EFFECT OF HIGH TIRE PRESSURES ON CONCRETE PAVEMENT PERFORMANCE

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In recent years, serious pavement damage on major highways throughout the United States and Canada has been attributed to the increased use of trucks equipped with radial tires and high tire pressures. For asphalt pavements, comprehensive research programs are being launched by several agencies to study these effects and to develop improved mixes and materials. The purpose of this study conducted by the Construction Technology Laboratories, Inc. for the Portland Cement Association, is to determine for concrete pavements, how high tire pressures affect pavement response, service life, and performance characteristics. Field testing at six separate sites in the States of Wisconsin and Pennsylvania were conducted to determine the effects of higher pressure. The pavement sections were loaded by single axle and tandem axle load trucks with incremental tire pressures ranging from 80 up to 120 psi. Pavement strains and deflections due to moving loads were measured for trucks placed at different positions on the pavement. Based on field test data and theoretical data developed using the computer program JSLAB, there is no significant effect on concrete pavement response due to increased tire pressure.

Surveys of truck tire pressure in Illinois, Florida, Texas, and Arizona indicate that pressures under operating conditions are considerably higher than those used during the AASHO Road Test. During the time this test was conducted single-axle loads (SAL) of 18 kips and tire pressure of 75 and 80 psi prevailed. Pavement design equations based on AASHO Road Test findings are therefore developed from 18 kip 80 psi contact pressure load equivalence factors (Equivalent Single Axle Load, ESAL). Measured inflation pressures have indicated that average pressures in excess of 100 psi are not uncommon. There are new concerns about tire pressure effects on pavement deterioration rates and the fact that present pavement thickness design procedures do not consider the effects of increased pressure.

The primary criterion in commonly used mechanistic concrete pavement thickness design procedures is flexural fatigue. The allowable number of load repetitions is determined based on the stress ratio (flexural stress divided by the design modulus of rupture). Use of the fatigue criterion is made on Miner's hypothesis that fatigue resistance not consumed by repetitions of one load is reserved for repetitions of additional loads.

Until recently, the primary design criterion used was limiting flexural stresses to provide concrete fatigue resistance for the pavement design life. In addition to flexural fatigue, the current Portland Cement Association (PCA) pavement thickness design procedure considers erosion of subgrade, subbase, and shoulder materials. Power, or rate of work (product of slab-subbase pressure and corner deflection) by which an axle load deflects the slab is considered in determining the required thickness to minimize pumping, subbase (subgrade) erosion, joint faulting, and voids.

Increases in critical edge stresses or corner deflections can reduce pavement design service life. A study sponsored by PCA was conducted to determine, for concrete pavements, how tire pressures affect pavement response, service life, and performance characteristics. This paper addresses current trends in the trucking industry regarding tire type and pressure, analytical research, and field test data on effects of increased tire pressure on concrete pavements.

Research Objectives

Objectives of the study were as follows:

1. Review current trends in the trucking industry regarding tire type and pressure.
2. Review past experimental, theoretical, and field testing research regarding tire/contact pressure.
3. Conduct theoretical analyses of the effects of increased tire pressure on rigid pavement response.
4. Verify analytical research findings by conducting full-scale load testing of pavements.
5. Discuss impact of increased tire pressure on concrete pavement performance and current design procedures.

Background

Several recent surveys have indicated that truck tire inflation pressures are significantly higher than was prevalent when the AASHO Road Test was conducted. For a given load, an increase in tire inflation pressure reduces the net contact area, resulting in an increase in contact pressure. Experimental and analytical research indicates that contact areas are nonuniform with localized areas of high pressure. The contact distribution can change with increases in tire pressure. Commonly used pavement thickness design procedures may not directly incorporate the effects of increasing tire pressure.

Tire Inflation Pressure Surveys

Several surveys have been made to determine the current magnitude, variability, and distribution of truck tire pressure. Recent surveys indicate that average hot tire inflation pressure ranges from 95 to 105 psi, as shown in Table 1. In a 1984 Illinois survey, tire pressures ranged from 72 to 130 psi (1). This is considerably higher than the 75 to 80 psi cold inflation pressure used at the AASHO Road Test. The standard deviation of recent tire pressure surveys typically ranges from 11 to 15 psi for both radial and bias ply tires. Tire pressure is significantly higher for radial than bias ply tires. Surveys indicate that inflation pressure of radial tires on average range from 13 to 20 psi higher than for bias ply tires.

Data from tire pressure surveys and truck tire suppliers indicate that the use of radial tires on long distance carrier trucks exceeds 70%. For radial tires, surveys from Florida, Kentucky, Texas, and Arizona indicate that steering axle tire pressure is on average higher than non-steering axle pressure. Differences in average radial tire pressure of up to 5 psi were noted between steering axles and non-steering axles. The Texas and Arizona surveys found that average pressure on steering axles was slightly higher than rear drive axles which was higher than rear trailer axles. For radial tires the Florida, Texas, and Arizona surveys had slightly lower pressure standard deviations for tractor axles than for trailer axles. Differences in standard deviations were less than 2 psi. Since drivers maintain optimum operating pressures for ride and handling it is expected that tractor axle pressure has lower variability than trailer axle pressure since many truckers do not own the trailers they haul (2). Proper tire inflation increases tread life, evenly distributes loads between dual wheels, provides greater stability, and ensures proper footprint area for traction, braking, and resistance to hydroplaning.

Tires are specified by nominal section width and rim diameter. Tire size designation consists of section width and rim diameter separated by either the letter "R" or symbol "-". The letter "R" designates a radial tire and the symbol "-" a bias ply tire. The section width designation is specified in inches or millimeters and the nominal rim diameter in inches. A third designation number preceded by a dash after the section width is used to indicate a low profile tire. The low profile number is the tire aspect ratio (height to width) expressed as a percentage. Tire designation was recorded in the Arizona tire pressure survey (2). Of the 926 radial tires surveyed, the predominant tire designation was 11R24.5 (55%). Other common designations were 11R22.5, 285/75R24.5, and 275/80R24.5 at 11, 11, and 10% of observations, respectively.

