VERIFICATION OF THE STRUCTURAL BENEFITS OF CONCRETE SHOULDERS BY FIELD MEASUREMENTS

Charles V. Slavis and Claire G. Ball, Paving and Transportation Department, Portland Cement Association

The justification and use of portland cement concrete shoulders with portland cement concrete pavement has for the most part been based on universal justification of paved shoulders combined with superior performance of the concrete as a paving material. Secondary benefits such as the ability to limit water infiltration, reduction in maintenance costs, and simplified construction procedures were also taken into consideration. Recent investigations have shown that portland cement concrete shoulders can significantly contribute to the structural integrity of the mainline PCC pavement. This benefit has been quantified to show greater life expectancy for existing pavements and also to design more cost effective new concrete pavements. The research leading to substantiate the structural benefit to the mainline pavement was conducted in two phases. In 1976, field measurements were conducted on a new pavement. These measurements established the structural benefit of the concrete shoulder and provided a base line condition for futher investigations to test these benefits over the design life of the pavement. In 1982, the 1976 sites were retested. The new data substantiated the findings of the original research. Using the field data from the 1982 field study and results of theoretical analysis, procedures showing the benefit of concrete shoulders in pavement design and pavement life expectancy were established.

Concrete shoulders have been used adjacent to mainline concrete pavements in the United States for over 20 years. Nineteen states have more than fifteen years experience with the use of concrete shoulders. More recently the recognization that the use of tied-shoulders contribute to improved performance of concrete pavements has been substantiated with field studies. Similarly, the use of widened lanes also contribute to 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.

Until recently thickness design methods for concrete pavements did not consider the contribution of tied-shoulders and widened lanes. These design methods resulted in the same thickness requirements for concrete pavements with or without tied-shoulders, or lane widening. However, tied-shoulders, widened lanes and tied curbs contribute to improved pavement performance by reducing deflections and stresses in portland cement concrete pavement. Therefore, it should be possible to use a less thick pavement and obtain the same pavement performance as that of a thicker pavement without tied-shoulders, lane widening or tied curbs.

A field study was sponsored during 1976 by the Minnesota Department of Transportation to evaluate the effect of tied-concrete shoulders and widened lanes. This study was performed by the Construction Technology Laboratories. The field study involved load testing of several newly constructed concrete pavement sections with and without tied-shoulders and widening. A report entitled, "Evaluation of Concrete Pavement with Lane Widening, Tied Concrete Shoulders, and Thickened Pavement" was submitted to the Minnesota Department of Transportation (1). The report showed significant reductions in pavement strains and deflections for pavements with tied-shoulders and lane widening. Implementation of the study results was not effected because of concerns that sufficient performance data gathered over a period of time are 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 in 1982 at the locations included in the 1976 study which at that time had 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.

Background

A brief discussion is presented to highlight the important aspects of the 1976 field study reported in Reference 1. During this study, measurements were obtained during the fall of 1976 at four pavement projects located in the State of Minnesota. Three of these projects, Projects 1, 2, and 3, were included for retesting in the 1982 study.

Based on these field measurements, laboratory slab testing, and theoretical analyses, recommendations were made for reduction in mainline slab thickness for pavements using tied-concrete shoulders. These recommendations based on edge strain reduction allow a permissible thickness reduction in the outer lane due to tied-shoulder of 1 to 2 in.

Recent studies conducted at the University of Illinois for the Federal Highway Administration have also demonstrated that mainline pavement response is greatly improved by use of tied-concrete shoulders (2). Theoretical analysis showed that calculated edge deflections and strain at the outside lane of a pavement with a tied-concrete shoulder were greatly reduced as compared to a pavement without a tied-concrete shoulder (2).

As part of the University of Illinois study, field measurements were made to determine joint efficiency across the outside lane-shoulder joint along experimental shoulders located on I-74 and I-80 (2). Joint efficiency is defined as the ratio of the deflection of unloaded slab over the deflection of the loaded slab. Field measurements showed that shoulder sections with tied-keyways on I-74 had retained joint efficiency in excess of 70% even after 10 years of service.

