

ANALYSIS OF FULL-DEPTH PCC PATCHES FOR JOINTED CONCRETE PAVEMENTS

by

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BACKGROUND

In many states, the majority of the interstate highways are jointed Portland Cement Concrete (PCC) pavements. Other major arterials and primary routes also have been constructed with PCC pavements. Most of these jointed PCC pavements have deteriorated or functionally failed due to heavy truck traffic and/or damaging climatic conditions. Much of the deterioration or failure has occurred at the transverse contraction joints. The condition failures include spalling, pumping, faulting, corner cracking, and transverse cracking.

In the past few years, some transportation agencies have maintained jointed PCC pavements without placement of overlays. This type of work, referred to as Concrete Pavement Restoration (CPR), includes joint sealing, subsealing, grinding, spall repair, and full-depth patching.

For several years, many states have used full-depth PCC patch repair for joint/crack rehabilitation. Unfortunately, this technique has not been completely successful because the design criteria for full-depth PCC patches are inadequate. The performance of full-depth PCC patches depends on the size and spacing of the dowel bars in the Load Transfer Device (LTD) system, the thickness of PCC pavement, and the length of the patches.

Scope of the Study

The scope of this investigation was an evaluation of the design of full-depth patches for jointed PCC pavements. The major highway pavements selected for this study were subjected to heavy axle loads of 34 kips for rear tandem axles, 30 kips for front tandem axles, and 8 kips for the steering axle of a typical truck with a length of approximately 60 feet. This study evaluated the loading scheme in which the tire loads were located at the slab corner and along the edge of the concrete pavement. Stresses and deflections were calculated with the finite element program JSLAB.

Load Transfer Analysis of Transverse Joints

Contraction joints are areas of structural weakness in jointed PCC pavements. Excessive

deflections at the joints due to loads passing over a joint without load transfer can permanently damage the subgrade. This also may lead to excessive vertical displacement of slab ends and eventually to the development of faulting and cracking at joints. Load transfer devices in transverse joints of PCC pavements are designed to:

- Control edge stresses
- Reduce slab deflections under the application of loads
- Maintain surface alignment of the two slab ends

The analysis theory associated with dowel bars in PCC slabs was developed mainly by Westergaard, Bradbury, and Friberg in the late 1920s and the 1930s (1-3). Friberg, using Timoshenko's analysis (4) of a long beam on an elastic foundation (bar embedded in concrete), showed that the following equations can be used to determine the deflection, moment, and shear of the dowel at the joint (5):

$$y = \frac{e^{-\beta x}}{2\beta^3 EI} [P_t \cos \beta x - \beta M_o (\cos \beta x - \sin \beta x)] \quad (1)$$

$$M = - \frac{e^{-\beta x}}{\beta} [P_t \sin \beta x - \beta M_o (\sin \beta x + \cos \beta x)] \quad (2)$$

$$V = - e^{-\beta x} [(2\beta M_o - P_t) \sin \beta x + P_t \cos \beta x] \quad (3)$$

where

y = dowel bar deflection, in

x = distance along the dowel from the face of the concrete, in

M = moment on the dowel at the face of the concrete, clockwise is positive, in-lb

P_t = load transferred by the dowel, kips

and the relative stiffness of the mass can be expressed as

$$\beta = \sqrt[4]{\frac{Gb}{4EI}} \quad (4)$$

where

G = modulus of dowel/concrete interaction, psi

b = dowel diameter, in

E = modulus of elasticity of the dowel, psi

I = moment of inertia of the dowel, in⁴

Friberg (3,5) showed that the moment at the dowel-concrete interface is

$$M = \frac{P_t z}{2} \quad (5)$$

where z is the joint opening, and the deflection of the dowel at the joint is

$$y = \frac{P_t}{4\beta^3 EI} (2 + \beta) \quad (6)$$

The bearing stress between the concrete and the dowel at any point can be expressed as

$$\sigma = Gy \quad (7)$$

Friberg (5) also showed that the slope of the dowel at the face of the joint is

$$\frac{dy}{dx} = - \frac{P}{2\beta^2 EI} (1 + \beta) \quad (8)$$

Moreover, the point where the bearing stress changes direction along the dowel is

$$\tan \beta L = \frac{2 + \beta Z}{\beta Z} \quad (9)$$

where L is the distance from the slab face.

Friberg's work provided the basis for the work by Teller and Cashell of the former Bureau of Public Roads (6). In their study, 4-feet by 10-feet PCC slabs were constructed at 6-, 8-, and

10-inch depths. Dowel sizes of 5/8, 3/4, 7/8, 1, 1 1/8, and 1 1/4 inches were included. The PCC slabs with four dowel bars per joint were supported in a machine that applied a known load alternately to each side of the joint. Most of the tests were conducted at a 10,000-lb load with up to 2 million load cycles.

Teller and Cashell's comprehensive testing provided significant information that has been used for rigid pavement design over the past 25 years. Some of their conclusions are listed below (6):

- A definite exponential relationship exists between dowel diameter and load transfer capacity (with other conditions being constant).
- A relationship exists between slab depth and dowel diameter required to transfer a given percentage of the applied load. For minimum size dowels, the dowel diameter in eighths of an inch should equal the depth in inches.
- Dowel looseness has an important effect on the structural performance of the dowel since it can function at full efficiency only after looseness is taken up by deflection.

ANALYSIS OF PCC PAVEMENT PATCH DESIGN

The finite element analysis (JSLAB) of jointed concrete pavements was applied to the structural behavior of full-depth patches with doweled joints (7). A parametric study determined the effect of material properties and loading on pavement responses. Different numbers of dowel bars and different dowel sizes across the transverse joints were analyzed for this evaluation of the design of full-depth patches.