Inflation pressures have increased due to

TABLE 1 Tire Pressure Survey Summary

State	Year	No. of Vehicles	Percent Radial Tires	Radials Average psi	Radials Std. Dev., psi	Bias Ply Average psi	Bias Ply Std. Dev., psi	Overall Average psi	Overall Std. Dev., psi	Ref. No.
Illinois (1)	1984	36	-	-	-	-	-	96	11	1
Montana	1984	-	-	105	-	84	-	-	-	3
Florida (2)	1985	-	-	103	11	88	12	96	11	3
Kentucky (3)	1985	59	74	105	11	90	10	103	13	4
Texas (4)	1986	1033	71	98	14	85	15	94	15	5
Arizona	1986	350	91	103	11	88	11	102	12	2
Oregon	1986	-	-	102	-	82	-	-	-	6
Nationwide (5)	1987	1008	-	-	-	-	-	97	14	7

Note: 1. Rear trailer axle only.
2. Average of steering and non-steering axle statistics for three sites.
3. Standard deviation estimated from grouped data.
4. AASHTO truck classification 3-S2.
5. Statistics estimated from grouped data.

larger allowable axle loads and the shift from the use of bias ply to radial tires, rather than perceived increases in fuel economy. In a 1987 nationwide survey of 1,008 five-axle tractor semitrailer trucks, approximately 56% of the 5,040 tire samples had measured inflation pressures ranging from 90 to 110 psi, as shown in Figure 1. The relative frequency histogram of inflation pressure in Figure 1 appears to follow a normal distribution. The theoretical normal distribution was derived using statistics estimated from grouped data. Approximately 83% had maximum rated tire pressures of 95 to 110 psi. Only 11% and 19% were overinflated or underinflated by more than 10 psi of the maximum specified tire inflation pressure rating, respectively. This survey suggests drivers do not perceive better fuel economy resulting from overinflated tires. Test data suggests that increasing tire inflation pressure by 10 psi would result in a 2-1/2% decrease in rolling resistance. This would theoretically result in less than a 1% decrease fuel consumption (8).

With the implementation of the 1982 Surface Transportation Assistance Act (STAA), the Interstate load limits increased to 20, 34, and 80 kips for single axle, tandem axle, and gross load, respectively. Minimum cold inflation pressures recommended by the Tire and Rim Association, Inc. (TRA) increase with the switch from bias ply to radial tires (for a given load range) and with increased load (9). Recommended inflation pressure for diagonal (bias) ply belted tires is 5 psi lower than radial ply tires for a given tire load.

The effect of axle weight on tire pressures was analyzed for AASHTO classification 3-S2 Trucks in the Texas study (5). A statistically significant increase in pressure was observed for increases in axle load. For both bias ply and radial tires it was found that pressure increased one psi for axle load increases of approximately 1400 lb. Using the linear regression equations developed in the study for radial tires with over a 1/4-in. tread, the expected pressure would be approximately 101 psi for a 34 kip tandem axle load.

For a given load, increases in inflation pressure will reduce the contact area and increase the contact pressure. With increases in tire inflation pressure, there is a need to research their effects on pavement contact pressure, contact area, and thickness design methods.

Review of Research on Tire Contact Pressure and Area

Several studies have been conducted to determine tire contact pressure distributions at different inflation pressures. Without a stiff tire carcass and presence of tread, the contact distribution is uniform and equal to the inflation pressure. The contact area is then equal to the wheel load divided by the inflation pressure. The bending stiffness of the tire structure and tread causes localized areas of high and low contact pressures within the tire footprint. As the inflation pressure and tire load changes, the nonuniform pressure distribution can also change.

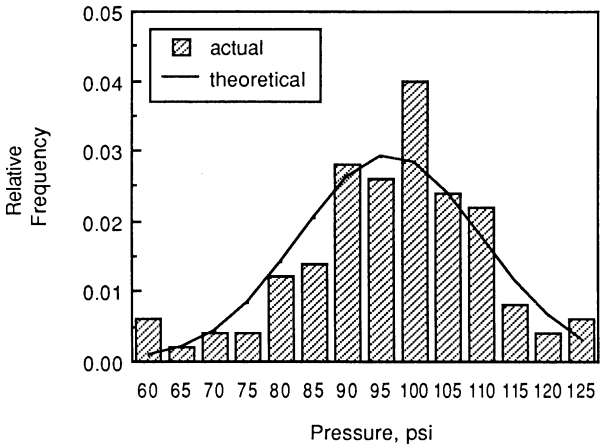

FIGURE 1 Relative Frequency Histogram of Tire Inflation Pressure

An experimental investigation was conducted by the Center for Transportation Research to determine contact areas and pressure distributions of statically loaded track tires for a variety of inflation pressure and wheel load combinations (10). Gross contact areas were determined by first obtaining a statically loaded inked tire print and then using an automatic digitizing imaging system to measure the imprint area. Increasing tire inflation by 50% reduced gross contact areas between 8 and 20%. Contact pressure distributions were determined using a pressure sensitive film with color intensity being proportional to the applied contact pressure and then reading the developed print with a densitometer. Higher localized contact pressure areas were produced near tread gaps and at the tire shoulder. As the inflation pressure increased from 70 to 110 psi (4500 lb load) the high pressure areas shifted from the shoulder toward the center of the decreased contact area. Near the center of the tire contact area pressures were more uniform and closer in magnitude to the inflation pressure. The change in net area does not appear proportional to the change in pressure. The net contact area increased by 4% and decreased by 1% as the inflation pressure changed from 90 psi (rated) to 75 and 110 psi, respectively.

Experimental results of nonuniform contact pressure were also discussed in a recent study on the effects of increased tire pressure on flexible pavement design (2). Contact pressure distribution information from several major tire manufacturers was presented. The rectangular contact area for a statically loaded tire had higher contact pressures near the shoulder than at the center, similar to the Texas study. For a 10.00R20 radial tire inflated to 105 psi, the measured contact pressure was as high as 193 psi in localized areas near the shoulder. Pressure of the 525 reported points ranged from 23 to 193 psi, averaged 112 psi, and had a standard deviation of 28 psi. For a rolling tire, two of the the three pressure

distributions also had higher localized contact pressure at the shoulder while the third was higher at the tread center. For five brands of an 11R24.5 truck tire, the contact area was approximately equal to the tire load divided by the inflation pressure. The net contact area was approximately 75% of the gross contact area.