These referenced studies positively indicate that use of tied-concrete shoulder, with a keyway, greatly improves mainline pavement performance. However, except for the Minnesota Department of Transportation's 1976 study (1), none of these studies incorporate the beneficial effect of a tied-concrete shoulder when determining the design slab thickness for the mainline pavement.

Pavement Test Sections

Field measurements were obtained at three pavement project sites located in the State of Minnesota. These projects were included in a 1976 field study on concrete shoulders and lane widening (1).

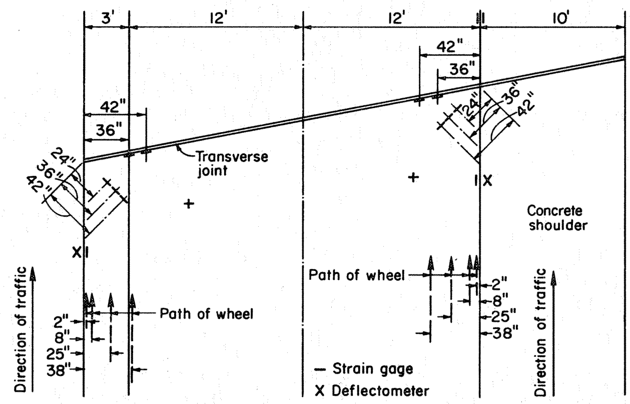
All three projects are located on I-90 between Albert Lea and Fairmont, Minnesota. Two test sites were selected at each project. At each site, both inside and outside lanes were instrumented and monitored to evaluate pavement response. At some of the sites the panels tested in 1976 were retested. Care 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 temperatrue 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 Projects 1 and 2 test sections are shown in Fig. 1. 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.

Figure 1. Instrumentation layout for projects 1 and 2.



Test Procedures

Strain and deflection data were recorded for 20 kip single-axle, 34 kip tandem-axle, 42 kip tandem-axle, and 42 kip tridem-axle loads. Loading was applied with two semi-tractor trailers. One truck applied the 20 kip single-axle and 34 kip tandem-axle loadings. The other truck applied the 42 kip tandem-axle and 42 kip tridem-axle loadings. Trucks used were supplied by the Minnesota Department of Transportation. Prior to 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 Fig. 1. Tire placements varied from 2 to 38 in. from the pavement edge. All wheel path measurements were from the pavement edge to the outside edge of the tire sidewall at its maximum width. In addition, pavement curl and temperature data were obtained periodically during the day.

Inside and outside lane test slabs 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 prior to 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

This section presents comparison of pavement responses measured along the edges of the outside lanes and those for the inside lanes at 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 single-axle, 34 kip tandem-axle, 42 kip tandem-axle, and 42 kip tridem-axle loading. 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 shoulder.

Summary of Data

Load tests were conducted during October 1982 when air temperatures at mid-day were about 55°F. Pavement responses measured at each of the three sites are listed in Tables 1 through 3. Each table lists edge and corner deflections and edge strains measured during October 1982 at inside and outside lanes for each of the four axle loadings. Each data point is an average of four readings comprised of data taken at two different times at each of the two replicate sections at each project location. A discussion of these measurements follows.

Edge Deflections

For Project 1, measured edge deflection ranged from 0.019 in. under the 20 kip single-axle to 0.029 in. under the 42 kip tandem-axle along the outside lane, and from 0.021 in. under the 20 kip single-axle to 0.038 in. under the 42 kip tandem-axle along the inside lane. Edge deflections along the outside lane with the tied shoulder were about 75 to 90% 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 due to malfunctioning of the deflectometers at that location.

Table 1. Measured Pavement Response at Project 1.

Parameter	20 kip SAL	34 kip TAL	42 kip TAL	42 kip TRDM
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, millionths	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, millionths	30	24	27	19
Shoulder Strain, millionths	3	3	8	6

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

Table 2. Measured Pavement Response at Project 2.

Parameter	20 kip SAL	34 kip TAL	42 kip TAL	42 kip TRDM
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, millionths	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, millionths	33	31	38	20
Shoulder Strain, millionths	7	6	12	9

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

Table 3. Measured Pavement Response at Project 3.

Parameter	20 kip SAL	34 kip TAL	42 kip TAL	42 kip TRDM
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, millionths	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, millionths	18	23	24	16

Notes: 1. Measurements were obtained during October 1982.

