue data for use in design. It is written in FORTRAN computer language for the IBM-360 digital computer but can be adapted for use on other computers with only minor modifications. The computer processing time for a design problem such as analyzing a range of shoulder thicknesses is about 9 s. The program requires 40 000 bytes of storage area. The designer must specify trial structural designs, determine the required inputs, run the JCS-1 program, and analyze the output fatigue data. The program is written to analyze any one or a combination of the following: shoulder thickness, mainline slab thickness, shoulder width, and mainline-shoulder tie. It can provide output for each combination while holding all other inputs constant. The designer can therefore examine a range of shoulder designs for a given traffic volume and foundation support in only one run of the program.

A complete, detailed example of the use of the program in the structural design of a PCC shoulder is given later in this paper.

JOINT DESIGN

PCC shoulders properly tied to either new or existing concrete pavement serve to stiffen the traffic lane and thereby decrease the deflection and consequent pumping near the longitudinal joint (1). The method of tying the PCC shoulder to the mainline concrete pavement is a primary factor in determining the magnitude and extent of load-transfer efficiency across the longitudinal joint throughout the design life. Therefore, some recommended methods for constructing concrete shoulders that are tied to both new and existing traffic lanes are discussed.

When a PCC shoulder is constructed for an existing slab, adequate load transfer can be provided for by means of closely spaced tiebars. Holes are drilled in the edge of the existing slab. This can be done by using a tractor-mounted drill that can drill several holes in the side of the mainline slab at one time. Tiebars are installed in the holes by using epoxy or a cement grout. The bars should be placed into the slab over such a length as to develop full bond strength [at least 22.9 cm (9 in) to avoid spalling over the base].

Malleable tiebars of smaller diameter (no. 4 or no. 5) and spacing 0.3-0.6 m (12-24 in) midway across the slab depth are preferable to stiffer, short bars at large spacing intervals. This will substantially reduce the possibility of stress concentrations above the tiebar, which will cause spalling of the joint in the vicinity of the bar and the eventual breakage of the slab and the loss of load transfer. The possibility of upward heave or drop-off of the shoulder in the area between the bars will also be substantially reduced when a short tiebar spacing is used [<60 cm (<24 in) is recommended], since there will be more steel to hold the lane and shoulder together. Problems with upward heave in the shoulder and spalling of the lane concrete were experienced in Pennsylvania and New York, where two-piece tie bolts [152 cm (60 in) center to center] were used to tie a 15-cm (6-in) concrete shoulder to the existing mainline pavement.

On I-80 in Illinois, shoulders were tied to the mainline slab (smooth edge) with no. 4 hooked bolts, 37.5 cm (15 in) in length, turned into 5-cm (2-in) snapoff expanding end anchors set into the edge of the mainline slab at 75-cm (30-in) intervals by use of a pneumatic hammer. Recent measurements of this project showed that the deflection efficiency of the lane-shoulder joint was very poor, ranging from 31 to 47 percent. The joint had opened an average of about 10 mm (0.4 in), and many of the bars had spalled the concrete over the bar in the traffic lane, where the 5-cm snapoff expanding end anchors were set. Some of the bars were set within 5 cm of the surface, which also contributed to the spalling and loss of load transfer. It is believed that placing bars at middepth of the slab would minimize any potential spalling.

The practice of not placing tiebars within 75 cm (30 in) of the transverse shoulder joint results in loss of load transfer along 150 cm (60 in) of traffic lane. On one continuously reinforced concrete pavement (CRCP) project in Indiana (I-65), several edge punchouts have occurred within this area because of no load transfer. Based on results from the I-74 and I-80 projects in Illinois, tie-bars can be placed much closer—e.g., half the normal tiebar spacing—to the transverse shoulder joint.