A finite element tire model, developed for the Federal Highway Administration (FHWA) to investigate tire-pavement interaction has also been used to analytically determine contact pressure distribution (5,11,12,13,). The cord reinforced tire model element can be used to calculate contact pressure within the contact area of a deflected tire. Similar to experimentally derived pressure distribution data, a nonuniform contact distribution occurs with localized areas of high pressure away from the center of the tire. For a 10.00-20 bias ply truck tire inflated to 125 psi (4500 lb tire load) the contact pressure increased as high as 220 psi in localized areas (11).

Both theoretical and experimental research indicate the common assumption of a uniform contact pressure acting over an area equal to the load divided by the inflation pressure is not valid. Localized areas of higher pressure are present within the contact area. The pressure distribution can be dependent on the tire structure, inflation pressure, load, and vehicle speed. The effects of nonuniform contact pressure distribution and increased tire pressure on concrete pavement response, service life, and mechanistic design procedures are addressed in this paper.

Analysis of Nonuniform Pressure Distribution

To analytically evaluate the effects of tire pressure on pavement response it has generally been assumed in the past that inflation pressure is equal to the tire-pavement contact pressure. An air spring model relationship is commonly assumed in analyzing pavement response where tire (contact) pressure increases are offset by decreases in contact area for a given wheel load. The loaded area is commonly assumed to be equal to the wheel load divided by tire inflation pressure. Longitudinal shear stresses, transverse shear stresses, and pavement friction effects are assumed minimal and are usually not directly factored into analytical rigid pavement models.

Effects of Nonuniform Contact Pressure

Program JSLAB, developed by the Construction Technology Laboratories, Inc. (CTL) for the FHWA, can analyze a large number of jointed slabs (14). Joints can be modeled as doweled, aggregate interlock, or keyed. Load is input in terms of load or pressure at any location on the slabs. Loss of support, variable support, or material properties can be considered. The subbase/subgrade support is characterized by the modulus of subgrade support.

An analysis was first done using JSLAB to determine the effects of nonuniform pressure and the presence of tire treads on pavement response. Stresses and deflections were computed for a single wheel positioned along the longitudinal edge and at the corner of a slab 15 ft long and 12 ft wide. Slab thickness in this analysis was 6, 8, 10, and 12 in. The modulus of subgrade reaction was 300 pci and concrete modulus of elasticity 5,000,000 psi. The nonuniform contact pressure distribution used is the one reported in a rigid pavement analysis done by the Center for Transportation Research at Austin. The pressure array and 63.6 sq in. contact area is an approximation to a distribution which was experimentally measured for a tire load of 4500 lb and inflation pressure of 110 psi, as shown in Figure 2 (15).

Pavement response was theoretically computed for a single load of 5941 lb distributed as follows:

1. Nonuniformly over gross area of 63.6 sq. in. (net area of 58.2 sq. in.)
2. Uniformly over net area of 58.2 sq. in.
3. Uniformly over gross area of 63.6 sq. in.
4. Uniformly over net area of 49.0 sq. in.

For the fourth condition of uniformly distributed load over a net area of 49.0 sq in., the contact area was modified. Three additional tread areas 0.4-in. wide were placed at the center and two edges of the middle row of elements shown in Figure 2. This reduced the net contact area to 77% of the gross area. This ratio of net to gross static loaded area is similar to reported values (2).

Maximum edge stresses and deflections for the four loading conditions are found in Table 2. There is no significant difference in pavement response between the nonuniform pressure and uniform pressure net area distribution. The change in stress and deflection is less than 2% and 1%, respectively. Similarly, there is no significant difference between the uniform pressure distributed over the gross and net contact areas. There is less than a 1% difference between maximum edge stresses and deflections. The addition of three extra tread areas does not affect maximum stresses or deflections. The reduced net area changes stresses and deflections less than 1% when compared to the uniformly loaded net area case with only two tread areas.

Maximum stresses and deflections were also computed for the four loading conditions using a single wheel load located at the slab corner. There is no difference in corner deflections and top tensile stress between all four loading conditions. There is less than a 6% increase in maximum bottom tensile stress. However, the bottom tensile stress is significantly smaller than the top tensile stress, averaging approximately 70% of the top tensile stress for the free corner loading condition.

Based on JSLAB analysis it appears that the presence of a nonuniform pressure distribution does not significantly differ in maximum stress or deflection when compared to the same load uniformly distributed over either the net or gross area. There is also no difference in edge or corner pavement response when the load is uniformly distributed over the reduced net contact area. Therefore the presence or absence of tire tread does not influence theoretical stresses or

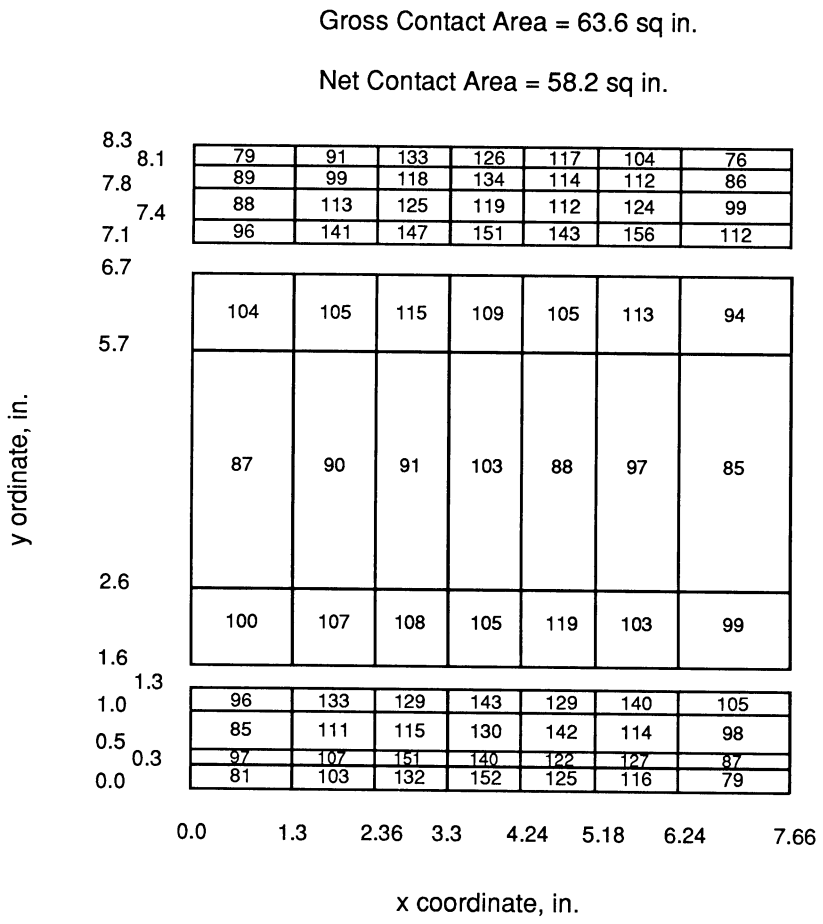

FIGURE 2 Nonuniform Contact Pressure Distribution, ref. 15

deflections computed using JSLAB. Plots of stress and deflection profiles for both the edge and corner load positions are not significantly different for the four loading conditions analyzed.

