Effect of Concrete Shoulders on Concrete Pavement Performance

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ABSTRACT

A field program of strain and deflection measurements was conducted by the Construction Technology Laboratories for the Minnesota Department of Transportation to evaluate the effects of frozen support, tied-concrete shoulders, and tridem-axle loading on concrete pavement performance. The effects of tied-concrete shoulders are presented. Field measurements were obtained at three pavement project sites located on I-90 in Minnesota. At two of these sites, a 6-in.-thick tied-concrete shoulder was used. Measurements included edge and corner deflections and edge strains. Loadings applied were a 20-kip single axle, a 34-kip tandem axle, a 42-kip tandem axle, and a 42-kip tridem axle. Theoretical analysis was also conducted by using a finite-element program to determine the effect of a tied-concrete shoulder on concrete pavement response. Field measurements and theoretical analysis indicate that concrete pavement performance is improved when a tied shoulder is used. Deflections along a tied-shoulder joint can be conservatively taken as 85 percent of those along a free edge. Based on study results and analysis of data, it is concluded that for application to the AASHTO thickness design procedure, only one-half of the design 18-kip equivalent single-axle load applications needs to be considered for concrete pavements incorporating a tied-concrete shoulder. This recommendation results in a reduction of 1 in. in the required main-line slab thickness given by the AASHTO design procedure.

A field program of strain and deflection measurements was conducted by the Construction Technology Laboratories for the Minnesota Department of Transportation (MnDOT). The objective of the measurement program was to evaluate the effects of frozen support, tied-concrete shoulders, and tridem-axle loading on concrete pavement performance. Results of the investigation are reported separately for each of the three topics. Results of the frozen-support and tridem-axle loading studies are given in reports prepared for MnDOT (1,2).

Concrete shoulders have been used adjacent to main-line concrete pavements in the United States for almost 20 years. More recently it has been noted that the use of tied shoulders has improved the performance of concrete pavements. Similarly the use of widened lanes has also resulted in improved pavement performance. The improved performance is due to reduced edge strains, reduced edge and corner deflections, and reduced water infiltration along the pavement edges.

Current thickness design methods for concrete pavements do not consider the contribution of tied shoulders and widened lanes. Use of these design methods results in the same thickness requirements for concrete pavements with or without tied shoulders or lane widening. However, both tied shoulders and widened lanes contribute to improved pavement performance by reducing deflections and stresses in the main-line pavement. Therefore it should be possible to use a less thick main-line pavement and obtain the same pavement performance as that of a thicker pavement without tied shoulders or lane widening.

A field study was sponsored during 1976 by MnDOT to evaluate the effect of tied-concrete shoulders and widened lanes. The field study involved load testing of several newly constructed concrete pavement sections with and without tied shoulders and widening. The report to MnDOT (3) showed significant reductions in pavement strains and deflections for pavements with tied shoulders and lane widening. Implementation of the study results has not been carried out because of concern that sufficient performance data gathered over a period of time were not available.

To alleviate these concerns and to obtain further field data to quantify the beneficial effects of using tied-concrete shoulders and lane widening, a follow-up study was conducted at locations included in the 1976 study. These pavement sections have experienced about 6 years of traffic. The study included field load testing, data analyses, and development of methods to facilitate incorporation of the study findings into Minnesota's concrete pavement design procedure.

Field testing was conducted during October 1982 and February 1983. This paper presents the results of field testing, analysis of results, and recommendations to incorporate study results in Minnesota's thickness design procedure.

BACKGROUND

A brief discussion is presented to highlight the important aspects of the 1976 field study (3). For this study measurements were obtained during the fall of 1976 at four pavement projects located in Minnesota. Three of these projects, projects 1, 2, and 3, were included for retesting in the current study.

Measured pavement strains are shown in Figure 1 for project 1 and in Figure 2 for project 2. The reduction in edge deflections due to the tied-concrete shoulder is shown in Figure 3 for project 1. A similar reduction in measured edge deflections due to the tied-concrete shoulder was also obtained for project 2. Based on these field measurements, laboratory slab testing, and theoretical analyses, recommendations were made for reduction in main-line slab thickness for pavements using tied-concrete shoulders. These recommendations based on edge-strain reduction are shown in Figure 4 in which the permissible thickness reduction in the outer lane due to the tied shoulder ranged from 1 to 2 in.

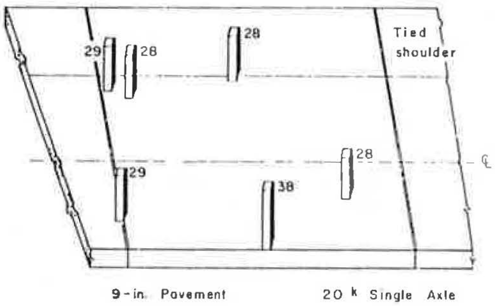

FIGURE 1 Measured strains for project 1 *(3)*.

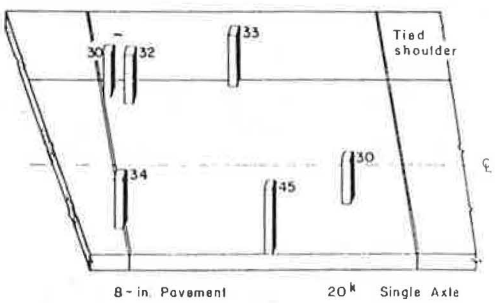

FIGURE 2 Measured strains for project 2 *(3)*.

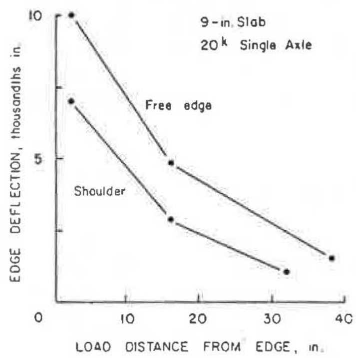

FIGURE 3 Measured edge deflection reduction due to tied shoulder at project 1 *(3)*.