Traffic Loading

The traffic loading for this study consisted of a typical tractor-trailer truck with the axle and tire dimensions shown in Figure 1. The truck carried legal axle loads consisting of 34-kip and 30-kip tandem-axle loads and an 8-kip steering single-axle load. Tire pressure was assumed to be 110 psi for the tires on the tandem axles and 100 psi for the tires on the single axle. For the analysis, the contact area of the actual tire imprint was converted to a rectangle using PCA's procedure (8).

Study Parameters and Levels

The Pennsylvania Department of Transportation's 1960s pavement configuration was selected for the finite element analysis because repairs are currently being made on this pavement type. In the 1960s, the concrete slabs were 61.5 feet long and 12 feet wide. (Typical full-depth patches used for today's repairs are 4 to 16 feet long and 12 feet wide.) Slab thicknesses were 8, 9, 10, and 11 inches for the slabs and the full-depth patches.

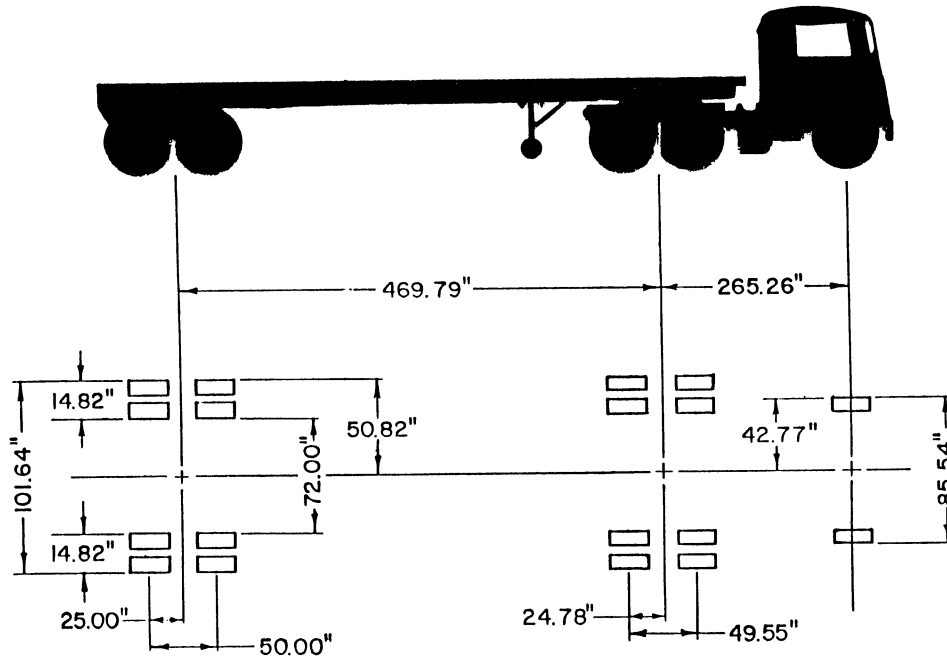


Figure 1. Dimensions of the study vehicle.

All dowels were round steel bars with a modulus of elasticity of 29×10^6 psi and a Poisson's ratio of 0.30. The dowels were 18 inches long with diameters of $3/4$, 1, $1\ 1/4$, and $1\ 1/2$ inches.

The modulus of elasticity of the concrete slabs and full-depth patches used in the study was a typical value of 4.5×10^6 psi with a Poisson's ratio of 0.15. The modulus of dowel/concrete interaction used in the study was a typical value of 1.5×10^6 psi and the joint width considered was $1/4$ inch. Values of the modulus of subgrade reaction, K, were 200, 400, 600, and 800 pci.

Conventional joints incorporate dowels typically spaced at a uniform 12 inches, center to center (5). However, dowel location is critical only in the vicinity of the outside slab corner. Thus, the use of a large number of dowel bars is not warranted along the transverse jointed concrete pavements away from the outside corner. The patterns of dowel placements studied are based on Tayabji's analysis (9); these patterns are illustrated in Figure 2. With the spacings indicated in the figure, no major changes would be required in the existing fabrication process designed for the twelve uniformly spaced dowels.

A total of 256 JSLAB computer program inputs were run on an IBM 4341 mainframe system. For the majority of the analysis discussed herein, a K value of 400 pci was chosen for the modulus of subgrade reaction; this practical average value is usually considered acceptable for design purposes. Table 1 summarizes the variables and the number of levels used as inputs in the JSLAB computer program.

Table 1. Input variables and levels.

Variables	Levels
Thickness	8, 9, 10, 11 inches
Dowel Bar Size	$3/4$, 1, $1\ 1/4$, $1\ 1/2$ inches
No. of Dowel Bars	6, 7, 8, 12
Modulus of Subgrade Reaction	200, 400, 600, 800 psi
Total Inputs	256

Effect of Study Variables on Concrete Stress and Deflection

Deflections and Joint Efficiency. The JSLAB finite element program was used to calculate pavement deflections along the transverse joint. Figure 3 illustrates the effect of the number of dowel bars on the deflections along the transverse joint. The number of dowel bars has a significant effect on deflection. However, the maximum deflection and its location (for 6-, 7-, 8-, and 12-dowel placements) were the same and were consistent up to approximately $2\ 1/2$ feet from the edge of the concrete pavements. This behavior is due to the placement of six, seven, eight, and twelve dowel bars, which remained similar up to 30 inches from the edge of the shoulder of the