Theoretical Effects of Increased Contact Pressure

The effects of changing tire pressure were analytically investigated using JSLAB. Data on 11R24.5 tires suggest the inflation pressure is approximately equal to the load divided by the net contact area (2). Since there is no significant difference using JSLAB when compared to a load nonuniformly distributed over the net contact area, a load uniformly distributed over a gross contact area was used in the analysis.

A static footprint of an 11R24.5 tire indicates the contact area is more rectangular than circular and is approximately 7.7-in. wide by 9.8-in. long (2). A uniformly loaded contact area with an aspect ratio (width to length) of 0.8 was selected and maintained in the JSLAB analysis. As pressure increased, the load and aspect ratio remained constant but the contact area was decreased. Gross contact areas were 70.5, 63.2, and 56.3 sq.in. representing areas at 80, 100, and 120 psi inflation pressure. Areas were interpreted from experimental data of gross contact areas and inflation pressure at a tire load of 6040 lb (rated load) (10). Gross contact areas at different inflation pressures measured for a 11R22.5 tire indicate that for a given load, the change in area does not decrease proportionally with pressure. The 6040 lb tire load was uniformly distributed over the gross contact area.

A dual wheel (single axle load) at the edge and a pair of dual wheels (tandem axle load) at a corner of a 15-ft long by 12-ft wide slab were analyzed using JSLAB for changing contact pressure, slab thickness, and subgrade support. The single axle edge load and tandem axle corner load give critical maximum edge stress and corner/joint deflection, respectively. A full parametric study of stress and deflection was done with slab thickness of 6, 8, 10, and 12 in. and subgrade support of 100, 300, and 500 pci. Concrete modu-

TABLE 2 JSLAB Edge Stress and Deflection at Different Load Conditions

Load Condition	Slab Thickness, in.	Maximum Bottom Tensile Stress, psi	Deflection, in.	Percent Difference from Nonuniform Pressure Stress	Deflection
Nonuniformly Loaded	6	396	0.0135	-	-
	8	248	0.0093	-	-
	10	172	0.0070	-	-
	12	126	0.0056	-	-
Uniformly Loaded Net Area 58.2 sq in. Pressure102.0 psi	6	389	0.0135	-1.7	-0.1
	8	244	0.0092	-1.5	-0.1
	10	169	0.0070	-1.4	0
	12	124	0.0056	-1.4	0
Uniformly Loaded Gross Area 63.6 sq in. Pressure 93.4 psi	6	388	0.0134	-1.9	-0.2
	8	244	0.0092	-1.7	-0.2
	10	169	0.0070	-1.6	-0.3
	12	124	0.0056	-1.5	-0.2
Uniformly Loaded Net Area 49.0 sq in. Pressure121.2 psi	6	391	0.0135	-1.2	-0.1
	8	246	0.0092	-1.1	-0.1
	10	170	0.0070	-1.0	-0.1
	12	125	0.0056	-1.0	0

Note: Total load 5941 lb, modulus of subgrade reaction 300 pci

lus of elasticity was 5,000,000 psi. The centroid of the loaded areas were maintained at 3.75 and 15.75 in. from edge of the slab for the dual wheels (12 in. spacing). For slabs loaded at the slab corner the centroid of the wheels were also positioned at a constant 4.7 in. from the joint. Tandem axle spacing was 50 in.

Stresses and deflections for loads positioned at the pavement edge are listed in Table 3. As pressure increased the maximum edge stress slightly increased. Larger percentage increases with pressure were observed for the thinner slabs. As slab thickness increased the change in stress decreased. For a given slab thickness, larger percentage increases in stress result as the subgrade support increases from 100 to 500 pci. The largest percentage change occurred for the 6-in. slab and subgrade reaction of 500 pci. A 2.9% change occurs as contact pressure increased from 80 to 120 psi. The smallest percentage increase occurred for the 12-in. slab and subgrade reaction of 100. A 1.9% increase in maximum edge stress occurred as the pressure was increased from 80 to 120 psi. Overall the average maximum edge stress and edge deflection increased 2.3 and 0.1% as contact pressure increased from 80 to 120 psi, respectively.

Pavement response was also computed for the outside set of dual wheels of a tandem axle load positioned at the slab corner. No significant changes in maximum top tensile stresses (between the two axles) or corner deflections were noted as contact pressure varied from 80 to 120 psi. Changes observed were less than one percent as contact pressure increased from 80 to 120 psi.

The theoretical effects of increased tire pressure on corner deflections and subgrade stress are negligible for subgrade support values between 100 and 500 pci and slab thicknesses between 6 and 12 in. There is a small increase in maximum edge stress as contact pressures increased to 120 psi. The increase in stress theoretically is less than 3% over the range of support and thickness values used in the analysis.

Field Tests

A field testing program was conducted at six sites in 1988 to check results of the theoretical analysis of the effects of increased tire pressure on concrete pavement performance. The theoretical analysis using the finite-element program JSLAB suggested that tire pressure has no effect on corner deflections and a small increase (average of 2.3%) in maximum edge stresses. Sites were instrumented to measure load induced strains and deflections at critical slab locations.

