The shoulder lanes have held up well under the increasing volume of traffic. The turf area in the outer separation that has been used for emergency parking has become rutted and requires considerable maintenance. New stabilized shoulders will be provided in those areas. The longitudinal joint between the main-line pavement and the old shoulder pavement has widened and requires maintenance. However, the quality and the safety of the ride over the joint has not been substantially reduced.

CONCLUSIONS

1. Adding a traffic lane in a bottleneck section of a freeway produces benefits in travel time, safety and quality of operation, and the volume of traffic that can be accommodated.
2. Such solutions are generally accepted by the public.
3. The additional capacity in a converted roadway section reduces accident rates and thus offsets any increase in accident potential attributable to narrow lanes and fewer emergency parking areas.
4. Additional capacity can be achieved at low cost by reconfiguring existing roadway and parking pavements. Benefit/cost ratios for these projects are very favorable.
5. Reconfigured roadways require additional maintenance to provide adequate lane delineation, structural integrity of the shoulder lane, and emergency parking areas.

ACKNOWLEDGMENTS

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This paper discusses one phase of a research project conducted by the Texas Transportation Institute and SDHPT in cooperation with the Federal Highway Administration. The contents reflect my views, and I am responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Structural Evaluation of PCC Shoulders

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A structural evaluation of portland cement concrete (PCC) shoulders has been conducted. The influence of the major design variables on the behavior of shoulders under load was determined by using a finite element analysis program and data from field surveys of several PCC shoulders. The major design variables studied include slab thickness and tapering, foundation support and loss of support, joint spacing, lane-shoulder tie, shoulder width, and design and condition of the adjacent lane. Results of analytical and field studies show that each of these variables can have a significant effect on the performance of PCC shoulders and also on the performance of the adjacent traffic lane. A minimum slab thickness of 15 cm (6 in) is recommended, but certain design situations—i.e., poor foundation support, need for significant load transfer support at the lane edge, heavy traffic, or a narrow shoulder—require greater thickness. The required thickness should be determined from structural analysis. To achieve the greatest structural benefits for the traffic lane and the shoulder, load transfer efficiency at the longitudinal joint should be greater than about 50 percent. Field studies indicate that this efficiency can be attained by providing tie bars across the longitudinal joint. Shoulder width should be at least 91 to 152 cm (3 to 5 ft) to contribute a significant structural benefit. A shoulder joint spacing of 4.6 m (15 ft) is recommended to minimize joint spalling and blowups and slab cracking. If the shoulder is designed properly, significant improvement in the performance of the traffic lane for both new construction and rehabilitation as well as long-term, low-maintenance performance of the PCC shoulder can be achieved.

Portland cement concrete (PCC) shoulders have been constructed for many years on some urban expressways but for only about the past 12 years on rural highways. They were first constructed on an experimental basis but have more recently become a part of regular construction. Because no structural design procedure is available, design has been based on engineering judgment and on the performance of a few experimental sec-

tions. The purpose of this study is to improve shoulder design by determining the effects of the major design variables on PCC shoulder performance and also the effect of shoulder design on the adjacent traffic lane. The evaluation includes the placement of PCC shoulders for the purpose of rehabilitating existing pavements and also as part of 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. Shoulder design has been inadequate in the past (usually because of an effort to minimize construction costs); this has often led to considerable distress and required major maintenance.

The influence of many of the major variables in the design of PCC shoulders has not been previously determined. To study their influence, a program of finite element slab analysis was used to compute critical stresses and deflections for several shoulder and lane design configurations. Surveys of several experimental PCC shoulders have also provided field data about some of the design variables. The guidelines for improved design presented in this study were formulated based on the study results for both rehabilitation and new construction.

DESIGN CONSIDERATIONS

The two major engineering objectives in shoulder design are to (a) provide a shoulder that will structurally support encroaching traffic loads for long-term, low-maintenance performance, and (b) provide a shoulder that will reduce the rate of deterioration of the adjacent lane of pavement (usually the heaviest traveled truck lane). If both objectives can be accomplished economically, placing PCC shoulders during new construction or replacing deteriorated shoulders on existing highways with PCC shoulders can be very beneficial.

The major design variables for PCC shoulders are (a) slab thickness and tapering of thickness, (b) joint spacing, (c) foundation support and loss of foundation support, (d) tie between the shoulder and the 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. The shoulder must withstand both repeated moving loads and static loads from parked vehicles. Both of these conditions involve edge loading caused by heavy trucks. Because the edge-loading condition is the most critical in fatigue damage (3), the stresses and deflections that result from that condition are referred to in this study as critical stresses and deflections. The actual amount of loading is relatively unknown but probably varies widely within a given project and from project to project. The effects of moisture and of loss of support caused by pumping and settlement should also be considered because of edge-loading conditions.

Several studies have been made of the critical effect of edge loadings on the performance of all types of PCC pavements. Recent field and analytical studies have concluded that edge loading results in transverse cracking of jointed concrete slabs and edge punchouts of continuously reinforced concrete pavement (CRCP) (1, 2, 3, 4). Studies of traffic encroachment have shown that much more edge loading of traffic-lane slabs and shoulder encroachment occur than was previously believed (5, 6). Structural design procedures that will attempt to consider these major design variables are being developed at the University of Illinois.

EFFECT OF DESIGN VARIABLES ON PERFORMANCE

The influence of the major design factors on the structural performance of PCC shoulders is determined by using a finite element program that was originally developed by Huang and Wang (7) but has been modified at the University of Illinois to handle problems such as PCC shoulder design. Stresses computed in the program have been found to agree very closely with stresses computed from measured strains at the AASHO Road Test (3).