In the case of new construction, tiebars can be inserted into the plastic concrete near the rear of the slip-form paver. Bent bars can be installed by mechanical means or manually. The bent portion can be straightened later to tie the shoulder to the mainline pavement. A three-piece tie bolt can be used, half of which is inserted in the traffic lane by machine, along with the coupler, and the other half of which is screwed into the coupler before the shoulder is added (15-17). In addition to the tiebars, a keyway can be formed to provide additional load-transfer capability.

A keyed joint with tiebars was used in the construction of the experimental shoulder sections built on I-74 in Illinois. The efficiency of load-deflection transfer on I-74 is still quite high (70-100 percent) after 10 years in service (2). This shows that with proper joint design and construction a high efficiency (i.e., >70 percent) can be attained over a long period of time. More comprehensive analysis of concrete pavement joint designs for different load-transfer systems was conducted at the University of Illinois (18). This study provides guidelines for the degree of efficiency to be expected from one load-transfer system or a combination of two or more (e.g., tiebars, dowel bars, aggregate interlock, and keyway) that can be used across the joint between the traffic lane and the shoulder.

On I-74, it was also found that a joint opening of as much as 25 mm (1 in) is experienced on a keyed joint when no tiebars are used. This opening results in complete loss of load deflection and an upward heave or a drop-off in the PCC shoulder.

The longitudinal joint between the traffic lane and the shoulder should be provided with a sealant reservoir and sealed with an effective sealant to reduce the possibility of foreign materials collecting inside the joint and thus reduce the potential for the joint to spall and minimize the amount of deicing salt that penetrates to the tiebars. There was significant corrosion of tiebars on I-80 after 11 years, which shows the necessity of providing either a good seal or corrosion-resistant tiebars to ensure long-term structural adequacy of the bar in transferring load across the joint (if the pavement is subjected to deicing salts).

The cross-slope of the bottom surface of the concrete shoulder should be great enough to permit drainage away from the longitudinal shoulder-pavement joint and avoid pocketing water at this critical location. This will contribute directly to a more effective and lasting load-transfer system across the joint.

Finally, for plain jointed concrete pavements, the shoulder joint pattern should match that of the traffic lane, although intermediate joints can be placed if the joint spacing of the traffic lane is greater than 6.1 m (20 ft). Intermediate contraction joints must be placed where the traffic lane is jointed reinforced concrete with long joint spacing. None of the transverse shoulder joints require dowels unless the shoulder is to be used as a regular traffic lane.

SHOULDER DESIGN

The design example presented here is for a PCC shoulder located on a stretch of I-80 near Joliet, Illinois. The existing asphalt paved shoulder has reached a point of severe deterioration that requires complete reconstruction. Moreover, the mainline pavement is a 20-cm (8-in) CRCP that is experiencing excessive edge deflections because of the combined effects of heavy truck traffic and loss of support at the vicinity of the outer edge of the pavement as a result of the excessive pumping of fine materials from under the CRCP slab. Edge punchouts have occurred to the extent that major rehabilitation of the pavement is needed before deterioration becomes excessive. Construction of a PCC shoulder was selected as part of the rehabilitation to replace the existing deteriorated shoulder and to improve the performance of the adjacent traffic lane through edge support.

Structural Design Inputs

The design life of the PCC shoulder is 20 years.

The slab properties are as follows:

1. Slab thickness—Trial thicknesses of 12.5, 15, 17.5, 20, and 22.5 cm (5, 6, 7, 8, 9 in) are chosen for the shoulder slab to provide a range of results that should encompass the appropriate slab thickness. The adjacent CRCP traffic lane is 20 cm (8 in) thick.
2. Slab width—A shoulder width of 3 m (10 ft) is standard practice for use on Interstate highways to accommodate emergency stops and other uses by traveling vehicles.
3. Shoulder-joint spacing—The design procedure was developed for a shoulder-joint spacing of <6 m (<20 ft). The length selected for this project is 4.76 m (15 ft).
4. Mean PCC modulus of rupture—The mean modulus of rupture that is used in this design example (third-point loading at 28 days curing) is 5,17 MPa (750 lbf/in^2).
5. Coefficient of variation of PCC modulus of rupture—An average coefficient of variation of 10 percent is typical for the PCC used in shoulder construction.