Pavement Test Sections

Field measurements were obtained at three pavement sites in Wisconsin and three sites in Pennsylvania. A brief description of each project follows:

TABLE 3 JSLAB Edge Stress and Deflection at Increased Contact Pressure

Subgrade Support, pci	Slab Thickness, in.	80 psi Inflation Pressure 70.5 sq in. Contact Area 85.7 psi Contact Pressure		100 psi Inflation Pressure 63.2 sq in. Contact Area 95.6 psi Contact Pressure		120 psi Inflation Pressure 56.3 sq in. Contact Area 107.3 psi Contact Pressure	
		Edge Stress, psi	Edge Deflection, in.	Change in Stress from 80 psi, percent	Change in Deflection from 80 psi, percent	Change in Stress from 80 psi, percent	Change in Deflection from 80 psi, percent
100	6	681	0.0439	1.0	0.0	2.0	0.1
	8	430	0.0319	0.9	0.2	2.1	0.2
	10	295	0.0258	0.8	0.0	2.0	0.0
	12	214	0.0225	0.8	0.0	1.9	0.0
300	6	571	0.0225	1.2	0.1	2.7	0.1
	8	370	0.0161	1.1	0.0	2.4	0.1
	10	261	0.0124	0.9	0.1	2.2	0.1
	12	194	0.0102	0.9	0.0	2.1	0.1
500	6	523	0.0164	1.3	0.0	2.9	0.1
	8	341	0.0118	1.1	0.0	2.6	0.0
	10	242	0.0091	1.0	0.0	2.3	0.0
	12	182	0.0074	0.9	0.0	2.2	0.0
			Average	1.0	0.0	2.3	0.1

Note: Contact areas experimentally determined for tire load of 6040 lb, ref. 10.

Site 1 - State of Wisconsin

Designation State Project No. I94-3(41) 243 is a truck weigh station located east of Madison, WI on Interstate 94 between Highway N and Route 73. The pavement is a 33-ft wide roadway consisting of a 16-ft wide outside lane, a 14-ft wide inside lane, and a 3-ft wide outside shoulder. The pavement is 9-in. thick reinforced concrete slabs placed over a 6-in. crushed stone base course and 9-in. granular subbase. Reinforcement consists of No. 3 bars spaced at intervals of 1 ft each direction. The asphalt concrete shoulder is 3-in. thick placed over the base and subbase. Transverse joints are spaced at 80-ft. Testing was done along an access road adjacent to a parking area. Transverse crack spacing in this area ranged from 11 to 24 ft and averaged 16 ft. Slabs selected for instrumentation were located in the outside lane between Station 12+54 and Station 15+62.

Site 2 - State of Wisconsin

Designation State Project No. 1111-3-81 is a bypass section located northeast of Madison, WI near Columbus, on U.S. Highway 151. The pavement is a 40-ft wide roadway consisting of two 12-ft wide lanes and two 8-ft wide shoulders. The 8-in. thick pavement is continuously reinforced with No. 6 bars spaced at 9 in. on center in the longitudinal direction and either No. 4 bars spaced at 3 ft or No. 5 bars spaced at 4 ft in the transverse direction. The pavement was placed on a 6-in. granular subbase. The 8-ft wide asphalt concrete shoulders are 3-in. thick. Areas selected for testing were located in the outside westbound lane stub-end area approximately 70 to 130 ft from the pavement terminal edge. Transverse crack spacing ranged from approximately 2 to 10 ft and averaged 5-1/2 ft in the test area. Crack widths typically ranged from 0.007 to 0.020 in. at the time of testing.

Site 3 - State of Wisconsin

Designation State Project No. 5310-0-72 is an unreinforced concrete pavement section of U.S. Highway 14 located just west of U.S. Highway 12 near the west end of Madison, WI. The highway is a divided section consisting of a 35-ft wide section in each direction. The section consists of two 12-ft wide lanes, an 8-ft wide outside shoulder and 3-ft wide inside shoulder. The 9-in. thick pavement was placed over a 6-in. crushed aggregate base course. The 4-in. thick recycled asphalt concrete shoulders were also placed over a crushed aggregate base course. Joints are skewed at 20 ft intervals. The area instrumented was located approximately one mile west of U.S. Highway 12 in the outside eastbound lane. The

approximately one year old pavement had no visible cracking or concrete deterioration in the area instrumented.

Site 4 and Site 5 - Commonwealth of Pennsylvania

Designated Pennsylvania Project L.R. 1061-Southbound is an unreinforced concrete pavement section located approximately 10 miles southwest of Altoona, PA in Blair County on U.S. 220. The highway is a divided section 38-ft wide consisting of two 12-ft wide lanes, a 10-ft wide outside shoulder, and a 4-ft wide inside shoulder. The 11-in. thick concrete pavement was placed over a 4-in. open graded and 5-in. granular subbase. The concrete shoulders are also 11-in. thick placed over a prepared subbase. Transverse skewed joints are spaced at 20-ft with 1-1/2-in. diameter dowels spaced at 12 in.

Slabs selected for testing at Site 4 were in the inside (passing) lane between Station 1177+10 and Station 1177+50. Slabs instrumented at Site 5 were in the outside (truck) lane between Station 1176+50 and Station 1176+90. Constructed in 1988 and not yet opened to traffic, the instrumented sections had no visible cracking or concrete deterioration in the areas instrumented.

Site 6 - Commonwealth of Pennsylvania

This site is located in the existing U.S. 220 southbound lanes. The highway is also a 38-ft wide divided section consisting of two 12-ft wide lanes, a 10-ft wide outside shoulder, and a 4-ft wide inside shoulder. The 10-in. thick concrete pavement is reinforced with wire mesh and placed over a 10 to 11-in. granular subbase. Asphalt shoulders in the area selected for load testing were approximately 4 to 8-in. thick placed over a prepared granular base. Right angle transverse joints are spaced at 40 ft. Constructed in the mid-1970's the reinforced slabs have numerous cracks in the area selected for testing. Average crack spacing was 10 ft and crack width at the time of testing ranged from 0.010 to 0.020 in. Slabs instrumented for testing were located in the outside southbound lane between Station 1175+50 and Station 1176+30.

Instrumentation

All six test sites were instrumented to measure load induced strains and deflections. Locations were selected to obtain the maximum values of load induced strain and deflection for three different load positions (interior, edge, and corner). In addition, air temperature, concrete temperature (top and bottom of slab), and slab curl were monitored with respect to time. Curl is the change in the vertical profile of the slab resulting from a differential change in the slab temperature (slab top and bottom).

Load induced strains were measured with 120mm-long electrical-resistant strain gages bonded to the pavement surface. Gages were placed at 2 in. and 18 in. from the slab edge located approximately halfway between cracks and/or joints to obtain maximum load induced edge and interior strains. For Site 2 strain gages were also placed transverse to direction of traffic 18, 30, and 42-in. from the edge. All gages were placed in recessed grooves to protect them from direct application of wheel loads.