Shoulder Thickness

The effect of the thickness of a PCC shoulder on the critical tensile stress caused by an encroaching 80-kN (18 000-lb) single-axle wheel load is shown in Figure 1. The design configuration is typical and has a traffic lane 20.3 cm (8 in) thick, 3.6 m (12 ft) wide, and 4.6 m (15 ft) long. The PCC shoulder is 3 m (10 ft) wide and ranges in uniform thickness from 10.2 to 30.5 cm (4 to12 in). Three different load transfer efficiencies are shown for the lane-shoulder longitudinal joint. If the load transfer efficiency is 0 percent, there is no tie between the shoulder and the lane and they act independently. If the efficiency is 100 percent, there is complete load transfer (i.e., the deflection of the loaded side of the joint is equal to the deflection of the unloaded side). Transfer of moment across the joint is zero in both cases because joints transfer very little, if any, moment.

As thickness increases from 10 to 31 cm (4 to 12 in), tensile stress decreases. The rate of decrease is much more rapid for slabs less than 20 cm (8 in) thick when load transfer efficiency is low (0 to 50 percent). When the shoulder is not tied to the lane (efficiency = 0 percent), the stresses approach or exceed the range of flexural strength of PCC for slabs less than 20 cm thick. Stresses greater than about 3450 kPa (500 lbf/in^2) will result in cracking of the shoulder after only a few heavy load applications.

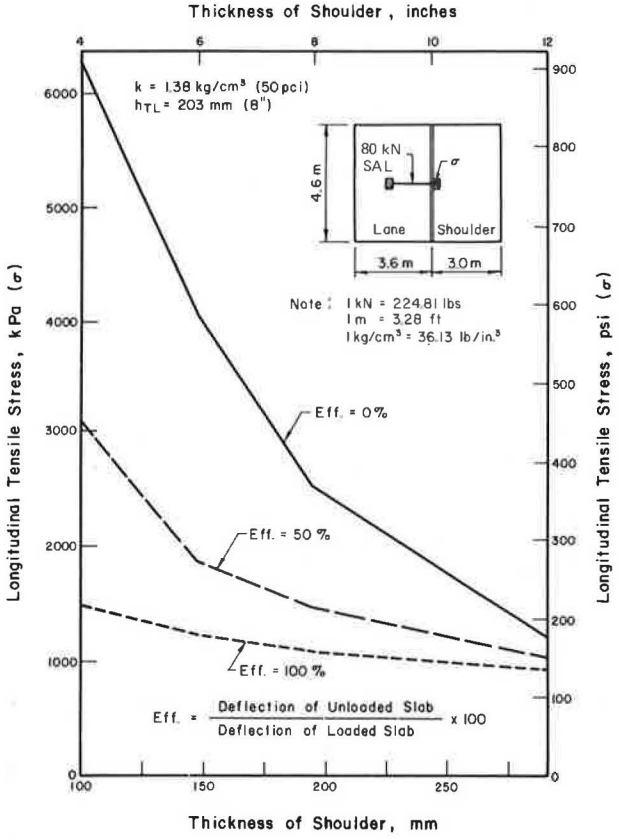
The effect of load transfer at the joint is significant. If there is reasonable load transfer (50 percent) and slab thickness (≥20 cm), the effect of increased thickness on stress is reduced at the lane-shoulder joint. Parked trucks impose a wheel load at the outside edge of the shoulder where the load transfer is of course 0 percent. Thus, the thickness design of PCC shoulders should consider both loading positions and the number of applications at each position.

Shoulder Width

The width of the shoulder affects both critical stress and deflections in the shoulder slab. Figures 2 and 3 show these effects for a range of design conditions. The load efficiency is 0 percent, thickness varies from 15.2 to 30.5 cm (6 to 12 in), and foundation support varies from poor for saturated clay [k = 1.38 kg/cm^3 (50 lb/in^3)] to excellent for a thick stabilized subbase [k = 13.84 kg/cm^3 (500 lb/in^3)]. Deflection increases very rapidly for a width of less than about 1.5 m (5 ft). For poor foundations, narrow PCC shoulders experience high deflections and thickness has only minimal effect. Thickness has a more significant effect on deflections in the case of wider shoulders (B > 1.5 m).

The effect of width on critical stress is shown in Figure 3. For example, for a slab that is 20 cm (8 in) thick, widening the shoulder from 0.9 to 1.5 m (3 to 5 ft) reduces stress by 20 percent, and widening the shoulder from 1.5 to 3 m (3 to 10 ft) causes a decrease of only 5 percent. The effect of shoulder width is about the same regardless of slab thickness. Thus, for structural pur-

Figure 1. Effect of shoulder thickness and lane-shoulder tie on tensile stresses at bottom of PCC shoulder.



poses, a shoulder wider than 1.5 m has a minimal effect on the critical stresses caused by encroaching truck traffic near the longitudinal joint. If a narrow shoulder is required, the critical stress can be reduced to allowable levels by increasing the thickness of the shoulder slab and joint efficiency. For example, a 3-m-wide shoulder of 20-cm thickness has a tensile stress of 2550 kPa (370 lbf/in^2) under an encroaching truck wheel load (Figure 3). If the shoulder were to be constructed only 0.9 m (3 ft) wide, the thickness required for the same stress would be 25 cm (10.1 in).

Tapering of the PCC shoulder has been used on some existing projects. The taper would not have much effect on the critical stress near the longitudinal joint if the full shoulder thickness were carried about 0.9 to 1.5 m (3 to 5 ft). The thickness could then be tapered to the outside edge of the shoulder. But critical stresses caused by trucks that park on the shoulder with their wheels at the outer edge limit the taper to some acceptable edge thickness. The outside shoulder edge will probably receive far fewer load applications than the inside edge near the traffic lane, but these high free-edge stresses must be considered in design.