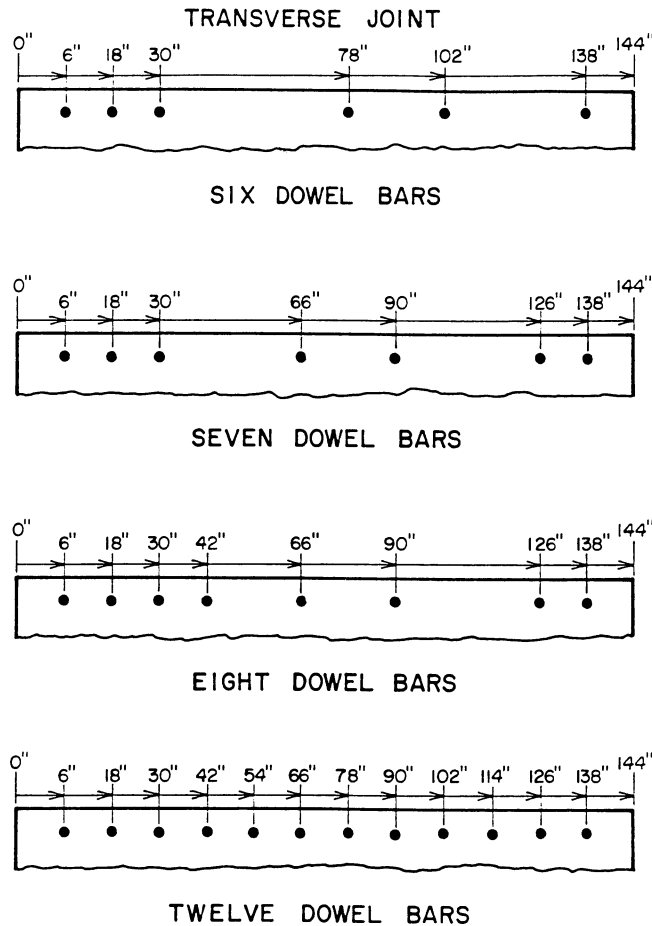


Figure 2. Illustration of dowel bars placement.

concrete pavements (see Figure 2). This figure also illustrates that the deflections for eight and twelve dowel bars follow the same pattern and are approximately equal in magnitude across the concrete pavements. However, this figure indicates that the deflections of six and seven dowel bars were different beyond 3 feet from the edge of the pavement; from 3 feet to approximately 9 feet from the edge of the pavement, the deflections tended to increase. This behavior shows that a smaller number of dowel bars do not adequately transfer the applied load; therefore, the pavement tends to deflect nearer the slab centerline.

Figure 4 illustrates the relationships between the distance along the transverse joint and the joint efficiency. This figure indicates that decreasing the number of dowel bars rapidly reduces joint efficiency. However, the difference in joint efficiencies associated with eight and twelve dowel bars was about 10 percent; the corresponding difference for seven and twelve dowel bars was about 40 percent (see Figure 4). Because the loaded slab carries more of the total load (the seven dowel bars do not efficiently transfer load across the joint), it is possible that the slab can begin to work independently, creating large stresses at the joint. It can also be concluded that the deflections at the joints decrease as the thickness of concrete pavements increases, and, therefore, joint efficiency increases. This conclusion is illustrated in Figure 5, where thickness is increased to 10.0 inches.

Analysis of Tensile Stresses. This method of analysis took into account only tensile stresses caused by the load applied along the x- and y-axes of the concrete slab. Also, only tensile stresses in static loading conditions were studied. For the levels of concrete pavement thickness and subgrade

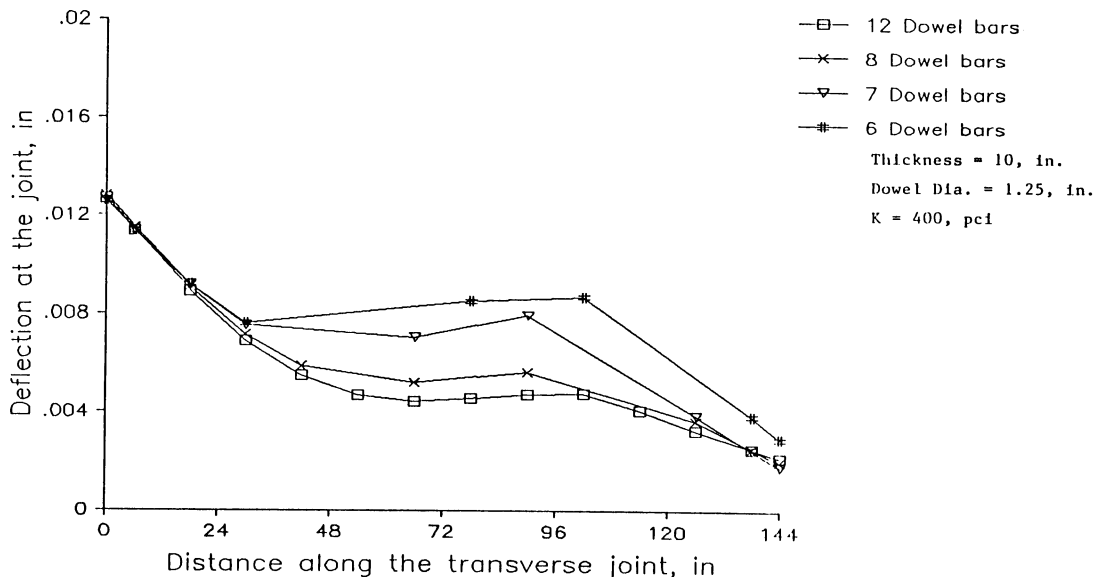


Figure 3. Relationship between deflection and distance along transverse joint.