Deflections were measured with resistance-bridge deflectometers attached to the pavement surface. The deflectometers were bolted to the surface or side of the pavement in areas where the shoulder was removed, except for Site 3 where the deflectometers were mounted in core holes located near the pavement edge. Deflection readings were referenced to encased rods driven in the subgrade to a depth of 6 ft.

Data were monitored and recorded with equipment carried in Construction Technology Laboratories' field instrumentation van. Strain and deflection data were recorded with a high-speed computer-based data acquisition system. Up to fourteen channels of instrumentation were monitored and recorded simultaneously for each vehicle loading. Computer programs were written to monitor, record, and tabulate all field data. All analog data from strain gages and deflectometers were digitized and stored on the computer hard disk. Readings from each item of instrumentation were digitized simultaneously at the rate of approximately 200 points per second. Detailed loading curves for each strain gage and deflectometer were stored on the computer hard disk for future examination.

Core Testing

The installation of deflectometers used to measure slab deflections required coring 4-in. nominal diameter holes along the pavement edge at Site 3 and in the concrete shoulder at Sites 4 and 5. Cores were later taken from Sites 1 and 2 after load testing. No cores were recovered at Site 6. The recovered cores were used to determine compressive strength and modulus of elasticity.

Average compressive strength at Sites 1 thru 5 ranged from 5250 to 8160 psi. Modulus of elasticity was measured for one core at Sites 1, 4, and 5. Modulus values for other cores were estimated from core compressive strengths. Average modulus of elasticity ranged from 4.15 to 5.30 million psi.

Load Testing

Loading for Sites 1 to 3 was applied using two trucks loaded with sand supplied by Dane County. For Sites 4 thru 6 two trucks were supplied by the Pennsylvania Department of Transportation. One truck was loaded to provide a 20-kip nominal single-axle load (SAL). The second truck was loaded to provide a 34-kip nominal tandem-axle load (TAL) for Sites 1 thru 3 and 42-kip nominal TAL for Sites 4 thru 6. Characteristics of the four trucks are given in Table 4.

Load testing in Wisconsin at Sites 1, 2, and 3 was done on June 29 and 30, 1988. In Pennsylvania at Sites 4, 5, and 6 testing was done on December 7, 1988. Testing at each site took less than two hours. Specific testing times were governed by preparation times required at each test site.

TABLE 4 Load Truck Characteristics

Item	Wisconsin Sites 1,2, and 3 20-kip SAL	Wisconsin Sites 1,2, and 3 34-kip TAL	Pennsylvania Sites 4,5, and 6 20-kip SAL	Pennsylvania Sites 4,5, and 6 42-kip TAL
Gross Weight, lb	30,660	47,720	33,650	57,050
Front-Axle Load, lb	10,820	13,940	10,000	14,150
Rear-Axle Load, lb	19,840	33,780	23,650	42,900
Dual Wheel Spacing, in.	13.5	13.5	11.0	12.0
Tandem-Axle Base, in.	-	54	-	50
Rear-Axle Track, in. (c.c. of duals)	72	72	61	66
Tire Manufacturer	Goodyear	Goodyear	General	Goodyear
Tire Construction	Radial	Radial	Bias	Bias
Tire Designation	11R22.5	11R22.5	11.00-20	11.00-20

Strains and deflections were continuously recorded for the single-axle and tandem-axle loadings with the trucks moving at creep speed. Two different wheel paths were used. For the first wheel path, tire placement was at 2 in. from the lane edge (edge loading condition). For the second wheel path, tire placement was at 18 in. from the lane edge (interior loading condition). The tire placement distance is defined as the distance from the lane edge to the outside edge of the tire sidewall. To ensure that wheel paths of the truck coincided with the desired paths painted on the pavement, the trucks were continuously guided during creep loadings.

For Sites 1, 2, and 3 rear axle tires were initially inflated to 120 psi prior to testing. One pass at each of two wheel paths for both trucks was then made. After the passes were completed the pressure was reduced in all rear tires to 100 psi. The procedure was then repeated. The final series of load tests were done at tire inflation pressures of 80 psi. The same procedure was followed for Sites 4, 5, and 6 at tire inflation pressures of 110, 95, and 80 psi. Passes were repeated to obtain representative data. Pavement temperature, edge curl, and corner curl were measured at intervals of approximately 30 minutes during load testing at each site.

At Site 3 tire contact areas were obtained at each of the three tire inflation pressures. Imprints were made by placing kraft paper in front of the rear axle. The outside set of dual tires were coated with motor oil. The trucks then slowly crept forward onto the paper. The centerline of the wheelprint was carefully determined by marking the longitudinal position of the axle on the paper. Finally the trucks were backed slowly off the paper transferring the oil and leaving an imprint of contact area.

Data Analysis

This section presents a summary of pavement response measured at the six sites. Pavement responses reported at different inflation pressures were measured under 20-kip SAL (Sites 1 thru 6), 34-kip TAL (Sites 1 thru 3), and 42-kip TAL (Sites 4 thru 6). Reported values of maximum edge strains and corner deflections, summarized in Tables 5 through 9, are averages of multiple passes and any replicated instrumentation at each section instrumented.

The slab temperature differential (slab top minus bottom) at all six sites averaged 4°F and was less than 6°F during period of testing. The effects on edge and corner curl due to changing slab temperature differentials is therefore relatively small. Edge and corner curl changes for Sites 1, 2, 4, 5, and 6 average 0.004 and were less than 0.005 in., and for Site 3 less than 0.015 in. Since the change in curl for sites 1, 2, 4, 5, and 6 are relatively minor and the effects of curl on strain are affected to a lower degree than deflection, no adjustment was made to reported values of strain and deflection. Effects of curl on Site 3 deflections are addressed later. Also, since the sites are considered independent from one another and only the relative effects of changing pressure was analyzed, no curling adjustments are necessary.

The reported strains are those measured at the surface. It is assumed that strains at the slab bottom are equal in magnitude but opposite in sign. Thus, a reported value of 20 millionths compressive strain (positive value) at the slab surface would imply a 20 millionths tensile strain at the slab bottom.

At Sites 4, 5, and 6 approximately half of the deflection measurements are not reported due to difficulties in setting the encased referenced rods. To measure absolute deflections the rods ideally should be driven in the subgrade to a depth of six feet. At this depth the applied loads do not influence the encased rod. Large boulders were hit both during augering holes for encasements and when rods were driven into the subgrade.

