

Effect of Tire Pressure and Type on Response of Flexible Pavement

PETER SEBAALY AND NADER TABATABAEE

Radial, bias, and wide-base radial single tires were tested in the laboratory under three levels of inflation pressures and axle loads. The measured characteristics of the tires were gross contact area, net contact area, tire deflection, and contact pressures. Distributions of the contact pressures were used in a mechanistic solution to predict various flexible pavement response parameters. A modified version of the BISAR computer program, which takes concentric circles of various pressures, was used to predict the response parameters. The response of various flexible pavement structures was investigated in terms of the tensile strains at the bottom of the asphalt layer, the compressive stress at the asphalt layer interface, and the surface deflection. The effects of tire inflation pressures and axle loads on the response parameters were evaluated for all tires and asphalt thickness combinations. The three tire types were also compared for underloaded, loaded, and overloaded cases.

During the past 20 years, truck tire pressures have increased. Today a majority of the trucking industry runs tires at pressures around 100 psi, up from 75 psi (1). A motive for this trend toward increased tire pressures can be found in the economics critical to the highly competitive trucking industry: load capacity, fuel economy, and durability.

However, tire selection and inflation pressures may have an impact on pavement response and long-term performance. Therefore, the pavement community and vehicle and tire manufacturers should cooperate to handle these sometimes conflicting needs in the most effective and practical way. Communication is essential to ensure that pavement design technology is based on realistic field parameters.

BACKGROUND

Several investigators have performed limited studies on the effect of tire inflation pressure on pavement. Roberts et al. (2) used the Tielking finite element model (3) to calculate the pressure distribution at the contact patch. For a common 10.00-20 bias-ply truck tire inflated to 75 and 125 psi, the highest local contact pressures were estimated to be twice the inflation pressures.

Their study concluded that an increase in tire inflation pressure from 75 to 125 psi produced an increase in the tensile strain ranging from 20 to 30 percent for the 1-in. surface. The stiffest base layer caused the greatest increase in tensile strain at the bottom of asphalt. Increasing the thickness of the asphalt concrete layer reduced pavement vulnerability to high tire pressures. The increase in tensile strain at the bottom of a 4-

in.-thick asphalt concrete layer for tire pressure of 125 psi was less than 10 percent, as compared to the strains under 75 psi inflation pressure (2). The study also compared calculated pavement strain for a uniformly distributed tire contact pressure (equal to tire inflation pressure) to a nonuniformly distributed one (2). The uniform contact pressure underestimated the tensile strains at the bottom of the asphalt layer.

Marshek et al. (4) used experimentally obtained contact pressure distributions from one treaded and one bald tire as an input to the multilayered elastic analysis program, BISAR. They found that higher truck tire inflation pressure corresponds to a significant increase in tensile strain at the bottom of the asphalt concrete layer and, therefore, a significant decrease in fatigue life of pavement. For example, changing tire pressure from 75 to 110 psi resulted in a 33 percent increase in tensile strain and a 60 percent reduction in a fatigue life of the pavement. Marshek et al. reported that the increase in tire inflation pressure increased the compressive strains at the top of subgrade by less than 2 percent for either the uniform pressure model or the nonuniform one (4). Therefore, they concluded that tire inflation pressure was an insignificant factor in causing subgrade rutting.

In this study, the Goodyear Tire and Rubber Company provided laboratory measurements for radial, bias, and wide-base radial tires. Current U.S. line haul trucking has made a transition from bias to radial tires, and wide-base singles could be an increasing factor, as they now are in Europe. In-service wide-base radial singles have higher load/tire contact area ratios than traditional duals and, thus, are of concern to some highway officials. The research presented in this paper evaluates the effect of each tire type on pavement response for various pavement structures and tire load/inflation conditions.

PAVEMENT PERFORMANCE

Field testing has shown that the performance of flexible pavements can be related to certain failure mechanisms. From a structural capacity standpoint, flexible pavement may experience two kinds of failure: fatigue, which shows as excessive alligator cracking, or rutting, which shows as permanent deformations along the wheel path.