For the control sections at Project 3, edge deflections along the free outside lane edge ranged from 96 to 115% 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 due to greater loss of support along the outside lane edge resulting from subbase/ subgrade consolidation and/or erosion. 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 single-axle to 0.029 in. under the 42 kip tandem-axle along the outside lane and from 0.035 in. under the 20 kip single-axle to 0.051 in. under the 42 kip tandem-axle along the inside lane. For Project 2, measured corner deflections ranged from 0.021 in. under the 20 kip single-axle to 0.025 in. under the 42 kip tandem-axle along the outside lane and from 0.026 in. under the 20 kip single-axle to 0.034 in. under the 42 kip tandem-axle along the inside lane.

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% for Project 1 and about 58 to 80% for Project 2.

For the control sections at Project 3, corner deflections along the free outside lane edge ranged from 125 to 150% of that along the untrafficked free inside lane edge. These results further verify that the outside free lane edge, which is subjected to a considerable amount of traffic exhibits higher deflections than the untrafficked inside free lane edge.

Edge Strains

For Project 1, measured edge strains ranged from 19 millionths under the 42 kip tridem-axle to 30 millionths under the 20 kip single-axle along the outside lane and 17 millionths under the 42 kip tridem-axle to 35 millionths under the 20 kip single-axle along the inside lane. For Project 1, measured tied-concrete shoulder edge strain ranged from 3 millionths under the 20 kip single-axle to 8 millionths under the 34 kip tandem-axle.

For Project 2, measured edge strains ranged from 20 millionths under the 42 kip tridem-axle to 38 millionths under the 34 kip tandem-axle along the outside lane and 18 millionths under the 42 kip tridem-axle to 35 millionths under the 20 kip single-axle along the inside lane. For Project 2, measured tied-shoulder edge strain ranged from 6 millionths under the 34 kip tandem-axle to 12 millionths under the 42 kip tandem-axle.

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

Theoretical Considerations

Analysis was conducted to determine the effect of a tied-concrete shoulder on concrete pavement response. A finite element program, Program JSLAB, developed by Construction Technology Laboratories for the Federal Highway Administration was used (3). 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/subgrade support is characterized by the modulus of subgrade support.

To simulate the field studies, analysis was conducted for a 9-in. thick concrete pavement with and without tied-shoulder and with dowel bars at transverse joints. For the case of tied-shoulder, a 6-in. thick slab was used. Values used for the modulus of subgrade reaction were 100, 150, and 250 pci. Calculated corner deflections and edge deflections are listed in Table 4. For both corner

Table 4. Calculated Pavement Responses.

Response	Shoulder Type	k, pci	Corner Deflection, in. 20 kip SAL	34 kip TAL	42 kip TAL	42 kip Tridem
Corner Deflection, in.	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
Edge Deflection, in.	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

and edge loadings, tire placements were 2 in. inward from the edge.

The computer program simulated a tied keyway with a calculated joint efficiency of about 80% for a modulus of subgrade reaction of 250 pci to about 90% 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%. The ratio of calculated edge strains along a tied-shoulder joint to those along a free edge is about 80%.

To expand the base data, additional analysis was conducted for a 9-in. thick slab on a subgrade with a modulus value of 250 pci and with an array of joint efficiencies. 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 efficiencies. These ratios are listed in Table 5.

Table 5. Ratios of Computed Pavement Responses Along a Tied-Shoulder Joint to Those Along a Free Edge.

Response	Ratio (%) JE = 80%	JE = 60%	JE = 50%
Edge Deflection	65	70	75
Corner Deflection	65	70	75
Edge Strain	80	85	90

<u>Note</u>: 1) JE = Joint Efficiency = $\frac{\text{Deflection of mainline slab}}{\text{Deflection of shoulder slab}}$

2) Mainline slab thickness = 9 in., shoulder slab thickness = 6 in.

3) Modulus of subgrade reaction = 250 pci

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. It can be seen from Table 6, that the reduction in the deflection response can be conservatively taken as 85%. This value corresponds to a calculated joint efficiency at the tied-shoulder joint of less than 50%. As discussed

Table 6. Improvement in Pavement Responses by Using Tied-Shoulder.