Foundation Support and Loss of Support

The effect of foundation support on deflections and stresses in the shoulder is shown in Figures 2, 4, and 5. Foundation support—measured by the k value, which has a significant effect on deflection—is shown in Figure 2. A poor foundation [k = 1.38 kg/cm^3 (50 lb/in^3)] has a very large deflection in comparison with a moderate foundation [k = 5.5 kg/cm^3 (200 lb/in^3)]. Large shoulder deflections may result in settlements and pumping problems. A stiff foundation [k = 13.8 kg/cm^3 (500 lb/in^3)]

Figure 2. Effect of encroachment of truck wheel loads on deflection of PCC shoulder for various conditions of support and thickness.

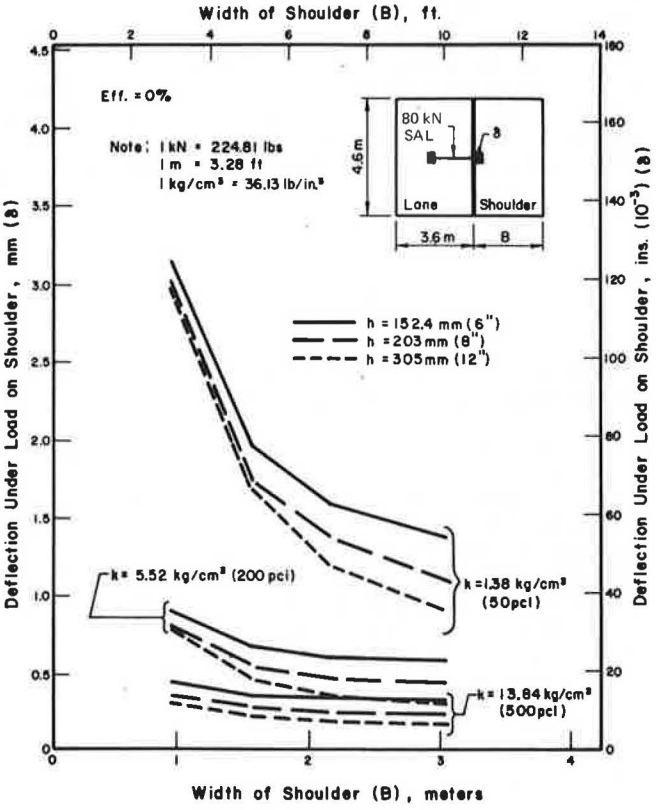


Figure 3. Effect of thickness and width of PCC shoulder on tensile stresses at bottom of shoulder.

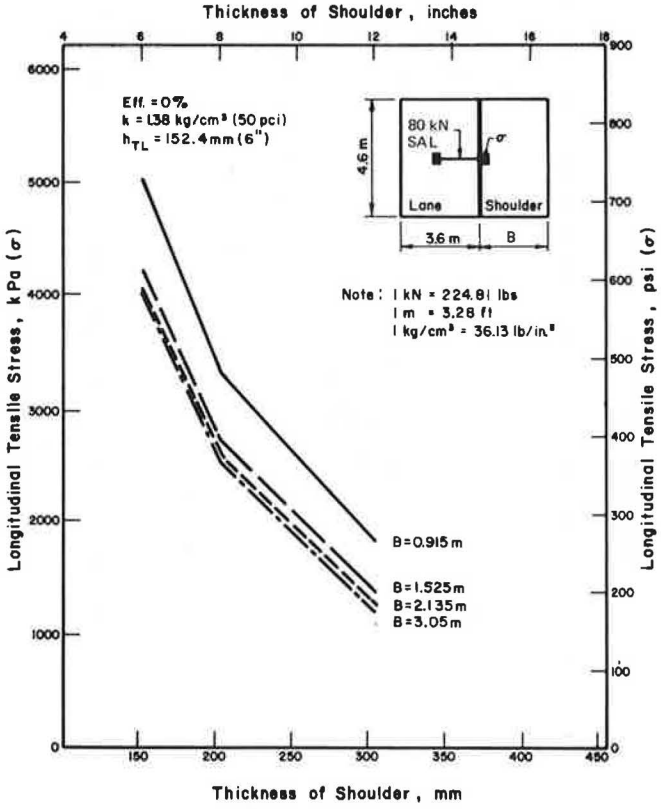


Figure 4. Effect of encroachment of truck wheel loads on tensile stresses at bottom of PCC shoulder for various conditions of support and thickness.