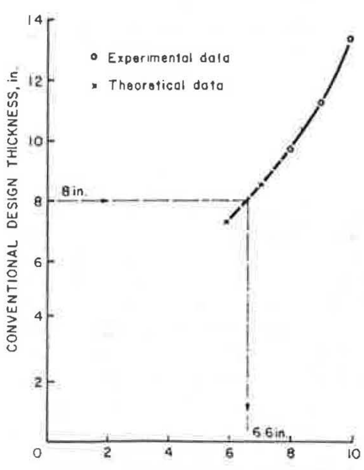

FIGURE 4 Recommended thickness reduction *(3)*.

Recent studies conducted at the University of Illinois for FHWA have also demonstrated that main-line pavement response is greatly improved by the use of tied-concrete shoulders (4). Theoretical analysis showed that calculated edge deflections and strain in the outside lane of a pavement with a tied-concrete shoulder were greatly reduced as compared with those in a pavement without a tied-concrete shoulder (4).

As part of the University of Illinois study, field measurements were made to determine joint efficiency across the outside lane shoulder joint along the I-74 and I-80 experimental portland cement concrete (PCC) shoulders (4). Joint efficiency is defined as the ratio of the deflection of the unloaded slab to the deflection of the loaded slab. Field measurements are summarized in Table 1. As shown in Table 1, shoulder sections with tied keyways on I-74 had retained joint efficiency in excess of 70 percent even after 10 years of service. It is also seen from Table 1 that the tied-shoulder sections on I-80 without keyways had much lower joint efficiencies.

TABLE 1 Field Data on I-74 and I-80 PCC Shoulders *(4)*

		Mean Edge Deflection (mm)		
Project	Shoulder Design	Traffic Lane	Shoulder	Load-Transfer Efficiency (eff)[a]
I-74[b]	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[c]	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

[a]Deflection of the unloaded slab divided by deflection of the loaded slab times 100.
[b]PCC shoulders 10 yr old.
[c]PCC shoulders 9 yr old.

Studies referred to earlier positively indicate that use of a tied-concrete shoulder with a keyway greatly improves main-line pavement performance. However, except for the MnDOT 1976 study (3), none of these studies incorporates the beneficial effect of a tied-concrete shoulder when the design slab thickness is determined for the main-line pavement.

RESEARCH OBJECTIVES

Objectives of the study were as follows:

1. To measure load-induced strains and deflections in pavement sections incorporating tied-concrete shoulders and
2. To analyze test results to establish the effects of tied-concrete shoulders on concrete pavement performance.

PAVEMENT TEST SECTIONS

Field measurements were obtained at three pavement project sites in Minnesota. These projects were included in a 1976 field study on concrete shoulders and lane widening (3). A brief description of each project follows.

Project 1: Designation State Project 2280-30 (TH-90) is a roadway 27 ft wide consisting of an inside lane 15 ft wide and an outside lane 12 ft wide with an outside tied keyed concrete shoulder 10 ft wide. Shoulders are tied at 30-in. spacing by using No. 5 tie bars 30 in. long. Shoulder thickness is 6 in. The pavement is plain concrete slabs 9 in. thick with skewed joints at a repeated random spacing of 13, 16, 14, and 19 ft. The subgrade at the site was classified as silty clay to clay loam and had a gravel subbase 5 in. thick over it. Dowel bars were placed only in the 12-ft-wide outside traffic lane. Dowels are No. 8 round bars spaced at 12 in. on centers; the first dowel is located 6 in. inward from the pavement edge. Panels selected for test are located at stations 538+65 and 540+10.

Project 2: Designation State Project 2280-30 (TH-90) is a roadway 27 ft wide and an outside tied keyed concrete shoulder 10 ft wide. Dowel size and location are the same as those for project 1. Pavement thickness is 8 in. Subgrade at the site was classified as silty clay to clay loam and had a gravel subbase 6 in. thick over it. The modulus of subgrade reaction was reported to be 270 pci. Panels selected for test are located at stations 520+55 and 521+81.

Project 3: Designation State Project 2280-31 (TH-90) is a roadway 27 ft wide with an inside lane 15 ft wide and an outside lane 12 ft wide. The pavement is reinforced concrete slabs 9 in. thick with skewed joints at a spacing of 27 ft. Subgrade at the site was classified as clay loam to silty clay loam to sandy clay loam. A gravel subbase 5 in. thick was used. Dowel bars were placed only in the 12-ft mainline pavement portion of both traffic lanes. Dowels are No. 8 round bars spaced 12 in. on centers. Panels selected for test are located at stations 985+53 and 987+11.

All three projects are located on I-90 between Albert Lea and Fairmont, Minnesota. Two test sites were selected at each project. At each site both inside and outside lanes were instrumented and monitored to evaluate pavement response. At some of the sites the panels tested in 1976 were retested. Care was taken to assure that the sites selected were representative of the project.

INSTRUMENTATION

All pavement test sections were instrumented to measure load-induced strains and deflections. In addition pavement temperature and slab curl were monitored. Curl is a change in the vertical profile of the slab resulting from changes in the slab temperature.

Strain gage and deflectometer locations for project 1 and 2 test sections are shown in Figure 5. Instrumentation locations were similar for project 3. These locations were selected to obtain the maximum values of strain and deflection for the different load positions. Curl measurements were made at deflectometer locations. Concrete temperatures were measured in instrumented test blocks placed in the subbase adjacent to the pavement.

Load Strains

Concrete strains were measured with electrical-resistance strain gages 4 in. long cemented to the pavement surface. Gages were placed at the free edge, shoulder edge, transverse joints, and joint corners and in the interior. Gage positions and loading locations shown in Figure 5 are referred to in subsequent discussions. All gages were placed in recessed grooves to protect them from direct application of wheel loads.