Response	Ratio of Response at a Tied-Shoulder Joint to that at a Free Edge, Percentage				
	Measured		Calculated		
	Project 1	Project 2	JE = 80%	JE = 60%	JE = 50%
Edge Deflection	75-90	NR	65	70	75
Corner Deflection	70-87	58-80	65	70	75
Edge Stress	80-85	94-97	80	85	90

Notes: 1) JE = Joint Efficiency
$= \frac{\text{Deflection of mainline slab}}{\text{Deflection of shoulder slab}}$

2) NR = data considered not reliable

previously, measured joint efficiency along the shoulder sections on I-74 in Illinois, that incorporated tied-keyways, had retained joint efficiency in excess of 70% even after 10 years of service. Therefore, properly constructed concrete pavements with tied-shoulder can be expected to retain at least 50% joint efficiency during its design life.

It should be noted that the measured level of improvement shown in Table 6 is based on response of the inside lane edge which has been subjected to very 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.

Since pavement damage or loss in 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 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, then 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 21 kip SAL applied on a pavement with a tied-shoulder can be considered to be equivalent to a 18 kip SAL applied on a pavement without a tied-shoulder.

Application of Benefits to Concrete Shoulders

There are several ways which the benefits of concrete shoulders can be used. They can be used to design new pavements capable of carrying greater numbers of trucks. They can be used to design thinner pavements for the same design traffic as thicker pavements without tied shoulders. They can decrease the thickness of unbonded concrete resurfacing. Theoretically, they can even be used to extend the life of existing pavements by being added as part of a 4R type project.

The benefits of tied concrete shoulders have been included in the latest Portland Cement Association Thickness Design Procedure (4). The procedure recognizes the benefits of tied concrete shoulders relative to both failure by fatigue and failure resulting from erosion at the joints. The benefit toward fatigue is recognized as the support the shoulder provides to the free edge and the corresponding reduction is stress. The benefit toward erosion is based on recognition of the superior effectiveness of sealed grouts between concrete slabs coupled with a reduction in pavement deflection attributed to tied concrete shoulders.

While the benefit of tied shoulders varies with concrete strength, subgrade-subbase support and traffic demand, the benefit is normally about a one inch reduction in pavement thickness for most designs. This saving in thickness can also be expressed as a pavement with a tied shoulder having the ability to accommodate the design traffic of a one inch thicker pavement which did not have tied shoulder.

It should be noted that a tied concrete curb on a city street has the same characteristics as a tied shoulder on an interstate highway.

The benefits of tied concrete shoulders also have an application to the 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 single-axle loads (5). The equivalence factors, when multiplied by the number of axle loads within a given weight category, give the number of 18-kip single-axle load 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 Tables 7 and 8, a tandem-axle is about 2.30 to 2.50 times as damaging as a single-axle weighing half as much as the tandem-axle. The ratio of edge deflection under a tandem-axle 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 a tandem-axle is less than that under a single-axle weighing half as much as the tandem-axle. Therefore, with respect to use of a tied-shoulder, the reduction in deflection response is considered more significant than the reduction in strain response.

Table 7. Traffic Equivalence Factors for Single-Axles on Rigid Pavements, p_t = 2.5.

Axle Load		D - Slab Thickness - inches					
Kips	kN	6	7	8	9	10	11
2	8.9	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
6	26.7	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
10	44.5	0.10	0.09	0.08	0.08	0.08	0.08
12	53.4	0.20	0.19	0.18	0.18	0.18	0.17
14	62.3	0.38	0.36	0.35	0.34	0.34	0.34
16	71.2	0.63	0.62	0.61	0.60	0.60	0.60
18	80.1	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
22	97.9	2.21	2.20	2.28	2.34	2.38	2.40
24	106.8	3.16	3.10	3.23	3.36	3.45	3.50
26	115.7	4.41	4.26	4.42	4.67	4.85	4.95
28	124.6	6.05	5.76	5.92	6.29	6.61	6.81
30	133.4	8.16	7.67	7.79	8.28	8.79	9.14
32	142.3	10.81	10.06	10.10	10.70	11.43	11.99
34	151.2	14.12	13.04	12.94	13.62	14.59	15.43
36	160.1	18.20	16.69	16.41	17.12	18.33	19.52
38	169.0	23.15	21.14	20.61	21.31	22.74	24.31
40	177.9	29.11	26.49	25.65	26.29	27.91	29.90

Table 8. Traffic Equivalence Factors for Tandem-Axles on Rigid Pavements, p_t = 2.5.

