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Publication of this paper sponsored by Committee on Pavement Condition Evaluation.

Evaluation of Concrete Pavements With Tied Shoulders or Widened Lanes

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Field and laboratory pavements were instrumented and load tested to evaluate the effect of widened lanes, concrete shoulders, and slab thickness on measured strains and deflections. Eight slabs were tested in the field and two in the laboratory. Pavement slabs were 203, 229, or 254 mm (8, 9, or 10 in) thick. Other major design variables included the width of lane widening, the presence or absence of dowels or of a concrete shoulder, joint spacing, and the type of shoulder joint construction. Generally, there was good agreement between measured strains and values calculated by using Westergaard's theoretical equations. Concrete shoulders were effective in reducing the magnitude of measured strains and deflections. A chart is presented to show the allowable reduction in thickness of the outer lane of the main-line pavement when there is a tied concrete shoulder. Lane widening of about 406 mm (16 in) was as structurally effective as a concrete shoulder in reducing edge strains and deflections. However, it should be remembered that a concrete shoulder provides the added advantage of draining runoff farther from the pavement edge. Because of the possibility of load encroachments on a widened lane, it is recommended that lanes be widened by a minimum of 0.46 m (1.5 ft) plus any additional width required to avoid encroachment. Under the conditions considered, tied-butt, tied and keyed, and keyed-joint constructions were equally effective in reducing load-induced pavement strains and deflections.

Existing pavements represent a major investment of highway funds. A road can seldom be abandoned or replaced. Every year many kilometers of pavements require rehabilitation to cope with increased traffic. Overlays are built for the purpose of restoring pavement serviceability and improving structural capacity, but this practice is expensive and alternative solutions are needed.

One alternative to resurfacing is the use of a widened lane or a paved concrete shoulder. This type of construction could be used not only to strengthen existing pavements but also to strengthen new pavements and thus defer rehabilitation. Another approach for the design of new pavements that include a tied concrete shoulder would be to reduce the thickness of the outer lane of the main-line pavement.

In addition to strengthening a pavement, concrete shoulders and lane widening provide a benefit not obtained by resurfacing in that runoff water is drained farther away from the wheel paths of traffic. A recent study for the Federal Highway Administration (1) determined that accumulation of water in the joint between an asphalt shoulder and a concrete pavement was a major factor in reducing pavement performance. Because of this problem, several states have installed costly longitudinal and transverse drainage systems. Thus, concrete shoulders and widened lanes have the potential for curing many drainage problems as well as providing additional slab strength.

Many design features contribute to pavement life. The effect of some of these features can be evaluated analytically. For example, analytical tools can be used to determine the effect of pavement thickness or subbase strength on pavement life. Thus, when analytical procedures are available, the engineer can combine a knowledge of pavement life with data on construction and maintenance cost to provide the most economical design.

Analytical tools often are unavailable or require the use of unknown or unverified coefficients. For example, tied shoulders reduce load deflections and stresses, but the amount of the reduction is a function of the unknown continuity across the joint between the pavement edge and the shoulder. In these cases, the most direct method of evaluating design features is a planned series of field data measurements extended by laboratory tests and analytical procedures. This paper reports on a project that incorporated these features. The principal objective of the project was to determine the effect of widened lanes, tied concrete shoulders, and slab thickness on measured strains and deflections. Field and laboratory pavements were instrumented, and measurements of load strains and deflections were obtained. The measured data were then analyzed to determine the effects of the variables on pavement life.

PAVEMENT TEST SECTIONS

Field measurements were obtained on four experimental pavement projects located in the state of Minnesota. All fieldwork was done under a contract between the Minnesota Department of Transportation and the Portland Cement Association (PCA).

Project 1 is a roadway 8.23 m (27 ft) wide that consists of a 4.57-m (15-ft) wide inside lane, a 3.66-m (12-ft) wide outside lane, and a 3.05-m (10-ft) wide outside tied and keyed concrete shoulder. Shoulders are tied at 762-mm (30-in) spacing by no. 5 tie bars 762 mm long. Shoulder thickness is 152 mm (6 in). The pavement is composed of plain concrete slabs 229 mm (9 in) thick that have skewed joints at a repeated random spacing of 3.96, 4.88, 4.27, and 5.79 m (13, 16, 14, and 19 ft). Dowel bars were placed only in the 3.66-m outside traffic lane. Dowels are no. 8 round bars spaced at 305 mm (12 in) on centers; the first dowel is located 152 mm (6 in) in from the pavement edge. Panels selected for testing were located at stations 539+16 and 540+10.