For all six sites the measured edge strain for both the 2-in. and 18-in. wheel paths do not change significantly with increasing the pressure. The difference in measured strain is generally less than 3 millionths for the three tire pressures. The precision of the strain gages and data acquisition system is approximately plus or minus one millionth.

Similar to edge strain response to increased inflation pressure, edge deflection did not change significantly. The difference in measured deflection was averaged less than 0.001 in. and generally was less than 0.002 in. for the six sites.

For Sites 1, 4, 5, and 6 increasing tire pressure did not result in an increase in maximum corner deflection. Differences in deflection were generally less than 0.002 in. and averaged less than 0.001 in. Precision of the deflectometers is approximately plus or minus 0.0005 in.

For Site 3 increases in corner deflection of up to 0.005 in. were measured. Largest increases were measured at the 2-in. wheel path for both the SAL and TAL. The difference may be due to the change in curl during load testing. The largest change in curl was measured at Site 3. Testing at this site was started early in the morning when the slabs were curled upward from their warped shape. Load tests at decreasing tire pressure were conducted as the slabs curled downward at the corners due to increasing mid-morning air temperature. As the slabs curled downward, subgrade support starts to recover causing a decrease in measured deflection. Since the other sites showed no significant deflection increase due to increased pressure, the change at Site 3 was attributed to curling rather than pressure effects.

The contact areas, determined from oil imprints at Site 3 indicated that the gross contact area decreased slightly with increased inflation pressure. Imprints indicated that the 11R22.5 radial tire contact area is rectangular. The TAL imprint exhibited a more rounded leading edge than the SAL. Areas were determined by measuring gross tire width and average length of imprint. As the tire increased in pressure from 80 to 120 psi, the gross contact area decreased 7 and 11% for the SAL and TAL, respectively. These results are consistent to laboratory investigations where decreases between 8 and 20% were measured for a 50% increase in inflation pressure. No significant change in area was observed as pressure increased from 80 to 100 and 100 to 120 psi for the SAL and TAL, respectively.

Application of Study Results

The observed changes in edge strain do not

TABLE 5 Pavement Response at Site 1

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta. 14+90	Sta. 15+70	Ave.	Edge Deflection, in. Sta. 14+97	Sta. 15+83	Ave.	Corner Deflection, in. Sta. 14+90	Sta. 15+70	Ave.
20 kip SAL	2	80	39	37	38	0.014	0.011	0.012	ND	0.016	-
		100	39	37	38	0.014	0.011	0.013	ND	0.015	-
		120	39	39	39	0.014	0.012	0.013	ND	0.015	-
	18	80	24	21	23	0.009	ND	-	ND	0.008	-
		100	23	24	23	0.009	0.006	0.007	ND	0.008	-
		120	25	24	24	0.008	0.006	0.007	ND	0.009	-
34 kip TAL	2	80	29	27	28	0.017	0.013	0.015	ND	0.017	-
		100	30	28	29	0.018	0.014	0.016	ND	0.017	-
		120	28	29	28	0.018	0.014	0.016	0.020	0.020	0.020
	18	80	18	21	19	0.012	0.007	0.010	ND	0.010	-
		100	21	19	20	0.012	0.008	0.010	ND	0.009	-
		120	18	18	18	0.011	0.008	0.010	ND	0.011	-

Note: Strains at Sta. 14+90 are average values measured at Sta. 14+83 and Sta. 14+97.
Strains at Sta. 15+70 are average values measured at Sta. 15+62 and Sta. 15+83.

Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with deflectometers.

TABLE 6 Pavement Response at Site 2

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta. 0+70	Sta. 1+21	Ave.	Edge Deflection, in. Sta. 0+71	Sta. 1+04	Sta Sta 1+18	Ave.
20 kip SAL	2	80	33	26	30	0.003	0.016	ND	-
		100	38	29	34	0.004	0.015	0.005	0.008
		120	33	ND	-	0.005	0.015	0.005	0.008
	18	80	25	ND	-	0.003	0.010	ND	-
		100	24	ND	-	0.004	0.010	0.004	0.006
		120	25	ND	-	0.003	0.008	0.003	0.005
34 kip TAL	2	80	23	18	21	0.006	0.019	ND	-
		100	23	22	23	0.006	0.018	0.007	0.010
		120	21	19	20	0.008	0.017	0.007	0.011
	18	80	18	ND	-	0.002	0.013	ND	-
		100	16	ND	-	0.003	0.013	0.007	0.007
		120	18	ND	-	0.003	0.012	0.005	0.007

Note: No deflection data available at Sta. 00+92 due to problems with deflectometer.

Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with instrumentation.

TABLE 7 Pavement Response at Site 3

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta. 0+11	Sta. 0+52	Ave.	Edge Deflection, in. Sta. 0+11	Sta. 0+52	Ave.	Corner Deflection, in. Sta. 14+90	Sta. 15+70	Ave.
20 kip SAL	2	80	34	32	33	ND	0.013	-	ND	0.008	-
		100	33	31	32	ND	0.013	-	ND	0.010	-
		120	34	29	31	ND	ND	-	ND	0.012	-
	18	80	24	20	22	ND	0.008	-	ND	0.005	-
		100	25	21	24	ND	0.009	-	ND	0.007	-
		120	25	17	22	ND	ND	-	ND	0.007	-
34 kip TAL	2	80	25	23	24	ND	0.016	-	ND	0.009	-
		100	24	24	24	ND	0.017	-	ND	0.011	-
		120	25	25	25	ND	ND	-	ND	0.014	-
	18	80	20	20	20	ND	0.010	-	ND	0.005	-
		100	20	19	20	ND	0.011	-	ND	0.007	-
		120	21	20	20	ND	ND	-	ND	0.009	-

Note: Strains at Sta. 00+11 are average values measured at Sta. 00+08 and Sta. 00+13.
Strains at Sta. 00+52 are average values measured at Sta. 00+50 and Sta. 00+54.

Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with deflectometers.