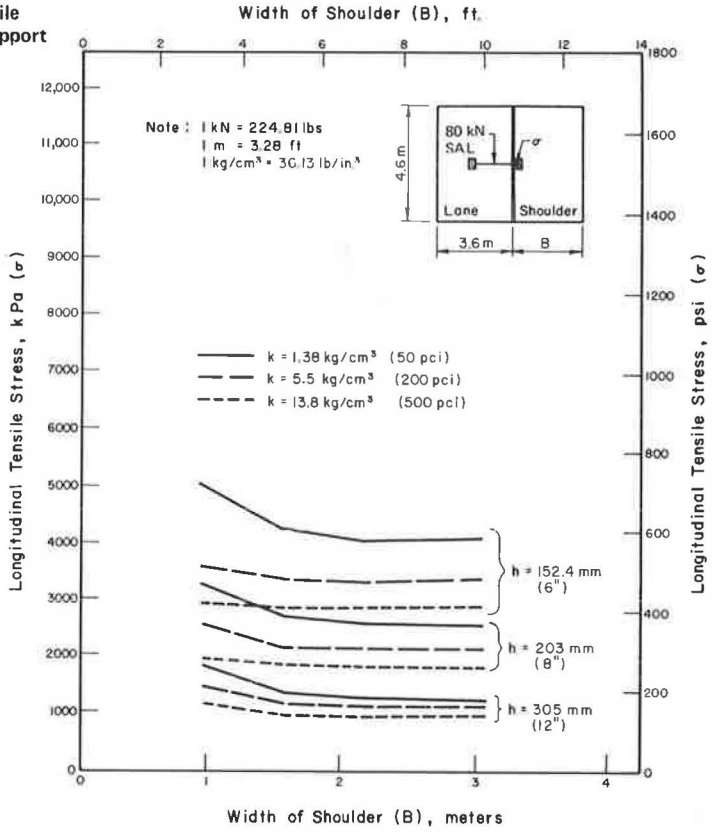
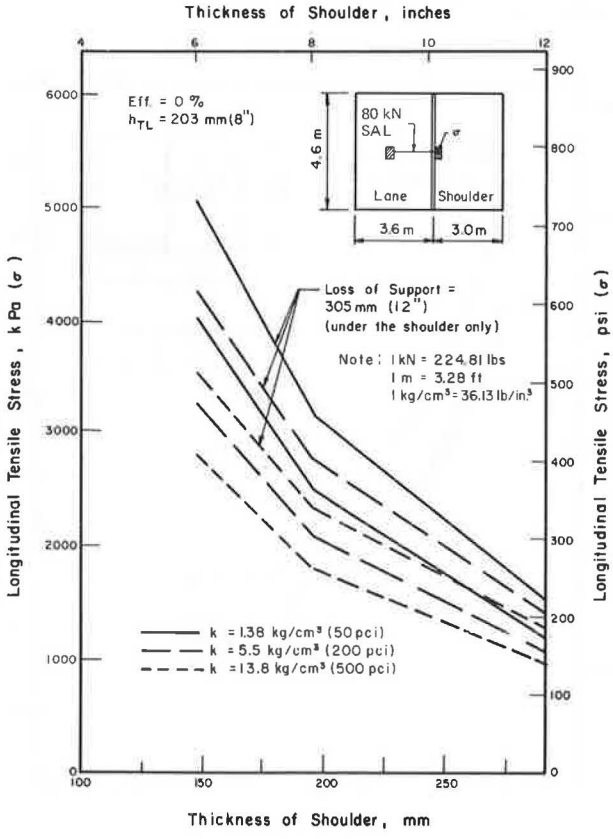


Figure 5. Effect of loss of support on tensile stresses at bottom of PCC shoulder.



reduces the deflections to 20 percent of those for a poor foundation.

The influence of foundation support on critical stress for a range of design variables is shown in Figure 4. Stresses are not as sensitive to foundation support as are deflections but, as foundation support increases, critical stresses decrease. The effect is much greater for thin shoulder slabs than for thicker slabs. For example, a shoulder 15 cm (6 in) thick and 3 m (10 ft) wide shows the following critical stresses for the three conditions of foundation support (1 kPa = 0.145 lbf/in^2):

Support	Critical Stress (kPa)	Ratio to Poor
Poor	4137	1.00
Moderate	3309	0.80
Stiff	2758	0.67

These data show that foundation support has a significant effect on critical stress, especially for the poor condition.

The effect of loss of support beneath the shoulder edge near the lane-shoulder joint is shown in Figure 5. A loss of support of 30 cm (12 in) could be caused by, for example, the settlement of a subsurface drain trench beneath the shoulder. In such a case, the increase in critical stress is about 25 percent. This can be adjusted for by increasing shoulder slab thickness by approximately 3.5 cm (1.4 in) for an original 15-cm (6-in) shoulder, for example.

Lane-Shoulder Tie and Load Transfer

The extent of the tie between the traffic lane and the shoulder affects load transfer, separation of the shoul-

Figure 6. Effect of joint spacing of PCC shoulder on joint spalling.

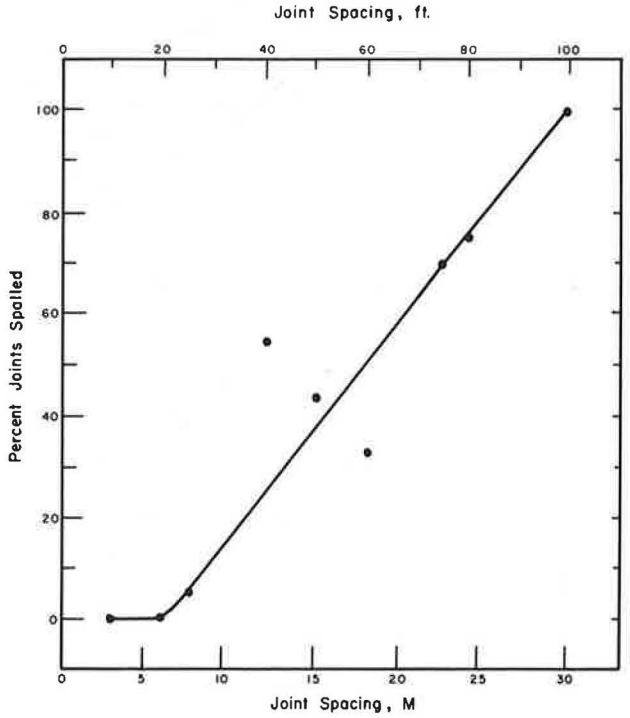
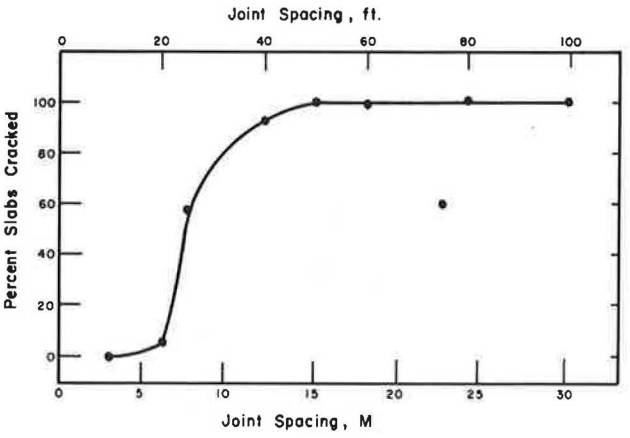


Figure 7. Effect of joint spacing of PCC shoulder on transverse cracking.



der from the lane, and settlement of the shoulder. The effect of the lane-shoulder tie (as indicated by joint load transfer or efficiency) on critical stress in the shoulder is shown in Figure 1. At the 10- to 20-cm (4- to 8-in) range of thickness, the extent of joint efficiency has a very large effect on stress. Changing from 0 to 50 percent efficiency reduces stress by a factor of 2.1 and to 100 percent by a factor of 3.3 for a 15-cm (6-in) shoulder slab. The reduction in critical stress from 0 to 50 percent efficiency is most significant.