Project 2 is a roadway 8.23 m (27 ft) wide with a 3.05-m (10-ft) wide outside tied and keyed concrete shoulder. Dowel size and location are the same as for project 1. The pavement thickness is 203 mm (8 in). Panels selected for testing were located at stations 519+80 and 521+81.

Project 3 is a roadway 8.23 m (27 ft) wide with a 4.57-m (15-ft) wide inside lane and a 3.66-m (12-ft) wide outside lane. The pavement is composed of reinforced concrete slabs 229 mm (9 in) thick that have skewed joints at a spacing of 8.23 m. Dowel bars were placed only in the 3.66-m portion of main-line pavement in both traffic lanes. The dowels are no. 8 round bars spaced 305 mm (12 in) on centers. Panels selected for testing were located at stations 985+53 and 987+11.

Project 4 is a roadway 7.62 m (25 ft) wide with a 3.66-m (12-ft) wide inside lane and a 3.96-m (13-ft) wide outside lane. The pavement is composed of plain concrete slabs 203 mm (8 in) thick that have skewed joints at a repeated random spacing of 3.96, 4.88, 4.27, and 5.79 m (13, 16, 14, and 19 ft). Dowel bars were placed only in the inner 3.66 m of the 3.96-m outside traffic lane. The dowels are no. 8 round bars spaced 305 mm (12 in) on centers. Panels selected for testing were located at stations 870+64 and 872+21.

Projects 1, 2, and 3 are located on TH-90 between Albert Lea and Fairmont, Minnesota. Project 4 is located on TH-14 near Rochester, Minnesota. None of the projects had been opened to traffic before testing.

Two test sites were selected on each project for instrumentation and data recording. Sites were located within 60.96 m (200 ft) of each other to facilitate load testing and data acquisition. Care was taken to ensure that the sites selected were representative of the project and were similar in joint opening. The field test pavements were 203 or 229 mm (8 or 9 in) thick and either had or did not have a tied and keyed concrete shoulder 152 mm (6 in) thick.

Supplementary data were obtained from two pavement slabs constructed and tested at the PCA laboratories. These slabs included tied and keyed, keyed, and tied-butt shoulder joints. The laboratory slabs were 254 mm (10 in) thick and had shoulders that were also 254 mm thick. They were constructed indoors directly on a soft clay subgrade.

The indoor test area was equipped with thermostatically controlled heaters to provide a uniform temperature of 18°C (65°F). Overhead steel frames provided reaction for loading test specimens. The testing area was 30.48 m (100 ft) long and 7.32 m (24 ft) wide. The subgrade was a clay soil 1.52 m (5 ft) thick compacted to American Association of State Highway and Transportation Officials (AASHTO) standard density at 2 percent above optimum moisture. The k value of the subgrade (modulus of subgrade reaction), determined from tests of plates 762 mm (30 in) in diameter, was 758 kPa (110 lbf/in^2).

For the slabs constructed and tested in the laboratory, the tied and keyed and tied-butt shoulder joints were included in a slab that was 9.14 m (30 ft) long and 3.66 m (12 ft) wide. Shoulder width was 2.13 m (7 ft). To provide continuity at doweled transverse joints, sections of concrete 2.74 m (9 ft) in length were cast at each end of the slab. The untied and keyed construction was tested in a slab 4.57 m (15 ft) long that had one doweled and one undoweled transverse joint.

INSTRUMENTATION

All pavement test sections were instrumented to measure load-induced strains and deflections. In addition, field sections were instrumented to measure air and slab temperatures and slab curling (a change in the vertical profile of the slab that results from changes in slab temperature).

Type and Location

Figure 1 shows locations of strain and deflection instrumentation used on field pavement slabs that included both a widened lane and a tied concrete shoulder. Curl measurements were obtained at deflectometer locations, and temperatures were measured in instrumented test blocks. Test blocks were placed in the subbase adjacent to the pavement at least 12 h before load testing. Air temperatures were monitored by a thermocouple that was shaded from the direct sun. Details on types of instrumentation, methods of installation, and monitoring equipment used are given elsewhere (2).