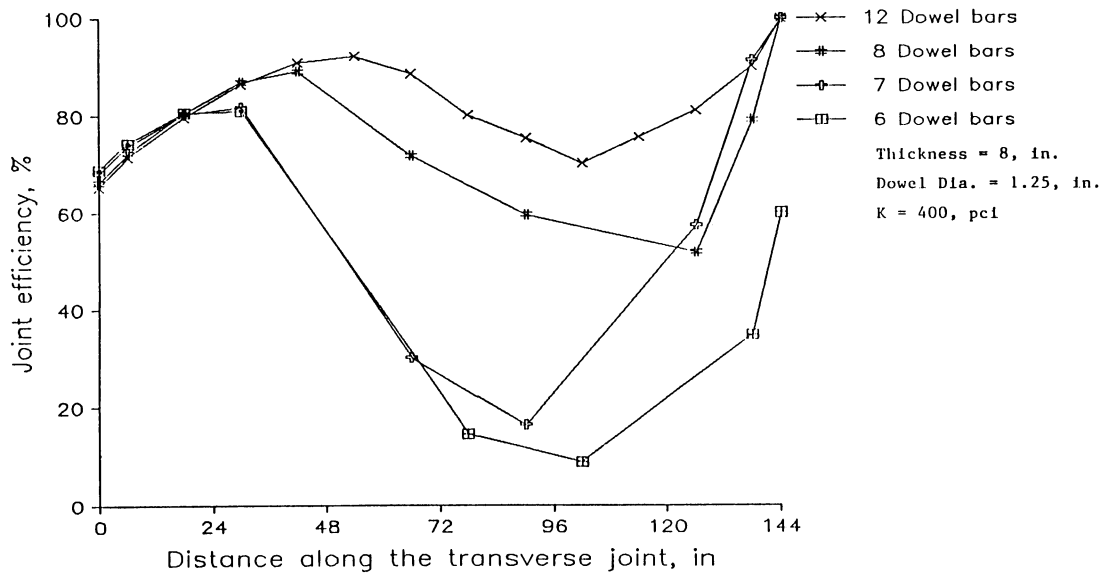


Figure 4. Joint efficiency versus distance along transverse joint.

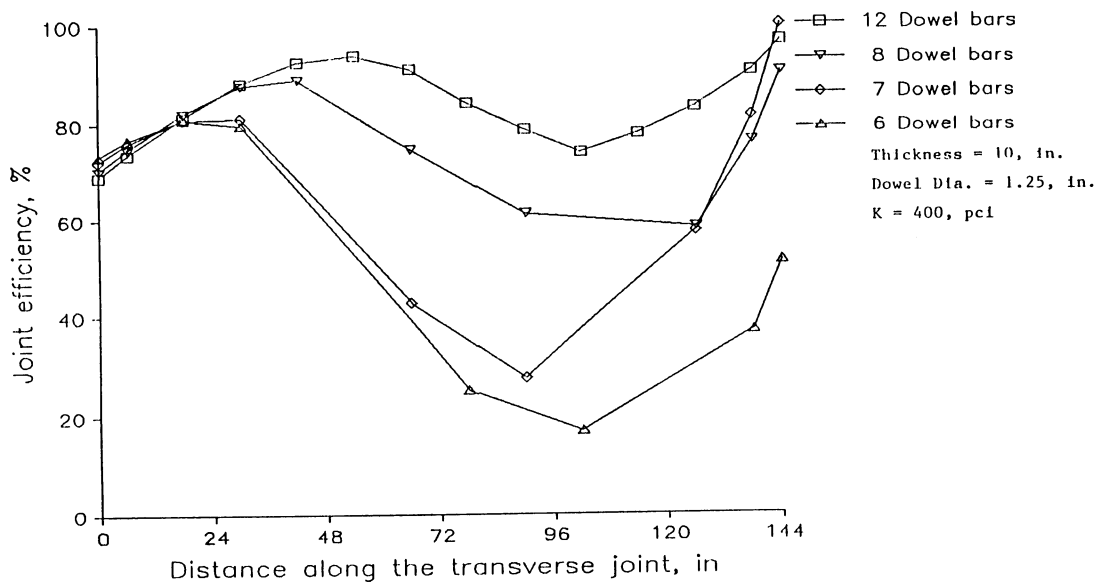


Figure 5. Joint efficiency versus distance along transverse joint.

modulus included in the study, Figure 6 illustrates the relationship between the longitudinal distance and the edge stresses, σ_x , along the x-axis. According to the sign convention, a negative value indicates that the concrete is in tension. The figure shows that the critical stresses decrease slightly as thickness of concrete pavement increases. Also, it was shown that the location of the maximum edge stresses in the concrete slabs is not sensitive to the different number of dowel bars in the study. The location of the critical edge stresses was approximately 2 feet from the joint in the loaded slab. None of the stresses were large enough to cause cracking of the slabs (assuming a maximum tensile stress limit of 400 psi).

The maximum stress, σ_x , along the x-axis at the edge of PCC pavements is not affected by the number of dowel bars across the transverse joint (see Figure 7). In addition, the location of the maximum edge stresses remained unchanged for different number of dowel bars because maximum edge stress occurs at the edge of the concrete pavements (9) and six, seven, eight, and twelve dowel bars were similarly placed up to 30 inches from the edge of the concrete pavement.

The above analysis indicates that stresses alone are not an adequate criterion for the design of full-depth patches because the number of dowel