TABLE 8 Pavement Response at Site 4

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta. 1177+20	Sta. 1177+40	Ave.	Edge Deflection, in. Sta. 1177+20	Sta. 1177+40	Ave.	Corner Deflection, in. Sta. 1177+29	Sta. 1177+31	Ave.
20 kip SAL	2	80	ND	ND	-	0.001	ND	-	ND	0.003	-
		95	ND	11	-	0.001	ND	-	ND	0.003	-
		110	ND	12	-	0.001	ND	-	ND	0.004	-
	18	80	11	ND	-	0.001	ND	-	ND	0.001	-
		95	10	ND	-	0.001	ND	-	ND	0.002	-
		110	11	ND	-	0.001	ND	-	ND	0.002	-
42 kip TAL	2	80	ND	7	-	0.001	ND	-	ND	0.003	-
		95	ND	7	-	0.001	ND	-	ND	0.003	-
		110	ND	7	-	0.001	ND	-	ND	0.003	-
	18	80	8	ND	-	0.001	ND	-	ND	0.001	-
		95	8	ND	-	0.001	ND	-	ND	0.002	-
		110	8	ND	-	0.001	ND	-	ND	0.002	-

Note: Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with instrumentation.

TABLE 9 Pavement Response at Site 5

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta. 1176+55	Sta. 1176+75	Ave.	Edge Deflection, in. Sta. 1176+55	Sta. 1176+75	Ave.	Corner Deflection, in. Sta. 1176+64	Sta. 1176+66	Ave.
20 kip SAL	2	80	18	19	18	0.001	0.001	0.001	ND	0.004	-
		95	17	20	19	ND	0.002	-	ND	0.005	-
		110	18	20	19	ND	0.002	-	0.006	0.005	0.005
	18	80	12	13	13	ND	ND	-	ND	0.003	-
		95	14	14	14	ND	0.002	-	ND	0.003	-
		110	14	13	13	ND	0.001	-	ND	0.004	-
42 kip TAL	2	80	15	14	15	ND	0.002	-	ND	0.004	-
		95	15	15	15	0.002	0.002	0.002	ND	0.004	-
		110	15	15	15	ND	0.003	-	ND	0.005	-
	18	80	12	10	11	ND	0.001	-	ND	0.003	-
		95	10	10	10	0.001	0.001	0.001	ND	0.003	-
		110	11	10	11	ND	0.001	-	ND	0.004	-

Note: Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with deflectometers.

TABLE 10 Pavement Response at Site 6

Axle Load	Wheel Path, in.	Tire Pressure, psi	Edge Strain, millionths Sta 1175+70	Sta 1176+10	Ave.	Edge Deflection, in. Sta 1175+70	Sta 1176+10	Ave.	Corner Deflection, in. Sta 1175+70	Sta 1176+10	Ave.
20 kip SAL	2	80	18	28	24	ND	0.003	-	ND	0.004	-
		95	19	30	24	ND	0.004	-	ND	0.004	-
		110	17	29	23	ND	0.003	-	ND	0.005	-
	18	80	17	12	14	ND	0.002	-	ND	ND	-
		95	18	13	15	ND	0.002	-	ND	0.003	-
		110	17	13	15	ND	0.002	-	ND	0.003	-
								-			-
42 kip TAL	2	80	18	21	19	ND	0.004	-	ND	0.005	-
		95	ND	19	-	ND	0.004	-	ND	0.005	-
		110	19	21	19	ND	0.004	-	ND	0.005	-
	18	80	14	10	12	ND	0.003	-	ND	0.003	-
		95	ND	11	-	ND	0.002	-	ND	0.003	-
		110	12	11	11	ND	0.003	-	ND	0.003	-

Note: Strain values for 18 in. wheel path are those measured 18 in. from edge.
For 18 in. wheel path, strain 18 in. from edge is larger than that measured at 2 in.

ND indicates that no data are available due to problems with instrumentation.

consistently change with increasing tire pressure. Although the theoretical analysis showed a very slight increase in edge stresses due to higher tire pressures, this effect is not borne out by the field measurements.

The PCA design method also considers corner slab deflection in an erosion analysis (16). Previous mechanistic design procedures for concrete pavements are based on the principle of limiting the flexural stresses in a slab to safe values. This is done to avoid flexural fatigue cracks due to load repetitions. Many repetitions of heavy axle loads at slab corners and edges cause pumping; erosion of subgrade, subbase, and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints, especially in pavements with undoweled joints. These particular pavement distresses are considered to be more closely related to pavement deflections than to flexural stresses. Power, or rate of work, with which an axle load deflects the slab is the parameter used for the erosion criterion -- for a unit area, the product of pressure and deflection divided by a measure of the length of the deflection basin (radius of relative stiffness, in inches). The concept is that a thin pavement with its shorter deflection basin receives a faster load punch than a thicker slab. That is, at equal pressure, deflection, and truck speed, the thinner slab is subjected to a faster rate of work or power (inch-pound per second).

The observed changes of corner deflection (edge deflection at Site 2) are generally within the 0.0005 in. precision of the deflectometers. Increases in deflection with tire pressure at Site 3 were attributed to curling effects. The changes in measured corner deflection averaged 0.0005 in. for the remaining five sites as pressure increased from 80 to 110 (or 120) psi.

There is no significant change in measured edge stresses or corner deflection with increased tire pressure up to 120 psi. Most measured differences in strain or deflection with tire pressure can be attributed to instrumentation precision.

Both field test and theoretical data suggest that the current PCA thickness design procedure does not have to be modified to account for tire pressure effects on pavement service life.

SUMMARY

Increases in tire inflation pressure have recently resulted in studies researching inflation effects on tire contact areas, contact pressure, pavement damage, and thickness design. Tire pressure surveys indicate that long distance carrier trucks are rapidly switching from bias ply to radial ply tires. Recommended tire inflation pressure for a given tire load are up to 50 psi higher for radial than bias ply tires. Several research studies have shown that the contact pressure is not uniform, as commonly assumed, and can change with increasing inflation pressure.

The effects of increasing pressure were investigated using the finite element program JSLAB. On average the maximum edge stress and corner deflection increased 2.3 and 0.1%, respectively, as contact pressure increased from 80 to 120 psi. Slab thickness ranged from 6 to 12 in. with subgrade support of 100 to 500 pci.

To check the results of the theoretical analysis a field testing program was conducted at six sites in the States of Wisconsin and Pennsylvania. Critical edge strains, edge deflections, and corner deflections were continuously recorded for a SAL and TAL moving at creep speed. Tire inflation pressure was varied between 80 and up to 120 psi. Results indicate that there is no measurably consistent increase in maximum edge strain or corner deflection with increase in tire pressure.

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