Monitoring Equipment

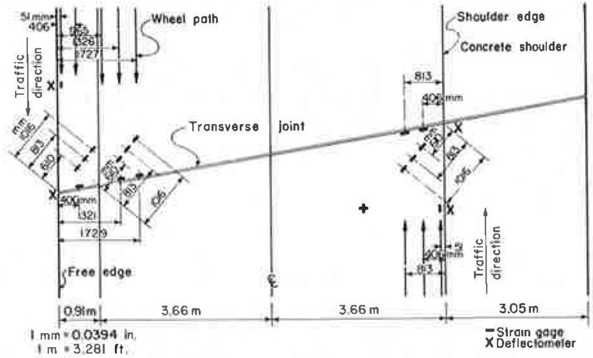
Data were monitored by equipment housed in a mobile instrument van. The equipment consisted of 38 channels of heat stylus recorders, a 14-channel magnetic tape recorder, a 50-channel temperature recorder, a portable strain indicator, and a portable temperature recorder.

TEST PROCEDURES

Trucks used to apply load to field pavement slabs were supplied by the Minnesota Department of Transportation. The trucks were an 89-kN (20 000-lb) single-axle, a 151-kN (34 000-lb) tandem-axle, and a 187-kN (42 000-lb) tandem-axle. Before testing, axle weights were checked and loads were adjusted to obtain uniform distribution to the rear wheels. Prints of the contact area for each of the rear tire assemblies were obtained for use in data analysis. All pertinent dimensions of axle and wheel spacing were also obtained.

Effects of axle weight and load location on strains and deflections were recorded as the trucks moved at creep speed in the wheel paths shown in Figure 1. Wheel-path

Figure 1. Instrumentation on field pavement slabs with widened lanes and tied concrete shoulders.



locations are shown as the distance from the pavement edge to the sidewall of the outside tire.

Instrumentation readouts for three loads operating in different wheel paths were obtained continuously during the day at each test site. Information for correcting data for the effects of temperature curling was obtained by hourly reading of selected instruments.

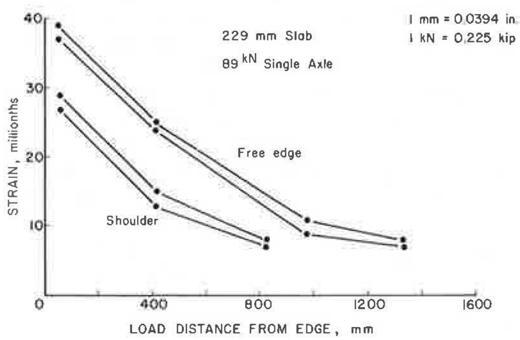
For indoor slabs, static loads were applied at edges, corners, and interiors. Loads were transmitted to slabs through a steel plate 406 mm (16 in) in diameter that rested on a rubber pad. Because slab temperature was kept constant, no correction for temperature was necessary.

RESULTS

Data for edge strain in slabs 229 mm (9 in) thick located at stations 539+16 and 540+10 are shown in Figure 2. Although strains were measured only on the top surface of the pavement, it is common engineering practice to assume a straight-line distribution of stress in a pavement slab. In this paper, therefore, bottom strains are assumed to be equal in magnitude and opposite in sign to measured top strains.

The close spacing of the data points for the two slabs shows that there was good agreement between strains obtained at the two test sites. As expected, edge strains decreased as the distance of the load from the edge was increased. In addition, based on data for the 51-mm (2-in) load position, strains measured at the shoulder edge were about 27 percent less than those measured at the free edge.

Figure 2. Edge strain at test stations 539+16 and 540+10.



The effect of load and axle configuration on the magnitude of strain may be demonstrated by comparing free-edge strains at the 51-mm (2-in) load position for the three loads. These strains were 38, 30, and 36 millionths for the 89-, 151-, and 187-kN (20 000-, 34 000-, and 42 000-lb) loads respectively. Thus, strain decreased as load was changed from an 89-kN single-axle load to a 151-kN tandem-axle load but increased as the tandem-axle load was increased to 187 kN.

Tables 1 and 2 give a summary of the data for the effect of axle loads on strain for two slab thicknesses. The values reported were obtained by dividing the strain obtained for the selected axle load by the strain for the 89-kN (20 000-lb) single-axle load. Average ratios for all data were 1.0, 0.84, and 1.0 for the 89-, 151-, and 187-kN (20 000-, 34 000-, and 42 000-lb) axle loads respectively. These ratios are in good agreement with the values of 1.0, 0.80, and 0.99 obtained at the AASHO Road Test for slabs 229 mm (9 in) thick (4).