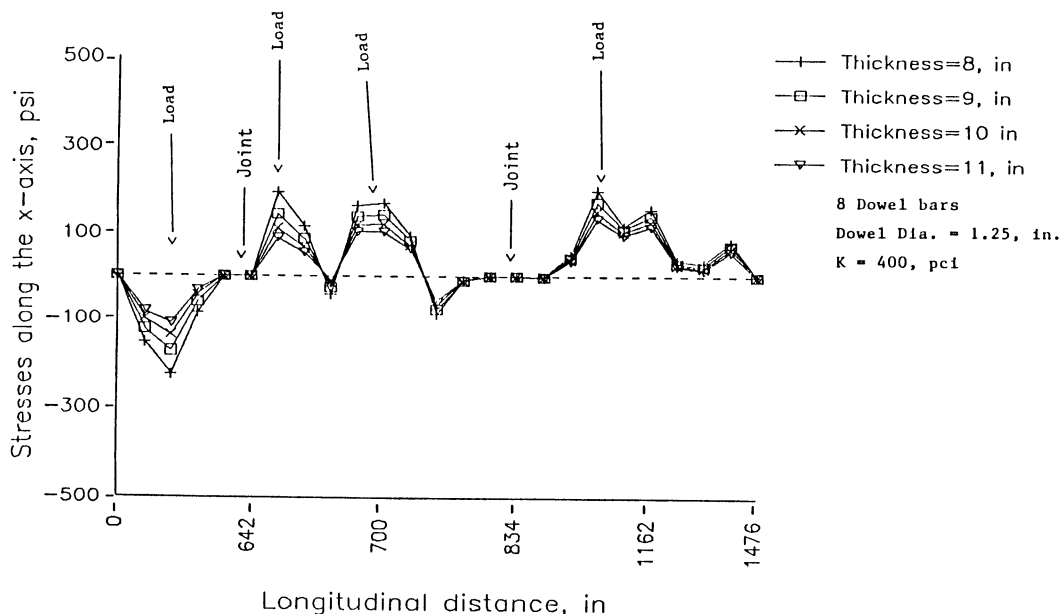


Figure 6. Stresses along the x-axis versus longitudinal distance.

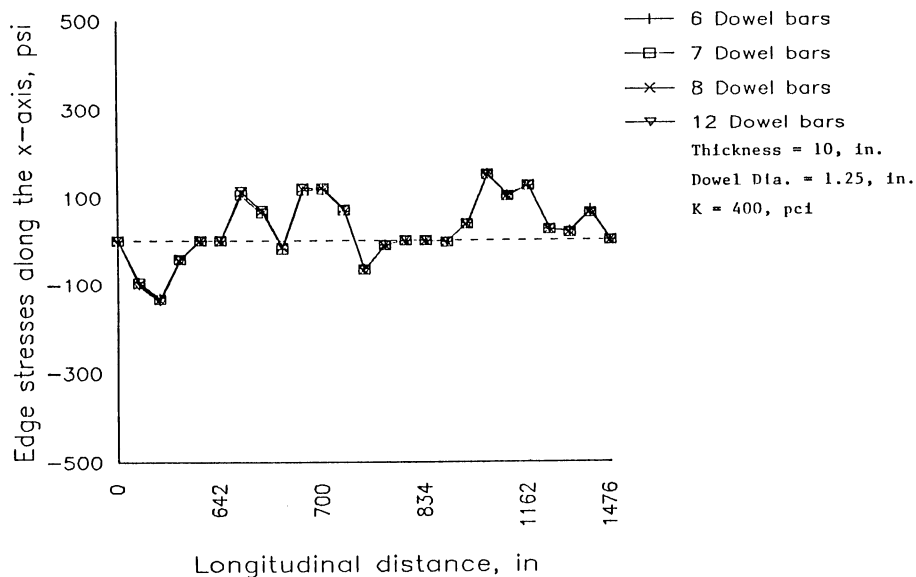


Figure 7. Stresses along the x-axis versus longitudinal distance.

bars does not significantly increase or decrease the tensile stresses, and the stresses never exceed the modulus of rupture. Other factors can significantly affect patch design: deflection (as discussed earlier), bearing stresses between the concrete and dowel bars, and bending moments in dowel bars.

Effect of Study Variables on Concrete and Dowel Bar Bearing Stress

Bearing stress in the concrete in the vicinity of the dowels can influence the structural performance of the load transfer systems. This bearing stress, between the concrete and steel

bars, is usually the controlling factor in the design of dowel bar load transfer systems. An increase in concrete bearing stress can fracture the concrete surrounding the dowel bar, which leads to dowel looseness and deterioration of the load transfer system with the eventual faulting of the slab (10).

The American Concrete Institute (ACI), Committee 325 (11), recommends the following equation for the calculation of allowable bearing stress on concrete:

$$f_a = \frac{(4 - D)}{3} f'_c \quad (10)$$

where

f_a = allowable bearing stress, psi

D = dowel diameter, in

f'_c = ultimate compressive strength of concrete, psi

The maximum bearing stress between the dowel bar and the concrete can be calculated by Friberg's equation or the equation developed by Barenberg (11):

$$\sigma_{br} = \frac{(800 + 0.068 E_c)}{D^{3/4}} (1 + 0.355 w) LT \quad (11)$$

where

σ_{br} = maximum bearing stress, psi

D = dowel diameter, in

E_c = concrete modulus of elasticity, ksi

w = joint opening, in

LT = maximum load transferred by dowel, kips

As seen by equation 10, the maximum allowable bearing stresses are a function of the dowel bar diameter. Laboratory experiments have shown that the bearing stress in lab samples can be 2 to 3 times greater than the ACI allowable without cracking the concrete (6). Therefore, 1 1/2 times the ACI allowable bearing stress was selected as a reasonable maximum limit for this analysis and engineering design.

The finite element program JSLAB was used to calculate the shear in the dowel bar, which in turn can be used to calculate the bearing stress for the slabs in this study. Examples of relationships between bearing stresses and dowel bar diameters for the variables and levels included in the study are illustrated in Figures 8 and 9.

Bearing stresses calculated for the patches containing eight and twelve dowel bars are much smaller than the calculated bearing stresses for the patches containing six and seven bars for all dowel bar diameters. This indicates that eight and twelve dowel bars transfer load more efficiently across the joints than six and seven dowel bars. Also, as the dowel bar diameter increases, the bearing stresses decrease slightly for eight and twelve dowel bars, while the bearing stresses increase rapidly for six and seven dowel bars. This behavior occurs because bearing stress is a function of the dowel bar diameter and the shear in the dowel bar (equation 11).