Joint Spacing

The effect of joint spacing on the performance of PCC shoulders is shown in Figures 6 and 7. These are based on data obtained from a field survey of three sections of plain PCC shoulders located in Illinois. The sections, which are 9 to 12 years old, are located on Ill-116, I-74, and I-80 (9, 10). The traffic lanes were composed of CRCP, jointed reinforced concrete pavement (JRCP), and composite (asphalt over JRCP) pavement. Most of the sections were tied by rebars to the main-line pavement.

Figure 6 shows the effect of joint spacing on the percentage of joints spalled. As the shoulder joint spacing exceeds 6.1 m (20 ft), the proportion of spalled shoulder joints increases rapidly to the point where, at a spacing of 30 m (100 ft), all joints are spalled. The relation between shoulder joint spacing and percentage of shoulder slabs cracked is shown in Figure 7. Again, as the joint spacing exceeds 6.1 m, a very rapid increase in slab cracking occurs. A number of the transverse cracks had spalled. In addition, many blowups were found in sections that had joint spacings of about 12 to 18 m (40 to 60 ft), and one blowup was found for a joint spacing of 6.1 m.

Other field surveys on main-line pavements and experimental field tests have shown the benefits of using small joint spacings (2, 3).

Effect of PCC Shoulder on Traffic Lane

A PCC shoulder may have an influence on the performance of the adjacent traffic lane. Figure 8 shows the influence of a shoulder on critical edge stress in the traffic lane. As load transfer efficiency increases from 0 percent (no effect) to 100 percent, the critical edge stress decreases by about 50 percent. The decrease is more rapid for up to 50 percent efficiency. The influence of the PCC shoulder on traffic-lane deflections is shown in Figure 9. If the joint has 100 percent efficiency, the deflection decreases by about 50 percent for this example.

Figure 10 shows the influence of both shoulder width and load transfer efficiency on critical stress. The width of the shoulder has a large influence in reducing stress in the traffic lane for a width of up to 0.9 m (3 ft). Beyond that width there is almost no effect. The strong influence of joint load transfer is again indicated. These analytical results show that PCC shoulders should have a beneficial influence on the performance of adjacent traffic lanes if load transfer is reasonable.

Table 1 gives the results of field surveys conducted along the entire length of two projects that included PCC shoulders. Both projects had been constructed about 10 years before and contained CRCP in the main traffic lanes. All types of distress were recorded in the traffic lane adjacent to the shoulders. In general, extensive structural distress was found in the portions of both projects that did not contain PCC shoulders, and little distress was found in the portions that contained the shoulders. On the I-74 project, there was evidence of extensive pumping in areas that did not include PCC shoulders.

Joint separation and settlement of the shoulders were also determined on the three projects. On I-74, it was found that sections that had tie bars experienced virtually no joint separation whereas sections that did not have tie bars experienced joint separation that ranged between 12.7 and 25.4 mm (0.5 and 1 in). On I-80, all the sections with PCC shoulders that were surveyed are tied to the traffic lane. Joint separation was very small [<5 mm (<0.2 in)].

The survey on Ill-116 showed that the sections that had tie bars had a joint separation of less than 5 mm (0.2 in) whereas the section that had a longitudinal keyway had a joint separation of up to 12.5 mm (0.5 in). The section that had neither tie bars nor keyway had a joint separation of up to 25.4 mm (1 in). Thus, tie bars are absolutely required to maintain a tight joint so that

high load transfer efficiency can be maintained over a long time period.

DESIGN GUIDELINES

Slab Thickness

PCC shoulder thickness has a very significant influence on critical stress caused by encroaching traffic loads (Figure 1). Two load positions must be considered to determine required thickness: (a) the inside edge near the lane-shoulder longitudinal joint and (b) the outside free edge. The inside edge of the longitudinal joint is subjected to many more load applications than the outside edge, but if the shoulder is tied to the lane so that there is reasonable load transfer, stress on the inside edge will be significantly reduced—from 4000 to 2000 kPa (580 to 290 lbf/in^2) for a 15-cm (6-in) shoulder that has 50 percent joint efficiency (Figure 1). Because the reduction in stress is so large, it is believed that the outer free edge may control design thickness when a reasonable lane-shoulder tie is provided. Fatigue analyses are being conducted to verify this point and to provide a rational design procedure for determining adequate thickness. A minimum thickness of 15 cm is currently recommended because thinner slabs loaded

Figure 8. Effect of concrete shoulder on critical edge stress for varying joint load transfer efficiency.