Maximum strains measured for an 89-kN (20 000-lb) single-axle load at corner, edge, interior, and transverse joint are shown in Figure 3. These data were obtained for slabs 203 mm (8 in) thick located at stations 519+80 and 521+81, but they are representative of trends measured at all test slabs that included paved shoulders. These trends were characterized by the fact that free-edge loading produced the largest measured strains. In general, free-edge strains were 36 to 50 percent greater than interior strains. In contrast, strains for cases of corner, tied shoulder, and transverse joint loadings were generally within 10 percent of strains measured at the interior load position.

Edge strains at test sites without shoulders were also

Figure 3. Maximum strains at test stations 519+80 and 521+81.

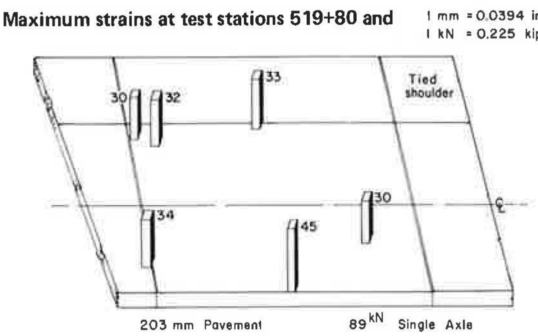


Table 1. Effect of axle load on strain in 203-mm (8-in) slab.

Load (kN)	Strain Ratio[a] Free Edge 519+80	Free Edge 521+81	Shoulder 519+80	Shoulder 521+81	Strain Ratio[a] Free Edge 870+64	Free Edge 872+21	Free Widened Edge 870+64	Free Widened Edge 872+21
89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
151	0.86	0.87	0.88	0.85	0.79	0.83	0.82	0.84
187	1.05	1.00	1.06	1.06	1.00	1.00	1.11	1.05

Note: 1 kN = 225 lb.

[a] Obtained by dividing strain for the selected axle load by strain for the 89-kN (20 000-lb) axle load.

Table 2. Effect of axle load on strain in 229-mm (9-in) slab.

Load (kN)	Strain Ratio[a] Free Edge 539+16	Free Edge 540+10	Shoulder 539+16	Shoulder 540+10	Strain Ratio[a] Free Edge 985+53	Free Edge 987+11	Free Widened Edge 985+53	Free Widened Edge 987+11
89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
151	0.79	0.78	0.72	0.70	0.90	0.92	0.87	0.88
187	0.95	0.95	0.83	0.89	1.03	1.00	0.97	0.98

Note: 1 kN = 225 lb.

[a] Obtained by dividing strain for the selected axle load by strain for the 89-kN (20 000-lb) axle load.

the maximum measured values. However, strains measured at the transverse joint and corner locations were sometimes greater than interior strains by 30 percent or more.

Measurements of edge strain shown in Figure 4 were taken from a laboratory-tested 254-mm (10-in) slab that had a 254-mm shoulder. Load strains obtained from the laboratory slabs were larger than those obtained from field slabs although the data followed the same trends. But indoor slabs were on a soft clay subgrade, and loads were applied at the edge rather than 51 mm (2 in) in from the edge. It will be shown later that there was good agreement between measured and theoretical edge strains for all slabs tested.

Figure 4. Edge strain in laboratory test slab.

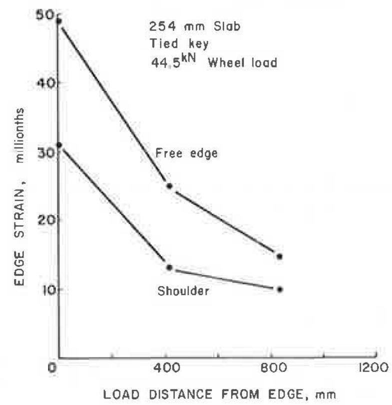
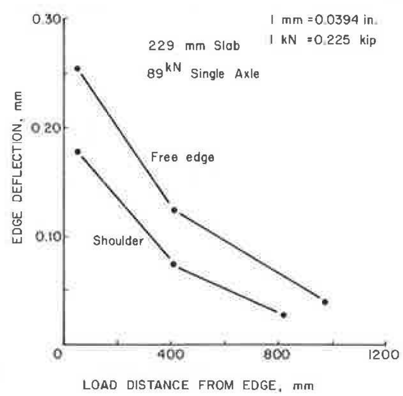


Figure 5. Edge deflection versus distance of load from the pavement edge.



One significant difference between the data for indoor and field tests was the amount of reduction in edge strain that resulted from the addition of a shoulder. The indoor slab designs showed an average strain reduction of 37 percent compared with an average reduction of 28 percent for the outdoor designs. A theoretical analysis indicated that this difference is due to the use of a 254-mm (10-in) thick shoulder with indoor slabs rather than the 152-mm (6-in) thick shoulder with outdoor slabs.