Load Deflections

Load deflections were measured with resistance-bridge deflectometers bolted to the pavement. Readings were referenced to encased rods driven into the subgrade to a depth of 6 ft. Construction details of the deflectometer are presented in Research and Development Bulletin D83 (5) of the Portland Cement Association.

Curl Measurements

Pavement curl was measured with 0.001-in. indicators placed at the same locations as the deflectometers. The dial indicators were bolted to the pavement and the movement was referenced to encased rods placed in the subgrade. Curl readings were taken approximately once an hour.

Temperature Measurements

Changes in pavement temperature were measured with copper-constantan thermocouples embedded in concrete blocks. The laboratory-cast blocks were 1 ft square and 8 or 9 in. thick. Thermocouples were located 0.125, 0.50, 1, 2, 4, and 6 in. from the top and 0.125 in. from the bottom surfaces. Temperature blocks were placed in the subbase adjacent to the highway at least 12 hr before testing. Air temperature was monitored with a thermocouple shaded from the direct sun.

Monitoring Equipment

Data were monitored and recorded with equipment carried in the Construction Technology Laboratories' field instrumentation van. Strain and deflection data were recorded with a high-speed computer-based data acquisition system. Twenty-two channels of instrumentation were monitored and recorded simultaneously for each vehicle loading. Computer programs were written to monitor, record, and tabulate all field data.

Temperature data were recorded with a 24-channel continuously monitoring temperature recorder. All monitoring and recording instrumentation was calibrated before testing.

TEST PROCEDURES

Strain and deflection data were recorded for a 20-kip single-axle load (SAL), 34-kip and 42-kip tandem-axle loads (TAL), and 42-kip tridem-axle load. Loading was applied with two semitrailers. One applied the 20-kip SAL and 34-kip TAL. The other applied the 42-kip TAL and 42-kip tridem-axle load. Trucks used were supplied by MnDOT. Before testing, axle weights were checked and loads were adjusted to obtain uniform distribution to the wheels.

The effects of axle weight and load location on strains and deflections were recorded with the trucks moving at creep speed along the wheel paths shown in Figure 5. Tire placements varied from 2 to 38 in. from the pavement edge. All wheel-path measurements were from the pavement edge to the outside

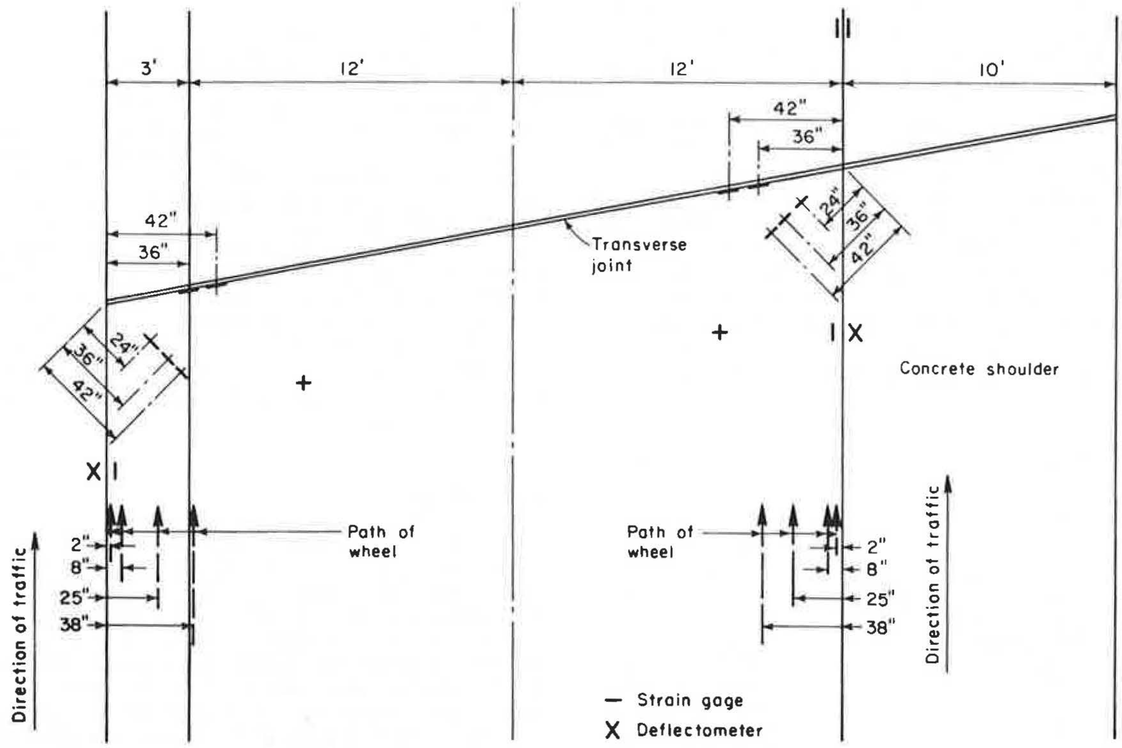

FIGURE 5 Instrumentation layout for projects 1 and 2.

edge of the tire sidewall at its maximum width. In addition, pavement curl and temperature data were obtained periodically during the day.

Test slabs from inside and outside lanes at each project site were tested on the same day. Primary readings were taken on both inside and outside lanes between approximately 11:30 a.m. and 2:00 p.m. In addition, readings were also taken on one lane before 11:30 a.m. and on the other lane after 2:00 p.m. Specific testing times were governed primarily by weather and traffic control requirements.

DATA ANALYSIS

In this section a comparison of pavement responses measured along the edges of the outside lanes and those for the inside lanes is presented for the three project sites. The outside-lane edge corresponds to a joint with a tied-concrete shoulder for projects 1 and 2. The edge of the inside lane corresponds to a free edge along the widened inside lane for projects 1 and 2. Project 3 has neither a concrete shoulder nor lane widening along the inside lane and was used as a control section to determine the influence of traffic along the outside lane.