The traffic factors considered are as follows:

1. ADT at the beginning of the design period—The current ADT in both directions is 17 100.
2. ADT at the end of the design period—The final ADT after 20 years is estimated from transportation planning studies to be 39 100.
3. Percentage trucks in the ADT—The average percentage of trucks for the highway, including panels and pickups, is estimated to be 21 percent. This percentage is for the entire 20-year period.
4. Percentage trucks in the most heavily traveled lane—The percentage of trucks in the most heavily traveled lane (the outer lane) is determined from manual counts to be 85 percent.
5. Percentage directional distribution of traffic—Since traffic is approximately equal in each direction, a value of 50 percent traffic in the design direction is selected.
6. Mean axles per truck—Traffic data from W-4 tables for the highway show an average of 2.6 axles/truck (including pickups and panels).
7. Percentage trucks that use the shoulder—For encroached traffic, a 16.1-km (10-mile) shoulder stretch was surveyed and the average length of total encroachments per truck over the 16.1 km was 0.39 km (0.24 mile), which produces 2.4 percent trucks encroaching on the shoulder (this estimate was obtained by following behind randomly selected trucks and recording the length of their encroachment over the 16.1-km section). For parked traffic, the percentage of trucks that park on a specific slab of the shoulder is generally estimated as follows. The surveyed stretch of shoulder is 3.2 km (2 miles) or 3221 m (10 560 ft) long. There are seven hundred and four 4.6-m (15-ft)

slabs in the surveyed stretch. A truck drives on the outer shoulder edge an average distance of about 61 m (200 ft) before it can come to a stop and then start up and move over to the traffic lane. This translates into thirteen 4.6-m slabs and divides the surveyed stretch into 53 groups of thirteen 4.6-m slabs each. If we assume, for example, that only one truck per day will park on the surveyed stretch and the probability of this truck using any one of the 53 slab groups is equal, the probability of any group of slabs being used by this truck on any day is 1/53; or, in other words, one truck will use a given group of slabs every 53 days on the average. The ADT in one direction on I-80 per day is ADT × T × DD = 28 100 × 0.21 × 0.5 = 2951 trucks/day/direction, and 2951 × 53 = 156 371 trucks in 53 days. Therefore, the percentage of truck traffic that will park on a given group of slabs is 1/156 371 × 100 = 0.000 64 percent of mainline trucks. Based on the limited field survey conducted on the stretch of I-80, it is believed that the average number of trucks that park within a 3.4-km (2-mile) stretch of shoulder could range from 1 to 25; therefore, this range is used in the design. Additional surveys would be necessary to determine the average number of parked trucks more accurately and whether the number varied along the project (particularly at interchanges). The percentage of truck traffic that will travel on a given group of slabs when 25 trucks park within the limits of the surveyed stretch is 0.000 64 × 25 = 0.016 percent.

8. Axle-load distribution—The axle-load distribution was established by weighing axle loads at a loadometer station near the project. This distribution should be modified if conditions indicate that legal loads will change during the 20-year period.

Foundation Support

The shoulder will be placed on embankment materials that are mostly fine textured. The soil is American Association of State Highway and Transportation Officials classification A-6 and A-7-6. The materials are principally relatively thin glacial drift of Wisconsinan age overlying dolomitic limestone bedrock (14). A 20-cm (8-in) layer of open-graded granular materials was evaluated as a subbase for the shoulder concrete slab. The k-value on top of the subbase is estimated to be about 54.2 N/cm^3 (200 lbf/in^3). The initial erodibility of the shoulder foundation is zero, and the final erodibility is estimated to be 20 cm (8 in) for the granular subbase.