To determine the benefit of dowels versus aggregate interlock, separate comparisons were made for test sites with and without shoulders. At field sites with shoulders, joint strains were reduced by an average of 4 percent when dowels were used. In the only laboratory comparison made to determine the benefit of dowels—the case of a slab with a shoulder—there was no reduction of strain at the doweled joint. For the one field site without shoulders, strains at joints with dowels were reduced by an average of 12 percent. These reductions are small, but it should be remembered that the pavements had not been opened to traffic. The value of dowels will increase as aggregate interlock is reduced by increased pavement age and traffic applications.

The effect of load placement on edge deflection is shown in Figure 5. As expected, edge deflections decreased rapidly as the load was moved inward from the pavement edge. In contrast to measured strains, however, deflections always increased as the total axle load increased. A summary of the effect of axle load on deflection for all edge measurements is given in Tables 3 and 4. Average deflection ratios for axle loads of 89, 151, and 187 kN (20 000, 34 000, and 42 000 lb) were 1.0, 1.15, and 1.45 respectively. At the AASHO Road Test (4), the ratios were 1.0, 1.42, and 1.75.

The larger deflections for tandem-axle loads measured at the AASHO Road Test may partially result from the times when the data were taken. Measurements were made both during the day and at night. In Minnesota, measurements were made only during the day. Upward curl is greater during the night and the early morning than it is during the day. In addition, the slab is unsupported over a greater distance inward from the pavement edge. Because the wheels of a tandem-axle vehicle are spread over a larger area than are those of an

Table 3. Effect of axle load on deflection in 203-mm (8-in) slab.

	Deflection Ratio[a]				Deflection Ratio[a]			
	Free Edge		Shoulder		Free Edge		Free Widened Edge	
Load (kN)	519+80	521+81	519+80	521+81	870+64	872+21	870+64	872+21
89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
151	1.17	1.14	1.13	1.10	1.27	1.00	1.08	1.15
187	1.58	1.36	1.38	1.30	1.45	1.50	1.58	1.46

Note: 1 kN = 225 lb.

[a] Obtained by dividing deflection for the selected axle load by deflection for the 89-kN (20 000-lb) axle load.

Table 4. Effect of axle load on deflection in 229-mm (9-in) slab.

	Deflection Ratio[a]				Deflection Ratio[a]			
	Free Edge		Shoulder		Free Edge		Free Widened Edge	
Load (kN)	539+16	540+10	539+16	540+10	985+53	987+11	985+53	987+11
89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
151	1.25	1.15	1.14	1.23	1.10	1.33	1.11	0.91
187	1.46	1.54	1.43	1.49	1.50	1.56	1.56	1.09

Note: 1 kN = 225 lb.

[a] Obtained by dividing deflection for the selected axle load by deflection for the 89-kN (20 000-lb) axle load.

equivalent single-axle vehicle, the larger length of non-supported slab is deflected more by tandem axles.

The use of a tied and keyed shoulder reduced edge deflections by an average of 32 percent. This is a larger reduction than the 27 percent obtained based on strain measurements. However, it has been demonstrated that deflections are more influenced than strains by warping and curling. So it is possible that the presence of the shoulder reduced drying shrinkage and that this resulted in less warping. The smaller warping was more effective in reducing edge deflections than in reducing edge strains.

Measured deflections for corner loading were greater than those for edge loading. The larger corner deflections are due to the loss in continuity and the greater upward warping that occur at joints. Corner deflections were 226 percent larger than edge deflections.

ANALYSIS OF DATA

Comparison of Theoretical and Measured Data

Theoretical stresses and deflections were calculated by using influence charts (5). These charts, which are based on Westergaard's equations, permit the calculation of edge stresses and deflections caused by loads placed inward from the edge. Stresses were converted to strains by using a concrete modulus of elasticity of 34.5 GPa (5 million lbf/in^2). The k values used for computations were 33 and 109 MN/m^3 (120 and 400 lb/in^3) for the laboratory and field tests respectively. The value of 109 MN/m^3 used for field tests was estimated on the basis that the in-place subbase k was 41 MN/m^3 (150 lb/in^3). At the time of testing, however, there was a freezing index of 9, which is sufficient to freeze subsoils. Thus, a k value of 109 MN/m^3 was selected.