Pavement responses reported were measured under 20-kip SAL, 34-kip and 42-kip TAL, and 42-kip tridem-axle load. Pavement responses compared are edge and corner deflections and edge strains. In addition results of theoretical analyses are presented to evaluate the effect of tied-concrete shoulders. Although measurements were obtained during October 1982 and February 1983, only the October 1982 measurements are presented and discussed in this report. Because of the frozen support, measured deflections during February 1983 were low for both the inside and outside lanes at each project site. Details of the February measurements are given elsewhere (1).

Curling and Warping Effects

Soon after concrete has been placed, drying shrinkage of the concrete begins. Drying shrinkage in a slab on grade occurs at a faster rate at the slab surface than at the slab bottom. In addition, because the subgrade and subbase may remain wet, the slab bottom remains relatively moist. Thus, total shrinkage at the bottom is less than that at the top. This differential in shrinkage results in a lifting of the slab from the subbase at edges and corners. Movements of this type resulting from moisture differentials are referred to as warping. Warping leaves slabs unsupported for distances of as much as 4 to 5 ft at slab corners and 2 to 3 ft at slab edges. Warping is almost never recoverable.

In addition to warping, a slab on grade is also subjected to curling. Curling is the change in the slab profile due to temperature differential between slab top and bottom. Curling is a daily phenomenon. Slabs curl up during the night and curl down during midday. Thus, curling deformation is additive to warping during the night and reduces the warping effect during the midday. It is believed by many engineers that the warping effect is almost never cancelled out by daytime curling and that some loss of support always exists under the slab even on hot days.

Because of curling effects, the measured deflections under load along a slab edge or a slab corner are greatly affected by the time of testing. Measured slab strains are also affected by time of

testing but at a lower level. Therefore, great care needs to be exercised in interpreting deflection and strain measurements if these measurements are made at different times of day or on different days. The usual procedure in reporting deflection measurements at a given location is to correct the measurements with respect to a reference time. The reference time is generally selected to be the time when the slab top and bottom temperatures are equal.

As discussed, temperature and curl measurements were made at each of the five test sites considered in this study. At each test site, pavement responses under load were generally measured at two different times, usually within a span of 3 hr around noon.

Figure 6 shows the variation with time of the air temperature, corner curl, and corner deflection under a 20-kip SAL at each of the five sites. It is

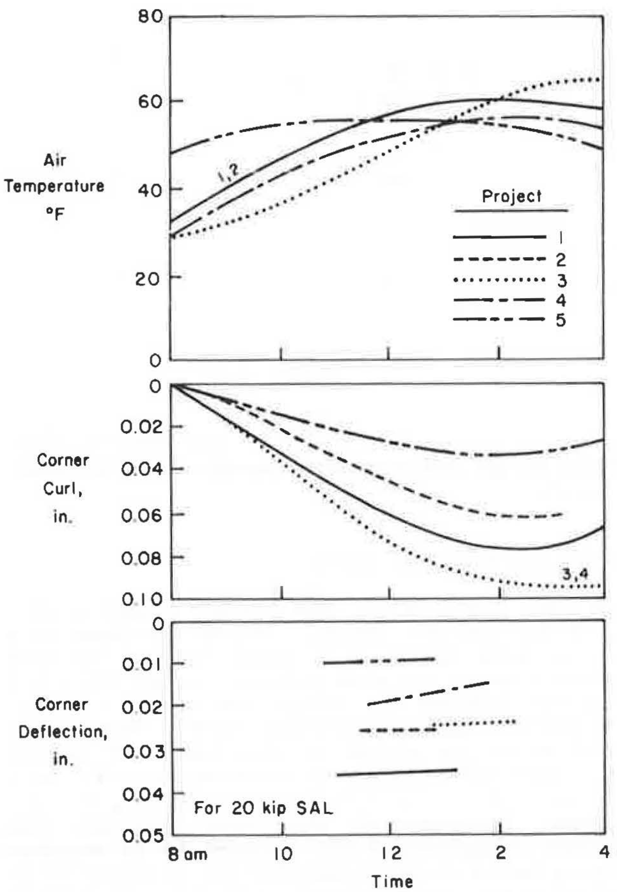

FIGURE 6 Variation of air temperature, corner curl, and deflection with time.

seen that although slabs at each site exhibit pronounced curling, the deflections under load were not greatly influenced by the time of testing between approximately 11:00 a.m. and 2:00 p.m. Similar trends were obtained for edge curl and deflections and edge strain. This is because the slabs have curled to their most downward profiles and changes from these profiles are gradual with respect to time, as shown in Figure 6. Therefore, no temperature corrections were applied to these readings. The measurements reported in this paper are the averages of the readings for the two test times and correspond to the period when each slab being tested was near its maximum downward curl.

Summary of Data

Load tests were conducted during October 1982 when air temperatures at midday were about 55°F. Pavement responses measured at each of the three sites are listed in Table 2. Edge and corner deflections and edge strains measured during October 1982 at the inside and outside lanes are listed for each of the four axle loadings. Each data point is an average of four readings made up of data taken at two different times at each of the two replicate sections at each project location. The measurements are shown in Figures 7, 8, and 9 for edge deflection, corner deflection, and edge strain, respectively. A discussion of these measurements follows. (In Figures 7-9 axles are denoted as follows: axle 1, 20-kip SAL; axle 2, 34-kip TAL; axle 3, 42-kip TAL; axle 4, 42-kip tridem-axle load. N denotes lack of reliable data.)

Edge Deflections

For project 1 measured edge deflection ranged from 0.019 in. under the 20-kip SAL to 0.029 in. under the 42-kip TAL along the outside lane and from 0.021 in. under the 20-kip SAL to 0.038 in. under the 42-kip TAL along the inside lane. As shown in Figure 7, edge deflections along the outside lane with the tied shoulder were about 75 to 90 percent of those along the untrafficked free edge of the inside lane.