Fatigue distress, the failure most encountered in flexible pavements, causes the greatest portion of rehabilitation cost. Researchers and investigators have proposed and implemented various types of laboratory tests and field measurements in an effort to predict the fatigue failure in actual pavements. Whether laboratory testing or theoretical analysis was used, the idea of relating tensile strain at the bottom of the

asphalt layer to the number of load repetitions was adopted by several researchers. Rauhut and Kennedy (5) showed 13 curves that related strains in asphalt concrete to number of load repetitions of 18-kip axle load. Their study indicated that the fatigue life of a flexible pavement may be predicted if the critical horizontal strain at the bottom of the asphalt layer is evaluated.

In a recent NCHRP study, Finn et al. (6) recommended equations to predict the number of load repetitions to develop 10 and 45 percent fatigue Class 2 cracking in the wheel path. The study was based on data from the AASHO Road Test and laboratory tests on material from the Road Test sections. This NCHRP study indicated that the amount of fatigue cracking is a function of the critical tensile strain and the stiffness of the asphalt layer.

Concerning rutting, several failure criteria have been recommended. The majority use correlations between strains and load repetitions. Correlations between the vertical strain on the surface of the subgrade and the number of equivalent single-axle load (ESAL) repetitions are widely used (7). Other rutting criteria correlate the rate of permanent strain to the elastic vertical strain and the number of load repetitions (8). The Asphalt Institute rutting criterion is among the most widely used in pavement design (8). The criterion provides the allowable number of ESAL repetitions for various levels of compressive strains at the surface or subgrade.

A rutting prediction criterion was also recommended by Finn et al. (6). A regression analysis procedure was used to correlate the rate of rutting with various combinations of primary response factors. The study concluded that the most significant correlations were obtained with vertical deflection at the surface of the pavement, followed by vertical compressive stress at interface with asphaltic concrete.

By examining fatigue and rutting criteria of flexible pavements, one can conclude that the performance of flexible pavements is affected by factors that influence the critical tensile strain at the bottom of the asphalt layer, surface deflection, and compressive stress at interface between the base and the asphaltic concrete. To evaluate the effect of high tire pressures and their nonuniform distributions on pavement performance, their effects on the strain, deflection, and stress components must be investigated.

In this study, a modified version of the BISAR computer program was used to evaluate the effect of variations in the truck tire pressures and their distributions on the flexible pavement performance indicators (i.e., tensile strains, compressive stress, and surface deflection). The actual pressure distributions for the various tire types were input as concentric circles with different pressures. A detailed discussion of the analysis procedure is presented later in this paper.

DATA ANALYSIS

Measurement of Tire Characteristics

Three truck tire types were analyzed for the following characteristics: footprint area (gross and net), footprint length, footprint width, spring rates, and footprint contact pressure profiles. The types of tires chosen were a dual 11-22.5 bias, dual 11R22.5 radial, and a wide-base radial single. The single

is an alternative to dual tires and more commonly used in Europe. All three tires were analyzed under a matrix of conditions that encompassed lightly loaded to overloaded, and underinflated to overinflated for each tire. Prior to any testing, each tire was run on a laboratory flywheel, under load, for a predetermined length of time to establish dimensional stability.

Tire footprints were obtained by inking the tread area of the inflated tire mounted on a specialized machine that loads it to a preset load. An imprint was left on a piece of paper between the tire and the machine's loading plate. All measurements were made from these imprints, with areas calculated by computer, using digitized boundary points as input.

To obtain deflection data, a machine similar to that used for footprints was employed; however, it monitored tire deflection in addition to load. Each tire was loaded continuously to a predetermined level, with all information recorded by strip chart recorder.

Tire footprint contact pressures were measured with a specially instrumented flatbed machine. Contact forces exerted by the loaded tire were obtained by a strain gauge located in the flatbed. This bed was capable of moving with the tire as it rotated at slow speed. Numerous points across the tire tread were tracked as they went through the length of contact to obtain an overall pressure profile. Typical distributions for the bias, radial and wide-base radial single are shown in Figure 1. The number of ribs differed from one tire to another: the bias tire had seven; the wide-base radial single, six; and the radial tire, five.

Pavement Response

To study the effect of tire pressures and distributions on the performance of flexible pavements, the response of various pavement structures and materials characteristics was investigated. For most of the analytical studies, a flexible pavement may be characterized by the thickness and stiffness of its layers. To perform a complete and meaningful study on the effect of tire types and tire pressures on the performance of flexible pavements, it was necessary to investigate pavement structures similar to that which exists on public highways. It has been well shown that high tire pressures have a large effect on pavements with thin surface layers (around 1-inch thick) and stiff base courses, but such a pavement design is atypical. The properties of the pavement structures investigated in this study are shown in Table 1.