Lane-Shoulder Tie

Tiebars could be installed in the existing mainline pavement and the new PCC shoulder to provide adequate load transfer across the joint. In this example, a load-transfer system that consists of a tied-butt joint with 76-cm (30-in) long no. 4 tiebars placed 46 cm (18 in) center to center is used to provide load transfer across the longitudinal joint. An average value of 80 percent (based on deflection) is used for the load-transfer efficiency of this joint to account for any lack of quality control of construction and materials that might occur during the construction phase and for the effect of millions of repeated loads applied near the joint.

The degree of load-transfer efficiency, which is defined as the ratio of the deflection of the unloaded slab to that of the loaded slab at the joint, is not necessarily the same as the degree of load-transfer efficiency when it is defined as the ratio of the flexural stress experienced by both slabs at the joints. The finite-element model used in the analysis does not take this factor into consideration. Thus, an adjustment for the difference between the two efficiencies is needed. A more comprehensive finite-element model (18) that accounts for the difference between the two efficiencies is used to establish an adjustment curve that can be used in design.

Figure 2 shows the relation between the load-transfer efficiency based on deflections and that based on stresses. Thus, for this design example, assuming 80 percent load-transfer efficiency (based on deflection) and using Figure 2 for adjustment, 42 percent load-transfer efficiency (based on stress) is obtained and is used for design.

Selection of Shoulder Design

A summary of the results obtained from the computer program output is given below (1 cm = 0.39 in):

Slab Thickness (cm)	Fatigue Damage Attributable to	
	Parked Traffic	Encroaching Traffic
12.5	4.81×10^{24}	3.53×10^{3}
15.0	5.74×10^{11}	6.95×10^{-1}
17.5	3.34×10^{4}	6.52×10^{-3}
20.0	1.06×10^{0}	3.16×10^{-4}
22.5	1.04×10^{-3}	3.51×10^{-5}

The volume of parked traffic used is 25 trucks/day in the 3.3-km (2-mile) shoulder stretch surveyed. These results are shown in Figure 3. The minimum design

Figure 2. Effect of thickness of PCC shoulder slab on accumulated fatigue damage at both shoulder edges.

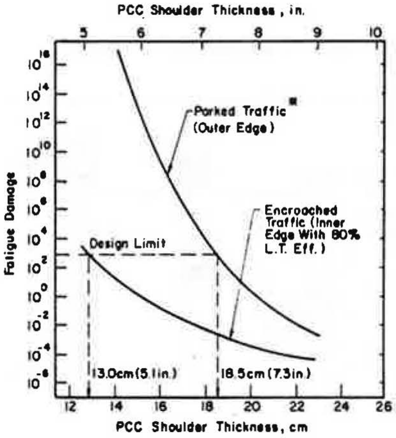
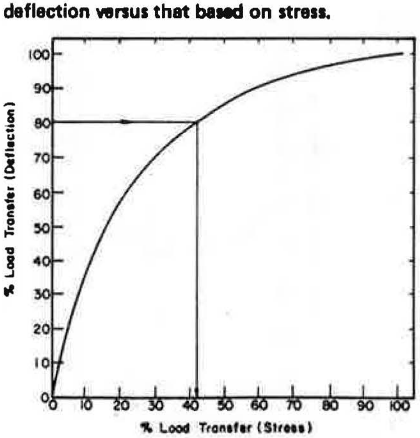


Figure 3. Load-transfer efficiency based on deflection versus that based on stress.



slab thickness at the inner and outer edges of the shoulder is determined as indicated [although the inner-edge thickness is shown in Figure 3 at 13 cm (5.1 in), a minimum of 15 cm (6 in) (2) will be used].

The outer-edge minimum thickness = 18.5 cm (7.3 in) due to parked traffic, and the inner-edge minimum thickness = 15 cm due to encroached traffic, with 80 percent load-transfer efficiency across the joint. Therefore, for these conditions of design life, slab properties, traffic, foundation support, and load transfer across the lane-shoulder joint, the structural design thickness would be 18.5 cm (7.3 in) minimum of PCC over a 20-cm (8-in) layer of open-graded granular subbase. By decreasing the volume of shoulder parked traffic in the 3.3-km (2-mile) surveyed stretch from 25 trucks/day to only 1 truck/day, as previously discussed, the structural design thickness of the PCC shoulder would be reduced to 17.8 cm (7 in), as shown in Figure 4.