For project 2 edge deflections measured along the outside lane do not show variation with different axle loads and are considerably lower than those along the free inside-lane edge. This is believed to be because of malfunctioning of the deflectometers at that location.

For the control sections at project 3 edge deflections along the free outside lane edge ranged from 96 to 115 percent of those along the untrafficked free inside lane. This indicates that the free outside-lane edge, which is subjected to a large volume of truck traffic, exhibits higher deflections than the untrafficked free inside-lane edge. This behavior is possibly caused by greater loss of support along the outside-lane edge resulting from subbase and subgrade consolidation or erosion or both. Thus, the effect of using tied-concrete shoulders at project 1 and possibly at project 2 is to significantly reduce edge deflections along the heavily traveled outside-lane edge.

Corner Deflections

For project 1 measured corner deflections ranged from 0.019 in. under the 20-kip SAL to 0.029 in. under the 42-kip TAL along the outside lane and from 0.035 in. under the 20-kip SAL to 0.051 in. under the 42-kip TAL along the inside lane. For project 2 measured corner deflections ranged from 0.021 in. under the 20-kip SAL to 0.025 in. under the 42-kip TAL along the outside lane and from 0.026 in. under the 20-kip SAL to 0.034 in. under the 42-kip TAL along the inside lane.

As shown in Figure 8, corner deflections along the outside lane with the tied shoulder as a percentage of those along the untrafficked free edge of the inside lane were about 70 to 87 percent for project 1 and about 58 to 80 percent for project 2.

For the control sections at project 3, corner deflections along the free outside-lane edge ranged from 125 to 150 percent of those along the untrafficked free inside-lane edge. These results further verify that the free outside-lane edge, which is

TABLE 2 Measured Pavement Response for Projects 1, 2, and 3

Parameter	20-kip SAL	34-kip TAL	42-kip TAL	42-kip Tridem-Axle Load
Project 1				
Inside lane				
Edge deflection (in.)	0.021	0.034	0.038	0.034
Corner deflection (in.)	0.035	0.044	0.051	0.044
Edge strain (x 10^{-6})	35	30	32	17
Outside lane				
Edge deflection (in.)	0.019	0.026	0.029	0.027
Corner deflection (in.)	0.030	0.034	0.037	0.031
Edge strain (x 10^{-6})	30	24	27	19
Shoulder strain (x 10^{-6})	3	3	8	6
Project 2				
Inside lane				
Edge deflection (in.)	0.016	0.026	0.027	0.023
Corner deflection (in.)	0.026	0.036	0.034	0.030
Edge strain (x 10^{-6})	35	32	33	18
Outside lane				
Edge deflection (in.)	0.007	0.007	0.007	0.009
Corner deflection (in.)	0.021	0.021	0.025	0.019
Edge strain (x 10^{-6})	33	31	38	20
Shoulder strain (x 10^{-6})	7	6	12	9
Project 3				
Inside lane				
Edge deflection (in.)	0.013	0.022	0.025	0.020
Corner deflection (in.)	0.024	0.030	0.032	0.026
Edge strain (x 10^{-6})	33	28	30	18
Outside lane				
Edge deflection (in.)	0.015	0.021	0.025	0.023
Corner deflection (in.)	0.036	0.040	0.040	0.034
Edge strain (x 10^{-6})	18	23	24	16

Note: All measurements were obtained during October 1982. Inside-lane measurements were taken along the edge of the 3-ft lane widening. Outside-lane measurements were taken along the joint with tied shoulder.

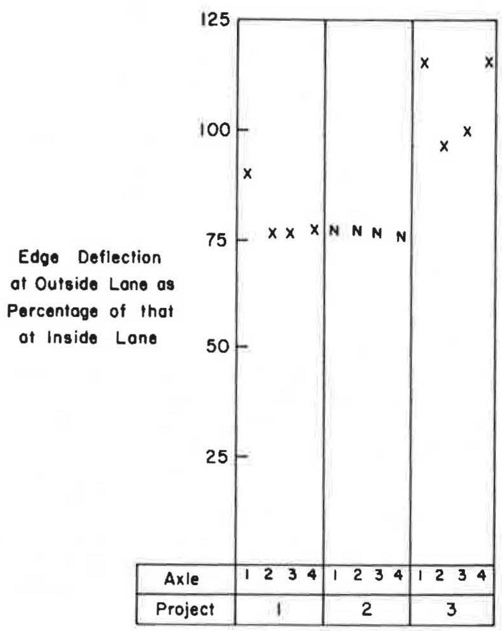

FIGURE 7 Comparison of edge deflections.

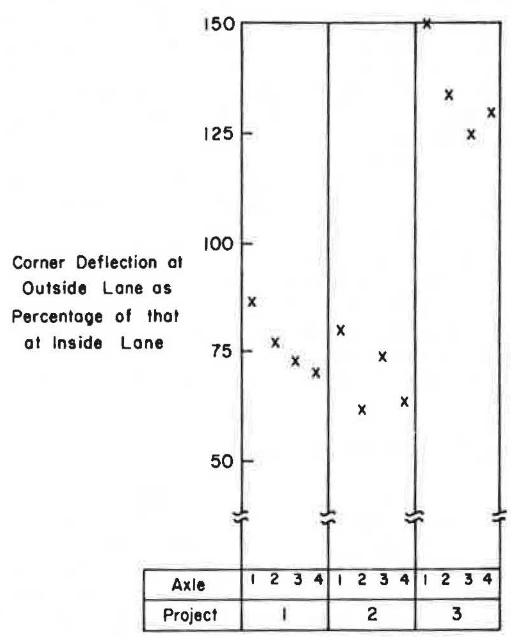

FIGURE 8 Comparison of corner deflections.

subjected to a considerable amount of traffic, exhibits higher deflections than the untrafficked free inside-lane edge.