Comparisons of measured and theoretical values are given in Table 5. The data show generally good agreement between measured and theoretical values. Based on averages, measured strains were 4 percent greater than theoretical strains. However, measured deflections were on the average 12 percent larger than theoretical deflections. The larger variation for deflections is consistent with data previously presented. These data indicated that deflections are more influenced by warping than are strains.

The field data may be used to determine the effect of pavement thickness on measured strains and deflections. For example, increasing slab thickness from 203 to 229 mm (8 to 9 in) decreased edge strains by 16 percent and edge deflections by 21 percent. These values are used later for comparison with reductions in strain and deflection obtained when a shoulder was added to the pavement.

Concrete Shoulders

Strain and deflection measurements were obtained at free edges and shoulder edges. Based on these measurements, average percentage reductions in strain and deflection attributable to the presence of a shoulder were computed for slabs 203, 229, and 254 mm (8, 9, 10 in) thick. Strain reductions were 26.5, 29.0, and 37.0 percent respectively.

Good agreement has been shown between theoretical and measured strains and deflections. Therefore, influence charts were used to compute theoretical percentage reductions in strain or deflection as a result of increasing pavement thickness. These data were plotted, and then the graph was entered at the value of the measured reduction to determine the increase in slab thickness required to reduce strains by the same magnitude as that obtained by the construction of a tied concrete shoulder. The same type of analysis was made by using measured deflections. The results showed that, to obtain the reduction in deflection achieved by adding a shoulder, thickness would have to be increased by 66, 84, and 107 mm (2.6, 3.3, and 4.2 in) for the 203-, 229-, and 254-mm (8-, 9-, and 10-in) slabs respectively. To achieve equal reductions in strain, pavement thickness would have to be increased by 43, 56, and 86 mm (1.7, 2.2, and 3.4 in) for the 203-, 229-, and 254-mm slabs respectively.

The same data can be used to determine an allowable reduction in thickness in the outer traffic lane of a mainline pavement when a tied concrete shoulder is incorporated in the design. In Figure 6, the conventional or "as-built" pavement design thickness is plotted versus the effective thickness with a concrete shoulder. The

Figure 6. Reduction in outer lane thickness with addition of tied concrete shoulder.

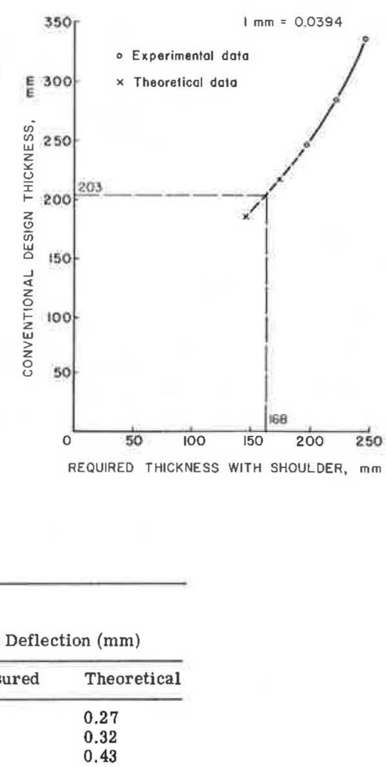


Table 5. Comparison of theoretical and measured data for edge and interior strains and edge deflection.

			Strain					
			Edge (millionths)		Interior (millionths)		Edge Deflection (mm)	
Test Location	Thickness (mm)	Load (kN)	Measured	Theoretical	Measured	Theoretical	Measured	Theoretical
Field	203	89	45	45	30	29	0.31	0.27
		151	38	35	21	21	0.36	0.32
		187	46	45	26	26	0.47	0.43
	229	89	38	38	28	26	0.25	0.20
		151	33	30	21	19	0.28	0.25
		187	38	38	25	24	0.36	0.32
Laboratory	254	89	48	49	27	26	0.38	0.41

Note: 1 mm = 0.039 in; 1 kN = 225 lb.

solid, curved line that passes through the three experimental data points has been extended by extrapolation. The validity of the extrapolation is demonstrated by the close agreement between the extended portion of the curve and the two points computed by using Westergaard's equation for edge load.

On the chart, the curved line is entered on the abscissa of the determined conventional design thickness. In the example (Figure 6), the conventional design thickness has been assumed to be 203 mm (8 in). A horizontal line is drawn to intersect the curve and is then extended vertically downward to the ordinate. The value of 168 mm (6.6 in) obtained at the intercept is the pavement thickness of the outer lane that could be permitted if a tied concrete shoulder were used instead of a 203-mm-thick pavement without a shoulder.