Figure 4. Effect of the number of parked trucks on accumulated fatigue damage at the outer edge of the shoulder.

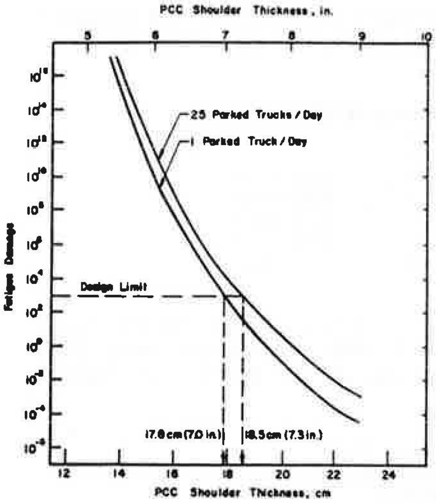


Table 1. Summary of alternate structural designs for PCC shoulder design example.

Alternate	Design Parameter Slab Width (m)	Subbase Type	Strength (kPa)	Design Thickness (cm)
1	3	20 cm, granular	5171	18.5
2	3	15 cm, stabilized	5171	16.3
3	3	20 cm, granular	6205	16.8
4	3	15 cm, stabilized	6205	14.7ᵃ
5	2.1	20 cm, granular	5171	18.8
6	2.1	15 cm, stabilized	5171	16.5
7	2.1	20 cm, granular	6205	17.0
8	2.1	15 cm, stabilized	6205	14.8ᵃ

Note: 1 m = 3.3 ft; 1 kPa = 0.145 lbf/in²; 1 cm = 0.39 in.
ᵃMinimum 15 cm.

The previous structural design selections (Figure 3) were obtained for a specific subbase, shoulder width, and concrete strength. There are other alternatives, however, that could be analyzed to obtain the most economical structural design. A summary of a few alternatives is given in Table 1. The other design inputs were held constant for each of these alternatives as a single parameter was varied. Required thickness varies from 15.0 to 18.8 cm (6.0-7.4 in), depending on the values of the design parameters controlled by the designer. Each alternative should be further designed and economic analysis conducted to determine the most economical alternative.

Final Design Selection Relative to Cost

A complete cost analysis of alternative designs that meet the limiting criteria can be conducted. Since no shoulder structural maintenance is expected over the 20-year design period, the cost analysis can be based on the first cost of the pavement. The design alternative that provides the lowest initial construction cost should be chosen as the optimum structural design alternative.

Sensitivity Analysis

A sensitivity analysis is conducted to illustrate the effect of changes in several of the design parameters on required shoulder slab thickness and to show the reasonableness of the design procedures. The average conditions are set as described in the design of the example project, and then one parameter at a time is varied over a range that might exist in actual situations. Shoulder width is the first parameter varied, from 0.46 to 3.05 m (1.5-10 ft), as shown in Figure 5. The shoulder slab thickness required decreases from [illegible] 17.8 cm (8-7 in) as shoulder width increases from 0.46 to 3.05 m (1.5-10 ft). A change in the 28-day modulus of rupture from 4.48 to 6.2 MPa (650-900 lbf/in²) produces a change of about 3.6 cm (1.4 in) in PCC shoulder slab thickness, as shown in Figure 6. A change in

Figure 5. Sensitivity analysis of design parameters: shoulder slab thickness versus shoulder width.

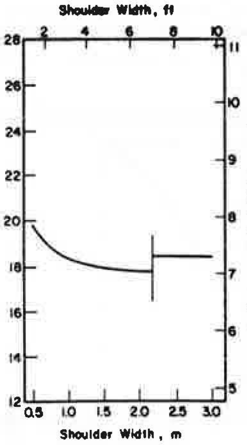


Figure 6. Sensitivity analysis of design parameters: shoulder slab thickness versus modulus of rupture.