Edge Strains

For project 1 measured edge strains ranged from 19×10^{-6} under the 42-kip tridem-axle load to 30×10^{-6} under the 20-kip SAL along the outside lane and 17×10^{-6} under the 42-kip tridem-axle load to 35×10^{-6} under the 20-kip SAL along the inside lane. For project 1 the measured tied-concrete shoulder edge strain ranged from 3×10^{-6} under the 20-kip SAL to 8×10^{-6} under the 34-kip TAL.

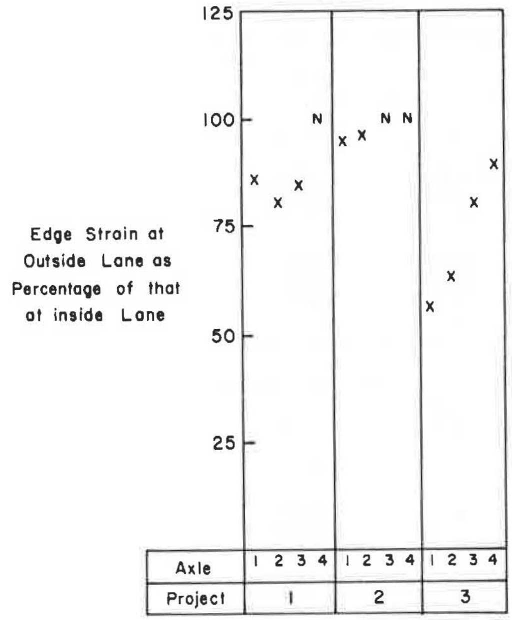

FIGURE 9 Comparison of edge strain.

For project 2 measured edge strains ranged from 20×10^{-6} under the 42-kip tridem-axle load to 38×10^{-6} under the 34-kip TAL along the outside lane and 18×10^{-6} under the 42-kip tridem-axle load to 35×10^{-6} under the 20-kip SAL along the inside lane. For project 2 measured tied-shoulder edge strain ranged from 6×10^{-6} under the 34-kip TAL to 12×10^{-6} under the 42-kip TAL.

For project 3 measured edge strains along the free outside-lane edge ranged from 55 to 89 percent of those along the untrafficked free inside-lane edge. These results are in contrast to the trend in measured deflections at project 3 in which measured deflections along the outside lane were generally greater than those measured along the inside lane.

In addition to the measurements at the three project sites reported here, similar measurements were also made at two additional project sites. These two sites did not incorporate tied shoulders or lane widening. Measurements from these two project sites are reported elsewhere (1). These measurements also indicate that corner and edge deflections as well as edge strains are larger along the trafficked free outside-lane edge as compared with those along the lightly trafficked free inside-lane edge.

Theoretical Considerations

Analyses were conducted to determine the effect of a tied-concrete shoulder on concrete pavement response. A finite-element program, JSLAB, developed by Construction Technology Laboratories for FHWA was used (6). The program can analyze a large number of jointed slabs. Joints can be modeled as doweled, aggregate interlock, or keyed. Load input is in terms of wheel loads at any location on the slabs. Loss of support, variable support, or material properties can be considered. In the program subbase and subgrade support is characterized by the modulus of subgrade support.

Analysis was conducted for a concrete pavement 9 in. thick with and without tied shoulders and with dowel bars at the transverse joints. For the case of the tied shoulder, a 6-in.-thick slab was used. Values used for the modulus of subgrade reaction were 100, 150, an 250 pci. Calculated corner deflections, edge deflections, and edge stresses are listed in Tables 3-5. For both corner and edge loadings, tire placements were 2 in. inward from the edge.

TABLE 3 Calculated Pavement Response: Corner Deflection

		Corner Deflection (in.)			
Shoulder Type	k (pci)	20-kip SAL	34-kip TAL	42-kip TAL	42-kip Tridem-Axle Load
Tied	100	0.025	0.026	0.032	0.026
	150	0.018	0.019	0.023	0.019
	250	0.013	0.013	0.016	0.012
None	100	0.035	0.040	0.050	0.040
	150	0.026	0.030	0.037	0.028
	250	0.019	0.020	0.025	0.019

TABLE 4 Calculated Pavement Response: Edge Deflection

		Edge Deflection (in.)			
Shoulder Type	k (pci)	20-kip SAL	34-kip TAL	42-kip TAL	42-kip Tridem-Axle Load
Tied	100	0.015	0.022	0.027	0.022
	150	0.012	0.016	0.020	0.016
	250	0.008	0.011	0.014	0.011
None	100	0.024	0.035	0.043	0.036
	150	0.018	0.025	0.031	0.026
	250	0.012	0.017	0.021	0.017

TABLE 5 Calculated Pavement Response: Edge Stress

		Edge Stress (psi)			
Shoulder Type	k (pci)	20-kip SAL	34-kip TAL	42-kip TAL	42-kip Tridem-Axle Load
Tied	100	236	180	222	114
	150	218	160	198	98
	250	199	139	172	81
None	100	286	230	284	152
	150	263	203	250	128
	250	236	172	212	103

In the computer program a tied keyway is represented by springs. For the analysis a spring stiffness value of 25,000 lb/(in. • in.) of joint length was used. This resulted in calculated joint efficiency of about 80 percent for a modulus of subgrade reaction of 250 pci to about 90 percent for a modulus of subgrade reaction of 100 pci. For this set of assumptions the ratio of calculated corner and edge deflections along a tied-shoulder joint to those along a free edge is about 65 percent. The ratio of calculated edge strains along a tied-shoulder joint to those along a free edge is about 80 percent.