Another method of evaluating the benefit of a concrete shoulder is to determine the added life expectancy of the pavement that is attributable to the reduction in edge stress. This is done by using the following equation developed at the AASHO Road Test (6):

$$\log W_{2.5} = 5.789 + 3.42 \log (S_c/\sigma) \quad (1)$$

where

$W_{2.5}$ = number of applications of stress σ,
S_c = 28-d flexural strength of the concrete, and
σ = predicted stress in the concrete caused by external loading.

The life expectancy of the pavement is increased because, at a reduced level of stress, the pavement can carry a greater number of traffic loads before reaching a level of terminal serviceability. Thus, if traffic remained constant with time, the life of the pavement would be extended.

Values of W were computed by substituting experimental data into the equation. The results show that the addition of a shoulder would extend the life of the 203-, 229-, and 254-mm (8-, 9-, and 10-in) pavements by factors of 3.2, 3.3, and 3.6 respectively.

Lane Widening

Experimental data were used to determine the effectiveness of lane widening in reducing pavement strains. An example of the procedure followed is shown in Figure 7. The data, which are the average of load strains measured at the free edge for test sites located at stations 539+16 and 540+10, show the decrease in measured edge strain as the load was moved inward from the edge. The dashed line represents the measured interior strain for the load being considered—a tensile strain that occurs at the bottom of the slab directly under the load.

By projecting downward from the intersection of the lines for interior and edge strain in Figure 7, it can be determined that an edge strain of 28 millionths was obtained when the load was 305 mm (12 in) in from the pavement edge. This means that, if the slab was widened by 305 mm, no further strain reduction could be obtained by additional widening. As the cross-hatching shows, the case of edge loading produced the largest strain until the load was 305 mm from the edge, and after that the strain directly under the load was larger. Results from a similar analysis for each of the test sites are given below (1 kN = 225 lb and 1 mm = 0.04 in):

Test Station	Load (kN)	Required Widening (mm)
985+53	89	305
987+11	151	356
	187	330
870+64	89	279
972+21	151	356
	187	330
539+16	89	305
540+10	151	305
	187	305
519+80	89	406
521+81	151	381
	187	559

With one exception, widening requirements varied from 279 to 406 mm (11 to 16 in).

Based on this analysis, it would appear that a lane widening of 406 mm (16 in) would be sufficient. This would be true, however, only if vehicles did not encroach on the widening.

To investigate the probability of encroachment, data from two studies of traffic distribution are shown in Figure 8. The data shown by the curve on the right were obtained by Taragin of the Federal Highway Administration in 1958 (7). These data, which are still used in pavement design, show that the highest frequency of travel and mean travel path distance occurred at slightly more than 0.61 m (2 ft) from the pavement edge. In addition, only about 4 percent of the traffic drove closer to the edge than 305 mm (12 in). The data for the curve on the left were obtained by Emery of the Georgia Department of Transportation in 1974 (8). In this case, 53 percent of the traffic traveled within 305 mm of the pavement edge. In addition, 9 percent of the traffic was observed to be driving in a 381-mm (15-in) wide wheel path that began 76 mm (3 in) inward from the pavement edge and extended outward to include 305 mm of the shoulder. Because these data were obtained from pavements that had asphalt shoulders, there was a highly visible delineation between pavement and shoulder. Therefore, it is

Figure 7. Effect of lane widening at test stations 539+16 and 540+10.

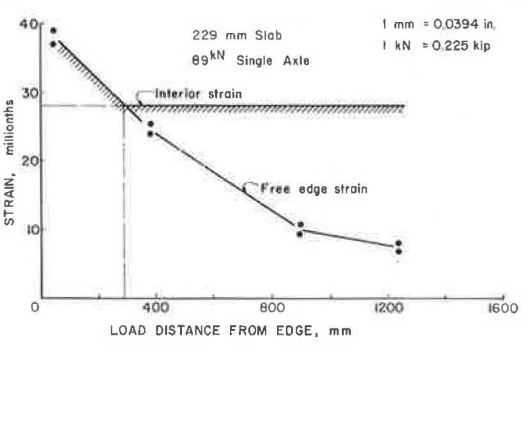
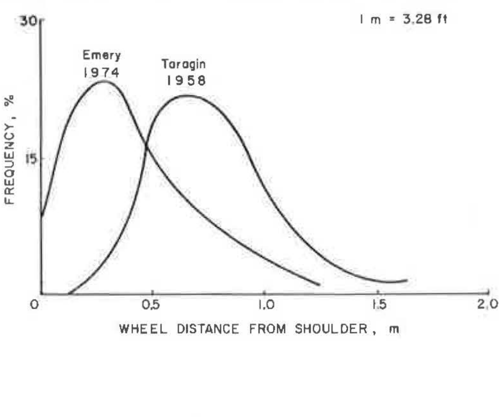


Figure 8. Traffic distribution: frequency versus wheel path.



highly improbable that a painted white stripe located 406 mm (16 in) from the pavement edge will prevent encroachment. If pavement widening is to be structurally effective, determination of the minimum width should include consideration of the effects of load encroachments.