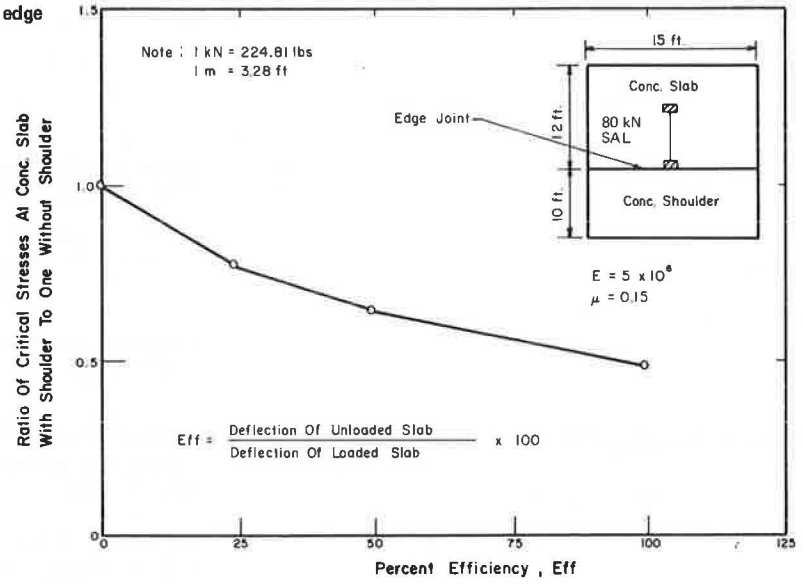
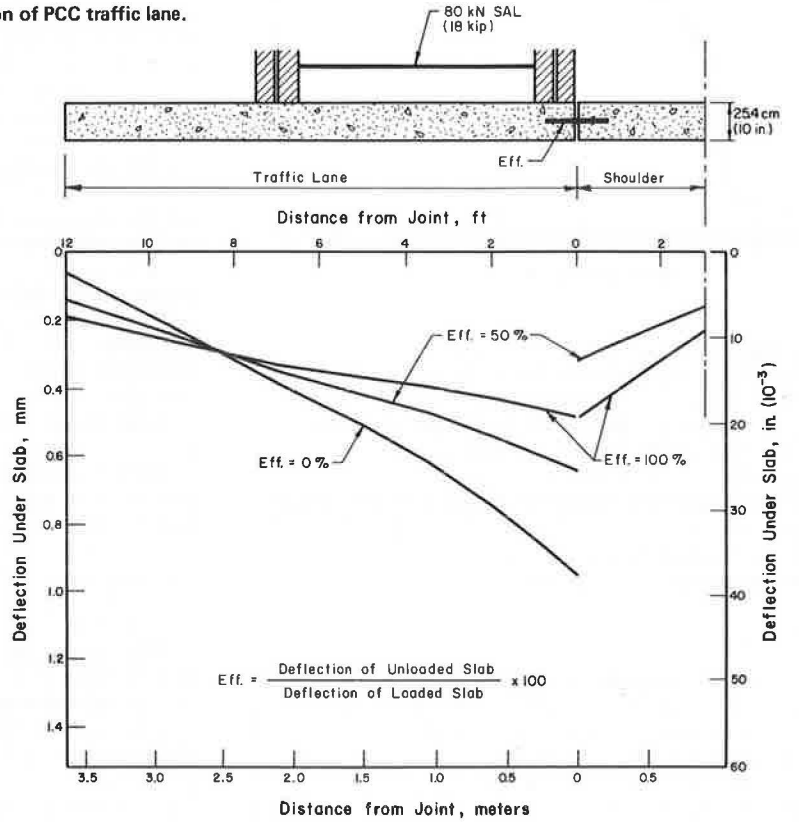


Figure 9. Effect of lane-shoulder tie on deflection of PCC traffic lane.



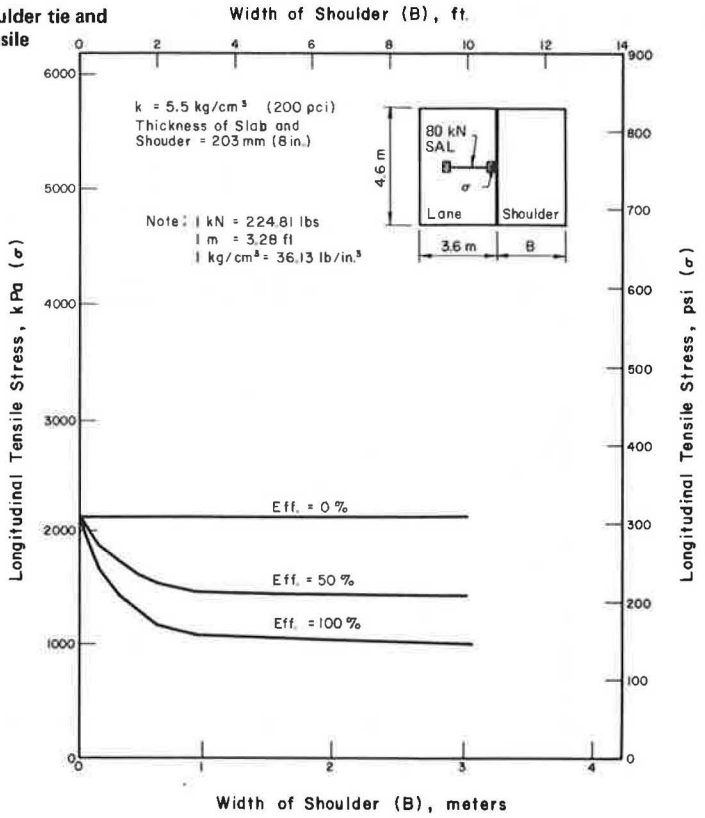


Figure 10. Effect of lane-shoulder tie and width of PCC shoulder on tensile stress of traffic lane.

Table 1. Distress in traffic lane for two CRCP projects that have PCC shoulders along a portion of their length.