Additional analysis was conducted for a 9-in.-thick slab on a subgrade with a modulus value of 250 pci and with keyway spring stiffness values of 5,000, 10,000, 15,000, and 20,000 lb/(in. • in.) of joint length. Based on these analyses, ratios of calculated deflections and strains along a tied shoulder joint to those along a free edge were determined for different values of shoulder joint efficiency (JE). These ratios are listed as follows for a main-line slab thickness of 9 in., a shoul-

der-slab thickness of 6 in., and 250 pci (JE = deflection of main-line slab divided by deflection of shoulder slab):

	Ratio (%) by JE		
Response	80 Percent	60 Percent	50 Percent
Edge deflection	65	70	75
Corner deflection	65	70	75
Edge strain	80	85	90

It should be noted that measured deflection values are much higher than calculated deflection values, even when a modulus of subgrade reaction value of 150 pci is used. Modulus of subgrade reaction values at the three locations were reported to be in excess of 250 pci. The reason for this anomaly in measured and computed deflection values is that the theoretical analysis was conducted for the case of full support under the pavement slabs. In practice there is always some loss of support along slab edges. This support loss results in higher measured slab deflections.

Analysis of Results

As indicated, it is clear that concrete pavement response is improved when a tied shoulder is used. The level of improvement, based on field testing and theoretical analyses, is summarized in Table 6, in which it can be seen that the reduction in the deflection response can be conservatively taken at 85 percent. This value corresponds to a calculated joint efficiency at the tied-shoulder joint of less than 50 percent. As discussed previously, measured joint efficiency along the shoulder sections on I-74 in Illinois, which incorporated tied keyways, had retained joint efficiency in excess of 70 percent even after 10 years of service. Therefore, properly constructed concrete pavement with tied shoulders can be expected to retain at least 50 percent joint efficiency during its design life.

TABLE 6 Improvement in Pavement Response

	Ratio of Response at Tied-Shoulder Joint to That at Free Edge (%)				
	Measured		Calculated		
Response	Project 1	Project 2	JE = 80 Percent	JE = 60 Percent	JE = 50 Percent
Edge deflection	75-90	NR[a]	65	70	75
Corner deflection	70-87	58-80	65	70	75
Edge stress	80-85	94-97	80	85	90

Note: JE = deflection of main-line slab divided by deflection of shoulder slab.
[a]Data considered not reliable.

It should be noted that the measured level of improvement shown in Table 4 is based on response of the inside-lane edge, which has been subjected to little traffic loading. Therefore, if the level of improvement had been determined based on a free longitudinal edge that had been subjected to the same amount of traffic as the outside lanes at projects 1 and 2, a greater reduction in pavement responses would have been determined for the tied-shoulder sections at projects 1 and 2.

Because pavement damage or loss of serviceability is a function of axle load magnitude and number of load repetitions, it can be concluded that a given axle would produce less deflection-related damage or loss of serviceability on a pavement with a tied shoulder than on a pavement without a tied shoulder. If a linear relationship is assumed between magnitude of axle load and pavement deflection response, an axle load (P) applied on a pavement without a tied shoulder can be considered to be equivalent to an axle load (P/0.85) applied on a pavement with a tied shoulder. Thus, based on similar deflection responses, an 18-kip SAL applied on a pavement without a tied shoulder can be considered to be equivalent to a 21-kip SAL applied on a pavement with a tied shoulder.

Application to AASHTO Design Procedure

The AASHTO Interim Guide uses the concept of traffic equivalence factors for converting mixed traffic to an equivalent number of 18-kip SALs (7). The equivalence factors, when multiplied by the number of axle loads within a given weight category, give the number of 18-kip SAL applications that have an equivalent effect on the performance of the pavement.

The AASHTO traffic equivalence factors give more weight to deflection response than to stress-type response. For example, according to the AASHTO traffic equivalence factors, presented in Table 7, tandem axles are about 2.30 to 2.50 times as damaging as a single axle weighing half as much as the tandem axles. The ratio of edge deflection under tandem axles to that under a single axle weighing half as much is about 1.64 based on theoretical analysis and about 1.90 based on field measurements. On the other hand, calculated as well as measured edge strain under tandem axles are less than those under a single axle weighing half as much as the tandem axles. Therefore, with respect to use of a tied shoulder, the reduction in deflection response is considered more significant than the reduction in strain response.

It should be further pointed out that the AASHTO design equation incorporates Spangler's equation for corner stress. For pavement and joint designs similar to that used at the AASHTO Road Test, the constant J of Spangler's equation cancels out. The constant J has a value of 3.2 for an unprotected corner. However, for pavements incorporating a tied shoulder, the value of J would be much less than 3.2 because the corner stresses would be reduced by the use of a tied shoulder. This further verifies that the AASHTO design equation would recognize the beneficial effect of a tied shoulder if the value of constant J of Spangler's equation was modified to account for use of a tied shoulder.

Thus, the establishment of a conservative level of reduction of 15 percent in the deflection response because of the use of a tied shoulder is considered valid. Similarly the assumption based on study results that an axle load (P) applied on a pavement without a tied shoulder is equivalent to an axle load (P/0.85) applied on a pavement with a tied shoulder is considered valid.

It is seen from Table 5 that for a 9-in.-thick pavement, a 21-kip SAL is 2.0 times as damaging as an 18-kip SAL. However, based on study results, a 21-kip SAL applied on a pavement with a tied shoulder can be considered to be only as damaging as an 18-kip SAL applied on a pavement without a tied shoulder. Thus, a 21-kip SAL applied on a pavement with a tied shoulder is only 1/2.0, that is, 0.5 times as damaging, as a 21-kip SAL applied on a pavement without a tied shoulder. If this logic is applied to different slab thicknesses and other axle