Shoulder Joint Design

Because all shoulder joints in the field projects used a tied and keyed design, laboratory slabs were constructed with keyed, tied and keyed, and tied-butt joints. Tie bars were 16 mm (0.7 in) in diameter and 965 mm (38 in) long and were spaced at 762-mm (30-in) centers.

Load strains and deflections were measured at the free edge and the shoulder edge for each design. These data were used to compute the percentage reduction in strain and deflection that occurred as a result of the presence of a shoulder. Figure 9 shows that edge strains and deflections were reduced by an average of 38 and 43 percent respectively. The small percentage difference in the performance of the three types of joints is not considered significant.

Although the keyed joint without tie bars was effective in reducing strains and deflections, its use would not be recommended in construction of outside lanes because of the possibility of shoulder joint separation. Such a separation might result from lateral traffic forces and differential vertical movements in the subgrade.

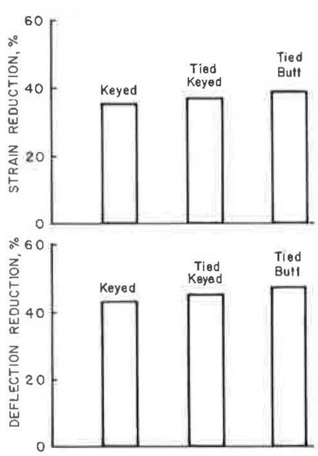
The excellent performance of the tied-butt joint suggests that this type of construction could reduce costs. Joints of this design, however, may lose some of their effectiveness under accumulated traffic loadings.

CONCLUSIONS

Pavement slabs were instrumented and load tested to determine the effects of concrete shoulders, widened lanes, and slab thickness on measured strains and deflections. The following results were obtained:

1. There was good agreement between measured strains and deflections and those computed by using Westergaard's theoretical equations.
2. The 152-mm (6-in) thick concrete shoulders of the 203- and 229-mm (8- and 9-in) thick highway slabs reduced edge strains by 28 percent.
3. Measured reductions in edge strain are used to demonstrate that the outer lane main-line pavement thickness may be reduced when a tied concrete shoulder is used. As an example, a conventional design of 203-mm (8-in) thickness could be reduced to 168 mm (6.6 in) with the addition of a tied concrete shoulder 152 mm (6 in) thick.

Figure 9. Percentage reductions in strain and deflection attributable to presence of a shoulder (by type of joint).



4. The effectiveness of concrete shoulders in reducing edge deflections was equivalent to increasing slab thickness by 66, 84, and 107 mm (2.6, 3.3, and 4.2 in) for the 203-, 229-, and 254-mm (8-, 9-, and 10-in) pavements respectively.
5. Lane widening was as effective as concrete shoulders in reducing strains and deflections.
6. A 254-mm (10-in) concrete shoulder was only slightly more effective in reducing edge strains and deflections than a 152-mm (6-in) shoulder.
7. Tied and keyed, tied-butt, and keyed joint construction were equally effective in reducing strains and deflections. However, it should be remembered that tied-butt joints might lose some effectiveness with accumulated traffic loadings.
8. In addition to reducing strains and deflections, tied concrete shoulders direct surface runoff away from the pavement edge.

ACKNOWLEDGMENTS

All fieldwork was conducted under a research contract with the Minnesota Department of Transportation. Minnesota Department of Transportation project supervision was provided by F. W. Thorstenson, director of materials, research, and standards; L. E. Warren, chief of concrete engineering; and R. M. Canner, Jr., research planning engineer. Field testing was coordinated by J. C. Hale, senior highway technician for the Minnesota Department of Transportation.

The project was conducted under the guidance of W. Gene Corley, director of engineering, Portland Cement Association. Special thanks are extended to PCA technicians Richard D. Ward and Fred Blaul for conducting the laboratory and field tests.

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Publication of this paper sponsored by Committee on Shoulder Design.