		Portion Without PCC Shoulders			Portion With PCC Shoulders		
Project	Age (years)	Length (km)	Edge Punchouts per Kilometer	Wide Cracks per Kilometer	Length (km)	Edge Punchouts per Kilometer	Wide Cracks per Kilometer
I-80	9	3.54	3.7	4.9	1.12	0.7	3.1
I-74	10	3.11	2.5	1.0	0.5	0	0

Note: 1 km = 0.62 mile.

by typical heavy trucks develop very high stresses and tend to crack after only a few such applications. Whether thicker shoulders may be required depends on truck traffic, the amount of structural support desired for the traffic-lane edge, foundation support, load transfer at the joint, and shoulder width.

The table below gives a summary of performance data from the two Illinois highway projects (1 cm = 0.39 in, 1 m = 3.3 ft, and 1 kN = 225 lb):

Parameter	I-74	I-80
Age (years)	10	9
Thickness of traffic lane	18-cm CRCP	20-cm CRCP
Thickness of PCC shoulder	15 cm	20 cm at joint, tapering to 15 cm at outside edge
Range of joint spacing	3-30.5 m	6.1 m
Tie	Tie bars and no tie bars (no. 4 bars 76 cm long, spaced 76 cm center to center)	Anchor bars
Mean average daily traffic in adjacent truck lane	950	2140
80-kN equivalent single-axle loads in adjacent lane (over life of pavement)	2 700 000	7 000 000
Percentage of slabs cracked		5
3.05-m joint spacing	0	
6.10-m joint spacing	5	
7.60-m joint spacing	60	
12.10-m joint spacing	90	
15.25-m joint spacing	100	
18.30-m joint spacing	100	
24.40-m joint spacing	100	
30.50-m joint spacing	100	

Both pavements (especially I-80) carried heavy truck traffic. The 50 percent slabs cracked on I-74 is cause for concern; the long 7.6-m (25-ft) joint spacing had an effect on the cracking because similar, adjacent 3-m (10-ft) long slabs did not show any cracking. The 20- to 15-cm (8- to 6-in) tapered shoulders on I-80 performed very well under heavy traffic: Only 5 percent of the slabs cracked.

Although tapering the shoulder thickness between the two edges has been thought to save on concrete, it may not be the best design for the following reasons:

1. The critical stress load position is probably the outside free edge because of parked trucks or moving traffic that uses the shoulder as a detour around a closed lane.
2. Tapering tends to put the entire pavement section

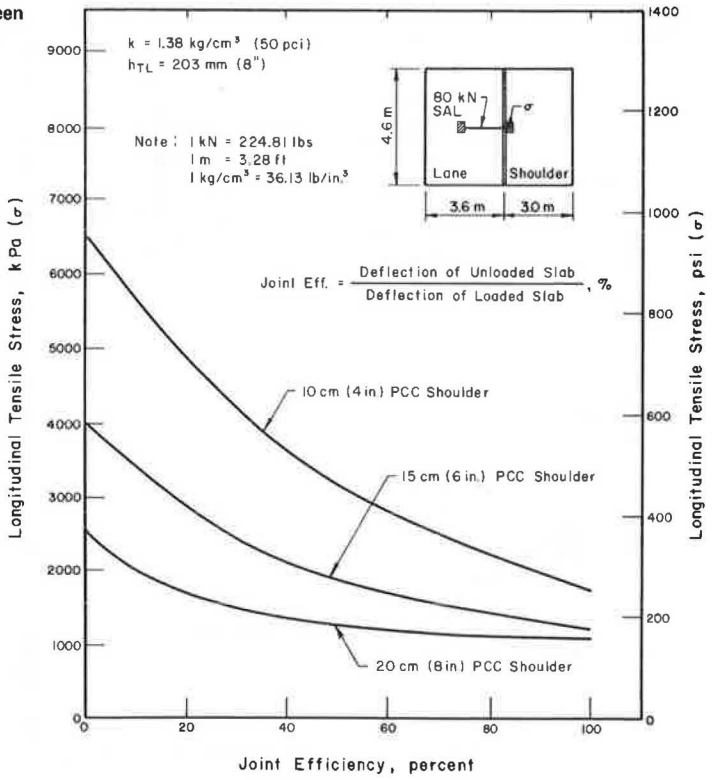


Figure 11. Effect of joint efficiency (tie between traffic lane and shoulder) on tensile stresses in bottom of PCC shoulders.

Table 2. Field data on I-74 and I-80 PCC shoulders to determine efficiency of longitudinal lane-shoulder joint.

Project	Shoulder Design	Mean Edge Deflection (mm)		Load Transfer Efficiency (%)
		Traffic Lane	Shoulder	
I-74[a]	Tie bars, keyway, and granular subbase	0.1143	0.1118	97.8
	Tie bars, keyway, and no subbase	0.1448	0.1016	70.2
	Keyway and granular subbase but no tie bars	0.2108	0.0330	16.0
I-80[b]	Tie bars and intermediate granular subbase	0.2311	0.0889	38.5
	Tie bars and coarse granular subbase	0.2464	0.0762	31.0
	Tie bars and no subbase	0.2159	0.1016	47.0

Note: 1 mm = 0.039 in.

[a] Ten-year-old PCC shoulders. [b] Nine-year-old PCC shoulders.

in a "bathtub" so that water is trapped in the structural section.

3. It is doubtful whether the additional grading required for tapering results in any construction-related cost saving.

Shoulder Width

Required shoulder width is generally dictated by geometric and safety considerations. However, the width influences stresses and deflections in the shoulder and the adjacent traffic lane if they are tied together. The width of a tied shoulder should be at least 91 to 152 cm (3 to 5 ft) to provide maximum structural benefits (stress and deflection) to the traffic lane and shoulder. A narrower shoulder could be used (with load transfer) to help reduce edge stresses in the traffic lane, but a thicker PCC shoulder slab is required.