In the case of eight and twelve dowel bars with diameters of 3/4 inches, $K = 200$ pci, and concrete slab thickness of 8 inches, the maximum shear in dowel bars was found to be 4.1 and 4.2 kips, respectively. Further, for the above variable levels with the dowel diameter of 1 1/2 inches, the shear in dowel bars was 8.4 and 8.5 kips, respectively. Therefore, the shear ratio between dowel bars of 1 1/2-inch and 3/4-inch diameters, was 2.02 and 2.05, respectively (see Table 2). The ratio of dowel bar size was 2:1. However, for six and seven dowel bars, with all other factors constant, the shear ratio between dowel bars of 1 1/2-inch and 3/4-inch diameters was 3.26 and 3.1, respectively (see Table 2). Thus, the shear for eight and twelve dowel bars increased at the same rate as the ratio of dowel bar sizes. The shear ratio associated with six and seven dowel bars, however, increased approximately 1.6 times the ratio of the dowel bar diameter.

In addition, the bearing stresses associated with eight and twelve dowel bars are always lower than the allowable stresses. In contrast, because the inadequate number of dowel bars does not distribute the load across the entire length of the joint, the bearing stresses associated with six and seven dowel bars are larger than the allowable stresses.

As shown in Figure 10, as the thickness of the concrete pavement increases, the bearing stresses between the dowel bars and concrete slabs decrease slightly for eight and twelve dowel bars. In contrast, as the thickness of the concrete pavement increases, the bearing stresses between the concrete and dowel bars decrease rapidly for six and seven dowel bars. Thus, for eight and twelve dowel bars, the distribution of load across a concrete pavement joint is controlled by the number of dowel bars rather than by the concrete pavement thickness. In contrast, for the smaller number of dowel bars, the load distribution is more controlled by the concrete pavement thickness.

Figure 11 shows that the maximum shear occurs at the corner of the concrete slab for six dowel bars. However, the maximum shear shifts to approximately 9 feet from the edge of the concrete slab. The shifting of the maximum shear implies that the interior dowel bars can experience failure before the external dowel bars.

It also should be noted that the calculated bearing stresses for eight and twelve dowels were almost equal, and calculated bearing stresses for six and seven dowel bars were almost equal between the concrete and dowel bars for all of the above analyses. Examples of the calculated bearing stresses using equation 11 for the variables and levels included in the study are presented in Table 3.

SUMMARY AND CONCLUSIONS

Many interstate and other major highways in the United States were constructed with jointed Portland cement concrete. These pavements have

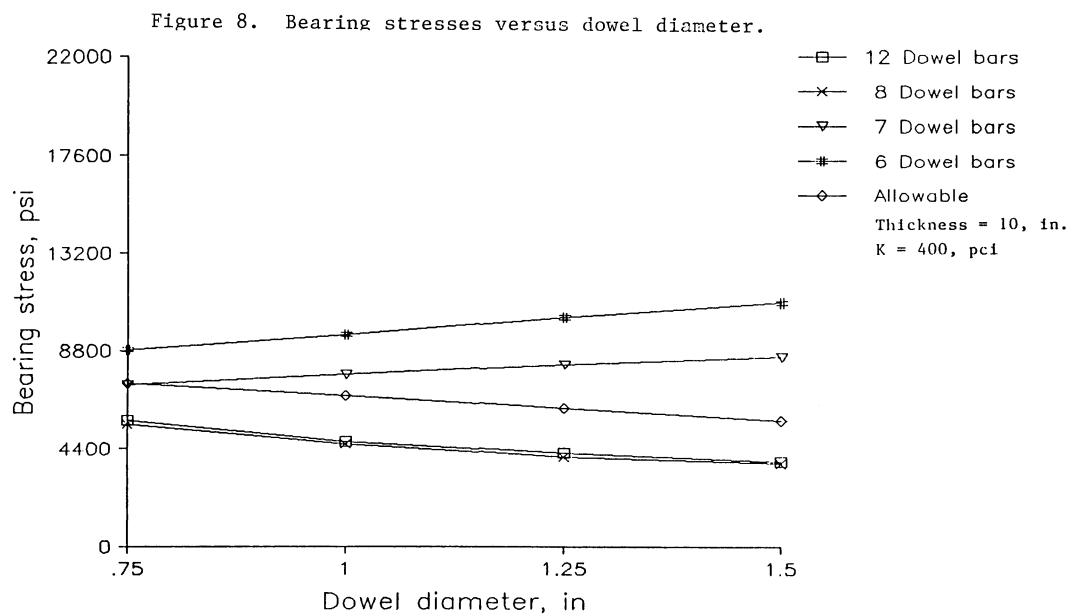
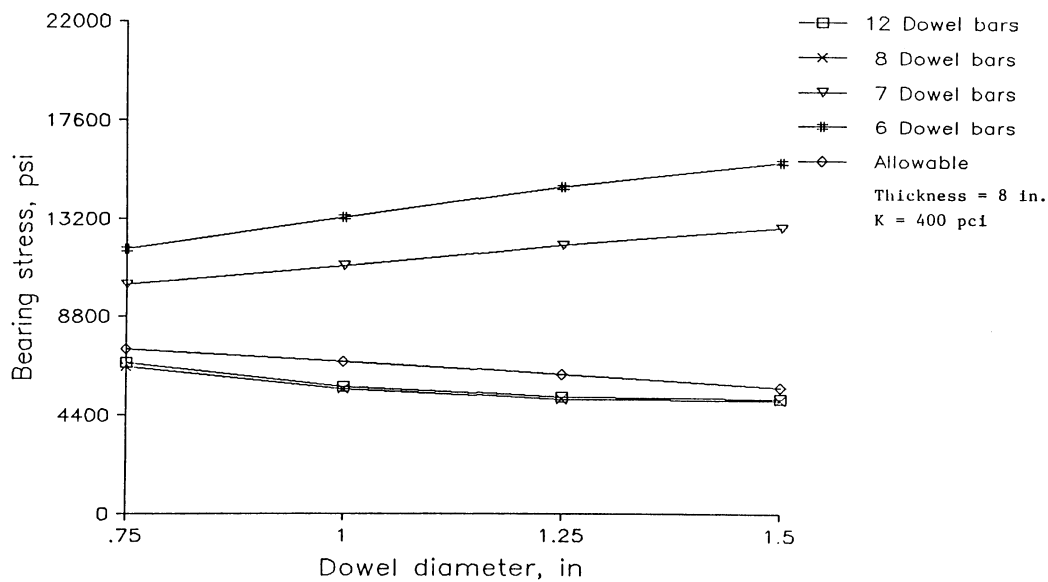