The BISAR computer program is a general purpose program that uses the multilayer elastic solution to predict stresses, strains, and displacements in pavement structures subjected to single and multiple wheel loads. Circular uniform pressure is the general distribution for the BISAR program. The laboratory studies conducted in the research indicated that the contact pressures are not uniform and their actual distributions depend on the load, tire type, and inflation pressure. Therefore, the BISAR program was modified to handle the nonuniform pressure distributions in the form of concentric circles with different pressures. The use of concentric circles is validated by the apparent symmetry in the contact pressure distributions as shown in Figure 1. The actual pressure values of the tires under various loads and inflation pressures are shown in Table 2.

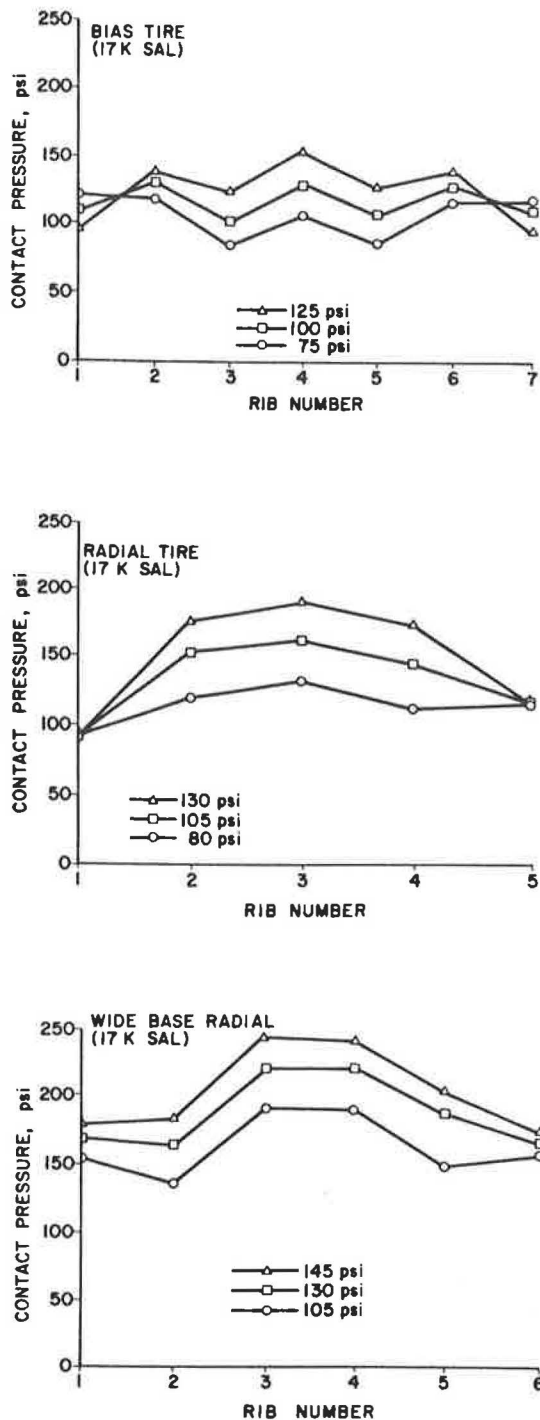


FIGURE 1 Typical pressure distribution of the three tires under 17,000-lb axle load.

Effect of Inflation Pressure and Load on Tensile Strain

The effect of inflation pressure on the tensile strain at the bottom of the asphalt concrete was evaluated for all three tires and three load levels. The results of the bias, radial, and wide-base radial single tire studies (Figures 2, 3, and 4) showed the effect of the increase in the inflation pressure as the thickness of the asphalt concrete increased. The average increase

TABLE 1 PROPERTIES OF PAVEMENT STRUCTURES

Layer	Thickness (in.)	Modulus of Elasticity (psi)	Poisson's Ratio
Asphalt concrete	2 } 4 } 6 } 8 }	400,000	0.35
Base	8	60,000	0.40
Subgrade	Infinite	6,000	0.45

in the tensile strain for the 2-in. asphalt layer was less than 15 percent for all load levels. The effect of inflation pressure was less than 5 percent for asphalt surfaces thicker than 4 in. The effect of load magnitude was more pronounced for all asphalt concrete thicknesses and tire types.