TABLE 7 Traffic Equivalence Factors for SALs and TALs

Axle Load		Slab Thickness D (in.)						
Kips	kN	6	7	8	9	10	11	12
Single Axle								
2	8.9	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	17.8	0.003	0.002	0.002	0.002	0.002	0.002	0.002
6	26.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8	35.6	0.04	0.04	0.03	0.03	0.03	0.03	0.03
10	44.5	0.10	0.09	0.08	0.08	0.08	0.08	0.08
12	53.4	0.20	0.19	0.18	0.18	0.18	0.17	0.17
14	62.3	0.38	0.36	0.35	0.34	0.34	0.34	0.34
16	71.2	0.63	0.62	0.61	0.60	0.60	0.60	0.60
18	80.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	89.0	1.51	1.52	1.55	1.57	1.58	1.58	1.59
22	97.9	2.21	2.20	2.28	2.34	2.38	2.40	2.41
24	106.8	3.16	3.10	3.23	3.36	3.45	3.50	3.53
26	115.7	4.41	4.26	4.42	4.67	4.85	4.95	5.01
28	124.6	6.05	5.76	5.92	6.29	6.61	6.81	6.92
30	133.4	8.16	7.67	7.79	8.28	8.79	9.14	9.34
32	142.3	10.81	10.06	10.10	10.70	11.43	11.99	12.35
34	151.2	14.12	13.04	12.34	13.62	14.59	15.43	16.01
36	160.1	18.20	16.69	16.41	17.12	18.33	19.52	20.39
38	169.0	23.15	21.14	20.61	21.31	22.74	24.31	25.58
40	177.9	29.11	26.49	25.65	26.29	27.91	29.90	31.64
Tandem Axles								
10	44.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	53.4	0.03	0.03	0.03	0.03	0.03	0.03	0.03
14	62.3	0.06	0.05	0.05	0.05	0.05	0.05	0.05
16	71.2	0.10	0.09	0.08	0.08	0.08	0.08	0.08
18	80.1	0.16	0.14	0.14	0.13	0.13	0.13	0.13
20	89.0	0.23	0.22	0.21	0.21	0.20	0.20	0.20
22	97.9	0.34	0.32	0.31	0.31	0.30	0.30	0.30
24	106.8	0.48	0.46	0.45	0.44	0.44	0.44	0.44
26	115.7	0.64	0.64	0.63	0.62	0.62	0.62	0.62
28	124.6	0.85	0.85	0.85	0.85	0.85	0.85	0.85
30	133.4	1.11	1.12	1.13	1.14	1.14	1.14	1.14
32	142.3	1.43	1.44	1.47	1.49	1.50	1.51	1.51
34	151.2	1.82	1.82	1.87	1.92	1.95	1.96	1.97
36	160.1	2.29	2.27	2.35	2.43	2.48	2.51	2.52
38	169.0	2.85	2.80	2.91	3.04	3.12	3.16	3.18
40	177.9	3.52	3.42	3.55	3.74	3.87	3.94	3.98
42	186.8	4.32	4.16	4.30	4.55	4.74	4.86	4.91
44	195.7	5.26	5.01	5.16	5.48	5.75	5.92	6.01
46	204.6	6.36	6.01	6.14	6.53	6.90	7.14	7.28
48	213.5	7.64	7.16	7.27	7.73	8.21	8.55	8.75

Note: Terminal pavement serviceability index (p_t) = 2.5.

loads, it is found that the damaging effect of a given SAL or TAL applied on a pavement with a tied shoulder is about 0.5 times that for the same axle load applied on a pavement without a tied shoulder.

For application to the AASHTO design procedure, it is recommended that the damaging effect of an axle load applied on a pavement with a tied shoulder be considered as one-half of that for the same axle load applied on a pavement without a tied shoulder. Thus, only one-half of the equivalent 18-kip SALs applied needs to be considered for thickness design of pavements with a tied shoulder.

Design Application

The following parameters are assumed:

1. Concrete modulus of rupture, 650 psi;
2. Concrete working stress, 490 psi;
3. Concrete modulus of elasticity, 4×10^6 psi, and
4. Modulus of subgrade reaction, 200 pci.

By using the design chart presented in the AASHTO Interim Guide, slab thicknesses for pavements with and without a tied shoulder are calculated as follows:

Design 18-kip SAL Applications (000,000s)	Required Pavement Thickness (in.)	
	Without Shoulder	With Shoulder
2.5	7.6	6.6
5	8.7	7.6
10	9.7	8.7
20	10.8	9.7

Required thicknesses for pavement with tied shoulders were determined by using one-half of the design 18-kip SAL applications. It is seen that as a minimum the use of a tied shoulder allows for reduction of 1 in. in the required main-line slab thickness.

Similar results are obtained for other values of the design parameters. Therefore, it is recommended that as a minimum, the use of a tied shoulder should allow for reduction of 1 in. in the required main-line slab thickness.

Future Modifications

It should be noted that study results are based on use of a 6-in.-thick concrete shoulder. If a shoulder thickness equal to the main-line slab thickness is used, a larger reduction in main-line slab thick-

ness may be warranted. Greater thickness reduction may also be warranted if future performance of other pavements incorporating tied shoulders indicates that a level of reduction in deflection response is more than the 15 percent established in the current study.

Future modifications can be made following the procedures presented in this paper. For example, let a level of reduction in deflection response of 20 percent be established. Then following procedures presented in this paper, it is found that for application to the AASHTO design procedure, only 40 percent of the design 18-kip equivalent SAL applications needs be considered for concrete pavements incorporating tied-concrete shoulders. This would result in a reduction of 1 to 2 in. in the required main-line slab thickness given by the AASHTO design procedure.

SUMMARY

A field study was conducted to evaluate the effect of tied-concrete shoulders on concrete pavement performance. Pavement deflections and strains were measured along tied-shoulder joints and along free edges at two project locations. In addition, a theoretical analysis was performed to determine the effect of tied shoulders on concrete pavement response. Study results indicate that pavement response is improved for pavements using a tied shoulder as compared with pavements not using a tied shoulder.

Based on study results, it is concluded that for application to the AASHTO thickness design procedure, only one-half of the design 18-kip equivalent SAL applications needs be considered for concrete pavements incorporating a tied-concrete shoulder. This recommendation results in a reduction of 1 in. in the required main-line slab thickness given by the AASHTO design procedure.

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