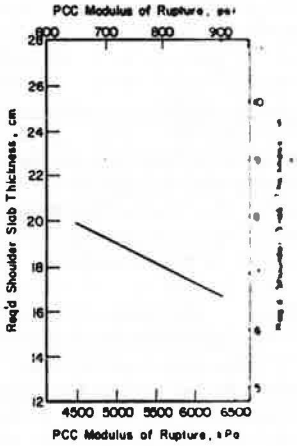


Figure 7. Sensitivity analysis of design parameters: shoulder slab thickness versus type of subbase or subgrade.

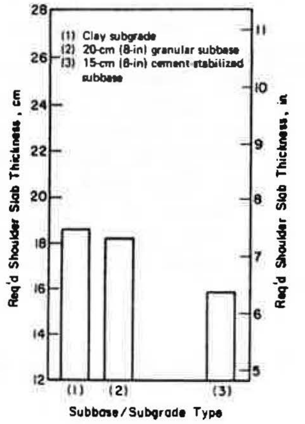
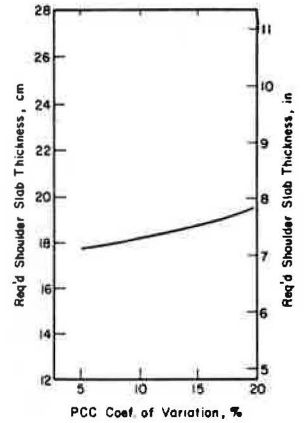


Figure 8. Sensitivity analysis of design parameters: shoulder slab thickness versus PCC coefficient of variation.



foundation conditions from no subbase over clay subgrade to 20-cm granular subbase to 15 cm (6 in) of cement-stabilized subbase reduces the required shoulder slab thickness by about 0.50 cm (0.2 in) and 2.8 cm (1.1 in) respectively, as shown in Figure 7. The variation in PCC strength shown in Figure 8 is indicated by the coefficient of variation. The variation from excellent quality control (5 percent) to poor (20 percent) causes an increase in the required PCC shoulder slab thickness of approximately 1.8 cm (0.7 in).

The effect of increasing the number of trucks that park on the shoulder stretch from 1 to 25 trucks/day, as shown in Figure 4, produces a change in required PCC shoulder slab thickness of 0.8 cm (0.3 in).

CONCLUSIONS

This paper describes the development of a comprehensive structural design procedure for plain jointed concrete shoulders as well as a design example that contains all the procedures necessary in actual design. A computer program designated JCS-1 is used to obtain fatigue-damage data for use in structural design. The program is written in FORTRAN and is easily adapted to most computers. The design procedure developed in this research can be used for both new construction and rehabilitation. Detailed documentation and a complete description of use of the JCS-1 program are presented elsewhere (19).

A procedure for comprehensive fatigue-damage analysis was developed that permits direct control of slab cracking. Stress attributable to traffic loadings is directly considered in the analysis through the use of the finite-element method. A fatigue-damage limiting design criterion was determined from field data.

The joint between the shoulder and the traffic lane has a major influence on the structural adequacy of PCC shoulders and on improving the performance of the adjacent traffic lane. Recommendations concerning the joint design are presented.

An example design application is provided that describes the use of the procedure in detail. The economic justification of the selection of the final PCC shoulder design is an important factor and should be a criterion in giving one design priority over another.

The design procedure discussed here can be used for new construction of PCC shoulders and also for rehabilitation of existing concrete pavements. The effect of many variables can be analyzed, including shoulder slab thickness, mainline slab thickness, concrete strength and variation, shoulder width, traffic that uses the shoulder, traffic overloads, foundation support (subbase and subgrade, including degree of saturation), and systems of load transfer across the lane-shoulder longitudinal joint.

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