Lane-Shoulder Tie

The lane-shoulder tie is an effective way of reducing critical stress and deflection and preventing separation at the joint. The effect of joint efficiency (or the extent of load transfer) on the critical shoulder stress is shown in Figure 11 for a typical design situation. A tie system that provided at least 50 percent load transfer would reduce critical stress to acceptable levels. The shape of the curves in the figure shows that there is really only a small advantage in providing more than 50 percent load transfer.

There are essentially three methods of obtaining this level of load transfer along the longitudinal joint:

1. Use of a keyed joint and tie bars that hold the joint very tight,
2. Use of tie bars that hold the joint very tight, and
3. Use of steel dowels.

Tie bars or anchor bolts have been used on most PCC shoulders constructed up to this time.

Field studies were conducted to determine load transfer efficiency in the I-74 and I-80 experimental shoulders (Table 2). On both projects, the procedure used was similar to that used at the AASHO Road Test (13) where the outside of dual tires was 7.5 to 15 cm (3 to 6 in) from the edge of the traffic-lane slab and the beam probe was at the edge of the traffic lane and the edge of the shoulder (creep speed deflection).

On I-74, deflections were measured by using the

Benkelman beam and a single-axle load of 84.4 kN (19 000 lb). After 10 years in service [2.7 million 80-kN (18 000-lb) equivalent single-axle loads (ESAL)], the load transfer efficiency for tied shoulders with a keyway ranged from 70 to 98 percent. Those without tie bars had very low efficiency (16 percent) because of lane-shoulder separation.

After 9 years of service (7 million 80-kN ESAL), load transfer efficiency on I-80 for tied shoulders without a keyway (butt joint) ranged from 31 to 47 percent (Table 2). The I-80 joint had opened an average of about 10 mm (0.4 in), and some of the bars had ruptured. Thus, joint design on I-80 did not provide a long-term joint efficiency of 50 percent or greater.

Laboratory tests by the Portland Cement Association showed that steel tie bars are effective in extending the endurance of aggregate interlock and keyed joints under repeated loading. Load transfer efficiency after about 5 million load applications was greater than 70 percent for aggregate interlock, keyway, and smooth joints, all of which had steel ties (12). Dowels have been shown to provide very high load transfer efficiency (>80 percent) even if the joint separates somewhat (11). Thus, as Figures 10 and 11 show, if a tied shoulder is used and at least 50 to 70 percent load transfer efficiency is attained, stresses in both the traffic lane and the shoulder are significantly reduced (by 30 and 55 percent respectively). One problem that has been noticed is that when PCC shoulders are on high fills the outer edge tends to settle; as a result, some joints have separated because the tie bars pulled out from the PCC or the steel ruptured. Consideration should therefore be given to increasing the number of tie bars for greater load transfer and to prevent separation.

Foundation Support

The PCC shoulder can be placed directly on the subgrade soil, a granular subbase, or a stabilized subbase. These foundation conditions can generally be considered poor, moderate, and stiff respectively. Analysis shows that PCC shoulders that have poor support [$k \cong 1.38$ kg/cm^3 (50 lb/in^3)] show large deflections and stresses. Providing a moderate level of support [$k \cong 5.5$ kg/cm^3 (200 lb/in^3)] appears to be justified. Using a stiffer foundation support is not very effective in further reducing deflections or stresses. Field results in Illinois have shown little difference in the performance of sections that have granular subbases and those that have fine-grain soil subbases. However, continuous drainage should be considered when subbases are selected to avoid a bathtub cross section.

Slab Length

Based on results from the field survey, a maximum slab length of 3.6 m (15 ft) is recommended. The reason for this choice can be seen in Figures 6 and 7, which clearly show that using a slab longer than 3.6 to 6.1 m (15 to 20 ft) will result in joint spalling and increased transverse cracking. Short slab lengths eliminate the need for steel reinforcement and reduce joint movement to an amount small enough that it does not force cracks to open up on the adjacent traffic lane in either CRCP or JRCP.

Effect of Shoulder on Traffic Lane

The shoulder affects stress and deflection of the traffic lane (a) through the load transfer of the longitudinal joints and (b) by minimizing the potential for edge pumping. Figures 8, 9, and 10 show that the efficiency of load transfer between the traffic lane and the shoulder is of significant importance to the traffic lane. Figures 8 and 10 show that critical edge stresses for the traffic lane could be reduced by more than 30 percent if a 50 percent joint efficiency were used. Figure 9 shows that edge deflection for the traffic lane could be reduced by about a third if there were 50 percent joint efficiency. Reduction of stresses and deflections would therefore improve the performance of the traffic lane (Table 1). Figures 8, 9, and 10 indicate that, to improve the performance of the traffic lane, optimum design of a shoulder would require providing maximum load transfer across the longitudinal joint (≥50 percent) and adequate shoulder thickness [≥15 cm (≥6 in)], width [>0.9 m (>3 ft)], and foundation support [≅ 5.5 kg/cm^3 (≅ 200 lb/in^3)]. Provision of a PCC shoulder either on new construction or for rehabilitation of an existing shoulder is expected to have a beneficial effect if these design requirements are met.

The condition and the design of the existing traffic lane should be determined. If distress associated with edge traffic loadings is occurring, special consideration should be given to providing high load transfer and adequate shoulder thickness to reduce critical stresses and deflections in the traffic lane.

CONCLUSIONS

Analytical and field studies have shown that PCC shoulders can be designed to (a) provide long-term, low-maintenance performance and (b) help to reduce the amount of distress in the adjacent traffic lane. The influence of major design variables on shoulder behavior under load was determined by using a finite element analysis program and data from field surveys of several PCC shoulders. Improvements in design practice are recommended. Additional work is under way at the University of Illinois to develop structural design procedures that consider the effect of repeated loadings on the shoulder so that slab thickness can be determined more adequately. Work is also under way to determine the amount of load transfer across various longitudinal joint designs.

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