Axle Load		D - Slab Thickness - inches					
Kips	kN	6	7	8	9	10	11
10	44.5	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
14	62.3	0.06	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
18	80.1	0.16	0.14	0.14	0.13	0.13	0.13
20	89.0	0.23	0.22	0.21	0.21	0.20	0.20
22	97.9	0.34	0.32	0.31	0.31	0.30	0.30
24	106.8	0.48	0.46	0.45	0.44	0.44	0.44
26	115.7	0.64	0.64	0.63	0.62	0.62	0.62
28	124.6	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
32	142.3	1.43	1.44	1.47	1.49	1.50	1.51
34	151.2	1.82	1.82	1.87	1.92	1.95	1.96
36	160.1	2.29	2.27	2.35	2.43	2.48	2.51
38	169.0	2.85	2.80	2.91	3.04	3.12	3.16
40	177.9	3.52	3.42	3.55	3.74	3.87	3.94
42	186.8	4.32	4.16	4.30	4.55	4.74	4.86
44	195.7	5.26	5.01	5.16	5.48	5.75	5.92
46	204.6	6.36	6.01	6.14	6.53	6.90	7.14
48	213.5	7.64	7.16	7.27	7.73	8.21	8.55

It is seen from Tables 7 and 8 that for a 9-in. thick pavement, a 21-kip single-axle load is about 2.0 times as damaging as an 18-kip single-axle load. However, based on study results, a 21-kip single-axle load applied on a pavement with a tied-shoulder can be considered to be only as damaging as an 18-kip single-axle load applied on a pavement without a tied-shoulder. Thus, a 21-kip single-axle load applied on a pavement with a tied-shoulder is only 1/2.0, that is, 0.5 times as damaging as a 21-kip single-axle load applied on a pavement without a tied-shoulder. Applying this logic to different slab thicknesses and other axle loads, it is found that the damaging effect of a given single-axle or tandem-axle load 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 being 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 single-axle loads applied need to be considered for thickness design of pavements with a tied-shoulder.

Design Application

The following parameters are assumed:

Concrete modulus of rupture = 650 psi
Concrete working stress = 490 psi
Concrete modulus of elasticity = 4,000,000 psi
Modulus of subgrade reaction = 200 pci

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	Required Pavement Thickness, in. Without Shoulder	With Shoulder
2,500,000	7.6	6.6
5,000,000	8.7	7.6
10,000,000	9.7	8.7
20,000,000	10.8	9.7

Required thicknesses for pavement with tied-shoulder were determined 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 mainline 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 mainline slab thickness.

Rehabiliation

Both PCA's Design Procedure and the AASHTO Design Procedure are based on the relation of pavement life to design traffic. The fact that when designing a pavement the addition of a tied concrete shoulder results to either a thinner pavement or an increase in the pavement life, i.e. design traffic. In the case of rehabilitation, for a pavement that is structurally adequate, the addition of tied shoulders should result in an increase in design life equivalent to approximately one additional inch of pavement thickness.

As historically, most concrete pavements have failed due to erosion. The ability to seal joints between concrete slabs, coupled with the reduction in deflections of slab edges and corners easily demonstrates the benefit of add-on concrete shoulders.

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 to 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 need to be considered for concrete pavements incorporating a tied-concrete shoulder. This recommendation results in a reduction of 1 in. in the required mainline slab thickness given by the AASHTO design procedure. This recommended reduction in slab thickness based on the benefits of tied-concrete shoulders has already been incorporated into the PCA design procedure.

As the research described here was conducted only on shoulders constructed along with the mainline pavement, the question of add-on shoulders should be investigated. In theory the benefits of shoulders should apply equally to add-on shoulders to extend existing pavement life. Field measurement would determine if the add-on shoulder with its grouted tie bars performs the same as those included with the mainline pavement construction.

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The opinions and findings expressed or implied in the paper are those of the authors. They are not necessarily those of the Minnesota Department of Transportation or the Federal Highway Administration.

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