Table 2. Dowel bar shear ratio.

Dowel Diameter (in.)	No. of Dowel Bars			
	6	7	8	12
Dowel Shear (Kips)				
3/4	9.2	7.4	4.1	4.2
1 1/2	30.0	23.0	8.4	8.5
Shear Ratio	3.26	3.10	2.02	2.05

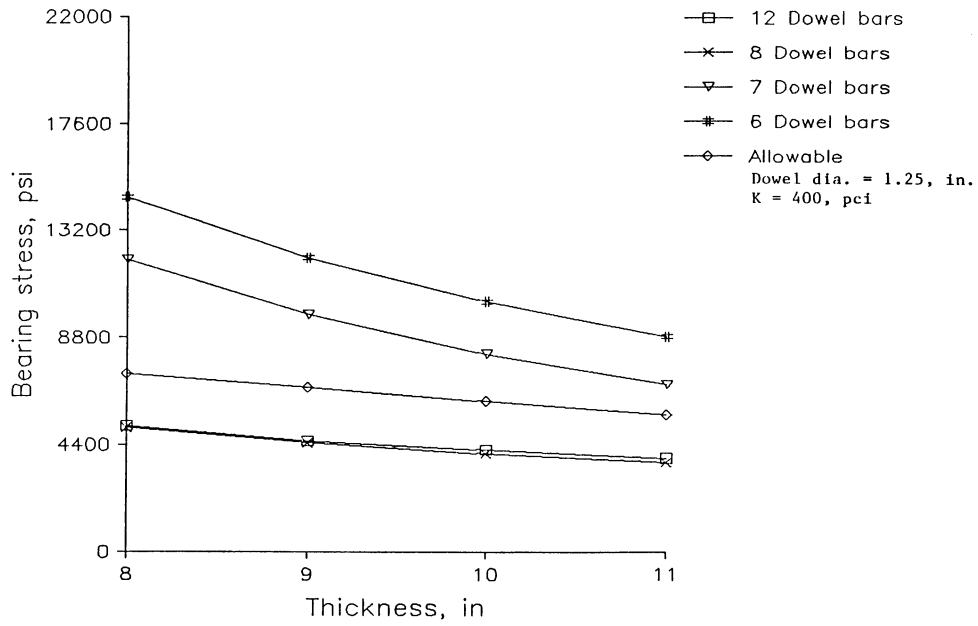


Figure 10. Bearing stresses versus slab thickness.

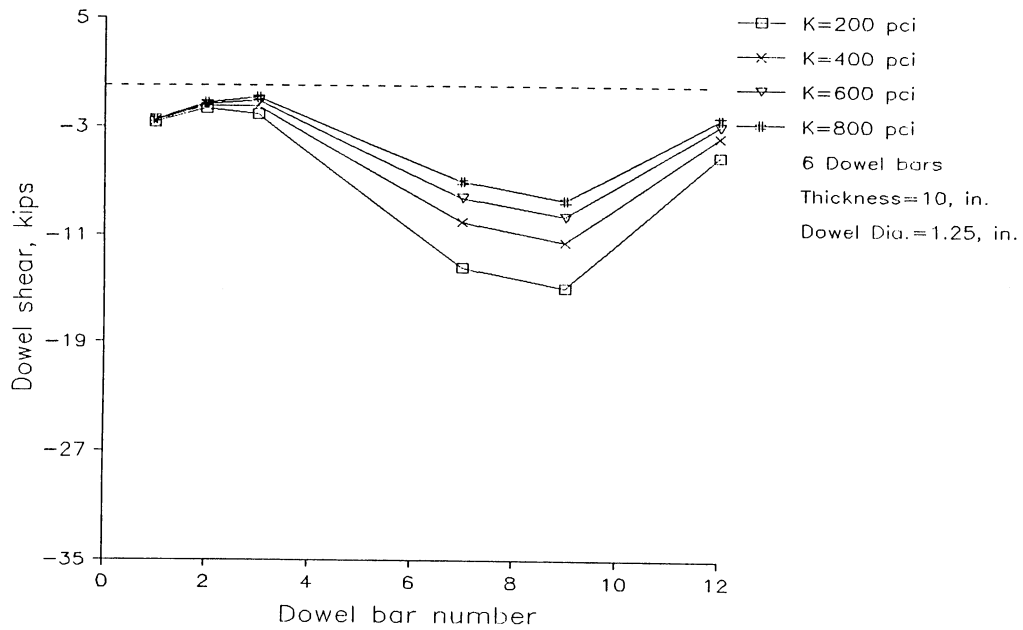


Figure 11. Illustration of dowel shear and dowel bar number.

Table 3. Calculated bearing stresses.

Thickness	Modulus of Subgrade Reaction	Dowel Bar Diameter in.	Calculated Bearing Stresses for all Levels of Study Variables, psi			
			12 Dowel Bars	8 Dowel Bars	7 Dowel Bars	6 Dowel Bars
8 in.	K=200, pci	.75	7421	7244	13075	16255
		1.00	6381	6140	13966	18060
		1.25	5901	5723	14932	19582
		1.50	5960	5890	15987	21106
	K=400, pci	.75	6714	6538	10248	11838
		1.00	5659	5538	11077	13244
		1.25	5186	5097	11982	14575
		1.50	5119	5049	12762	15707
	K=600, pci	.75	6184	6007	8658	9718
		1.00	5298	5177	9512	10836
		1.25	4739	4739	10283	11982
		1.50	4628	4628	11009	12972
	K=800, pci	.75	5831	5654	7598	8304
		1.00	4936	4816	8428	9391
		1.25	4471	4471	9210	10372
		1.50	4347	4277	9887	11219
9 in.	K=200, pci	.75	6891	6538	10778	13782
		1.00	5659	5418	11318	14809
		1.25	5097	4918	11892	16005
		1.50	4838	4768	12621	17109
	K=400, pci	.75	6184	5831	8481	10071
		1.00	5177	4936	9150	11077
		1.25	4560	4471	9746	12071
		1.50	4277	4207	10308	12972
	K=600, pci	.75	5654	5477	7244	8304
		1.00	4816	4696	7826	9150
		1.25	4292	4203	8405	10015
		1.50	3997	3927	8975	10798
	K=800, pci	.75	5301	5301	6361	7068
		1.00	4575	4455	6983	7946
		1.25	4124	3934	7600	8763
		1.50	3786	3716	8064	9396
10 in.	K=200, pci	.75	6361	6007	9188	11838
		1.00	5177	4936	9391	12522
		1.25	4560	4381	9746	13323
		1.50	4207	4067	10237	14094
	K=400, pci	.75	5654	5477	7244	8834
		1.00	4696	4575	7706	9512
		1.25	4203	4024	8137	10283
		1.50	3786	3716	8484	10939
	K=600, pci	.75	5301	5124	6184	7244
		1.00	4455	4334	6622	7946
		1.25	3934	3755	7064	8584
		1.50	3576	3506	7503	9186
	K=800, pci	.75	4947	4771	5477	6184
		1.00	4214	4094	6020	6863
		1.25	3755	3577	6349	7511
		1.50	3366	3296	6731	8064
11 in.	K=200, pci	.75	5831	5477	7951	10425
		1.00	4816	4575	7946	10836
		1.25	4203	4024	8137	11266
		1.50	3786	3646	8414	11850
	K=400, pci	.75	5301	5124	6361	7774
		1.00	4455	4214	6622	8308
		1.25	3845	3666	6885	8852
		1.50	3436	3366	7152	9326
	K=600, pci	.75	4947	4771	5477	6361
		1.00	4214	3973	5779	6983
		1.25	3666	3487	6080	7421
		1.50	3296	3155	6311	7923
	K=800, pci	.75	4771	4594	4947	5477
		1.00	3973	3853	5177	6020
		1.25	3487	3308	5454	6527
		1.50	3085	3015	5750	6942

provided good serviceability; however, many have exceeded their design life and have deteriorated significantly. In most cases, distress associated with these pavements is the deterioration of the transverse joints.

Transportation agencies frequently have no effective jointed PCC pavement rehabilitation program because of the lack of design alternatives and/or procedures for a particular technique, such as the design of full-depth patches. The purpose of this study was to determine the most efficient dowel bar spacing and dowel bar size for the design for full-depth patches.

The finite element program JSLAB was used to analyze full-depth patches with different numbers of dowel bars across the transverse joint. In this study, 256 computer runs for the JSLAB program were made with different levels of the variables selected for the study. Finally, this study considered only a typical heavy axle load truck that carried 34-kip and 30-kip tandem-axle loads and an 8-kip steering wheel single-axle load with tire pressures of 110, 110, and 100 psi, respectively, for each axle configuration.

Findings

1. Deflections along a transverse joint will increase as the number of dowel bars used for load transfer along a PCC pavement joint is decreased.
2. Joint efficiencies increase slightly as slab thickness increases, but the efficiencies increase significantly with an increase in the number of dowel bars from seven to eight. Six and seven dowel bars do not efficiently transfer load across the joints.
3. The number and size of dowel bars do not have a significant effect on the tensile stresses in either the X or Y directions. In all cases of study levels, the tensile stresses never exceeded the modulus of rupture limits. Consequently, tensile stresses are not a sole criterion for the design of full-depth PCC pavement patches.
4. The calculated bearing stresses are affected by the number of dowel bars across the transverse joints and, in turn, the dowel bar diameter has less effect on the calculated bearing stresses.
5. The bearing stresses for the six- and seven-dowel bar design exceed the maximum allowable bearing stresses (1 1/2 times allowable) as recommended by the American Concrete Institute for the majority of the variables and levels included in this study. The bearing stresses calculated for eight and twelve dowel bars, however, were essentially the same and less than the maximum allowable for almost all of the variables and levels.

6. An increase in the modulus of subgrade reaction, K, reduces concrete bearing stresses.
7. An effective design selection for the full-depth PCC pavement patches is a 10-in-thick patch with eight, 1 1/4-inch-diameter dowel bars.
8. Eight dowel bars across a transverse joint located at 6, 18, 30, 42, 66, 90, 126, and 138 inches from the shoulder edge are most effective for the design of the full-depth patches because eight and twelve dowel bars function similarly for the variables and levels investigated in this study.
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Conclusions

1. A full-depth PCC pavement patch with six or seven dowel bars will experience excessive bearing stresses. Consequently, this particular design should not be used.
2. Load transfer devices for full-depth PCC pavement patches should have no fewer than eight dowel bars of a minimum 1 1/4-inch diameter. Larger diameter bars (1 1/2 inches) will reduce the bearing stress even more, and thus, they should be considered for the patch designs.

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