The axle load levels of 10,000, 17,000, and 22,000 lb (20,000 lb for the wide-base tires) represent the case of underloaded, loaded, and overloaded axles, respectively. The bias tire (Figure 2) showed an average increase of 35 percent in the tensile strain when the axle load increased from 10,000 to 17,000 lb, and an average of 25 percent increase when the axle load increased from 17,000 to 22,000 lb. This increase in the tensile strain was present for all asphalt layer thicknesses between 2 and 8 in.

The radial tire study (Figure 3) showed a trend similar to the bias tire, but the increase in the tensile strain was less than 20 percent for all cases of loads and asphalt concrete thicknesses. For an asphalt concrete thickness of 2 in., the radial tire data indicated that an axle load of 17,000 lb at 80 psi was less damaging than one of 10,000 lb at 130 psi, and an axle load of 22,000 lb at 80 psi was less damaging than one of 17,000 lb at 130 psi. Therefore, the 130 psi pressure for the radial tire may be critical for asphalt concrete pavements with thicknesses of 2 in.

The wide-base radial single tire study (Figure 4) was also similar to the bias and radial tire studies except that the 2-inch-thick asphalt concrete layer showed about a 40-percent increase in the tensile strain with an increase in inflation pressure from 130 to 145 psi at an axle load of 20,000 lb. For asphalt concrete layer thicknesses of 6 and 8 inches, the strain increased by less than 10 percent for an increase in the axle load from 10,000 to 17,000 lb.

Effect of Inflation Pressure and Load on Surface Deflection

The effect of surface deflection on the rutting failure of flexible pavements was emphasized in the NCHRP study discussed earlier (6). It was shown that surface deflection was a significant factor in the development of surface rutting. Studies of the dual-fitting bias and radial, and single-fitting wide-base radial tires indicated that inflation pressures had minimal effect on the surface deflection response for asphalt surfaces between 2 and 8 in. (Figures 5, 6, and 7). The increase in axle load showed a large effect on the surface deflections under all three tires. The surface deflection under the bias, radial, and wide-base radial single tires showed an increase of 75 percent when the axle load was increased from 10,000 to 17,000 lb for all asphalt surfaces between 2 and 8 inches. When the axle load increased from 17,000 to 22,000 lb for

TABLE 2 PRESSURE DISTRIBUTIONS FOR THE RADIAL, BIAS, AND SUPER SINGLE TIRES

Tire Type	Inflation Pressure (psi)	Load, lb	Rib Pressure (psi)						
			1	2	3	4	5	6	7
radial 11R22.5	80	2500	54	120	132	115	72		
		4250	92	120	132	112	115		
		5500	117	117	129	109	135		
	105	2500	40	146	163	145	71		
		4250	92	152	162	143	115		
		5500	117	151	160	145	140		
	130	2500	34	162	185	162	69		
		4250	94	177	191	172	115		
		5500	117	175	188	172	143		
bias 11-22.5	75	2500	57	98	80	105	82	100	60
		4250	123	118	85	122	63	115	117
		5500	158	128	85	108	86	122	132
	100	2500	40	102	98	123	100	103	45
		4250	110	131	102	129	108	128	108
		5500	145	143	105	131	94	140	143
	125	2500	32	103	145	152	120	105	37
		4250	97	138	125	154	128	140	92
		5500	132	157	128	157	129	155	126
wide base radial single 385/65R22.5	105	5500	115	135	180	183	169	115	
		8500	184	137	191	189	149	157	
		10000	169	131	191	189	149	169	
	130	5500	122	158	206	206	175	120	
		8500	169	166	220	222	188	166	
		10000	185	168	234	229	185	182	
	145	5500	126	174	223	220	189	118	
		8500	165	183	246	242	205	174	
		10000	192	189	249	245	206	189	

bias and radial tires, and to 20,000 lb for wide-base tires, the surface deflections under all three tires were increased by an order of 30 percent. The surface deflection response indicated that, under all three tires, the increase in surface deflection was linear with the increase in the axle load and remained constant over the entire range of asphalt surfaces.

Effect of Inflation Pressure and Load on Compressive Stress

Various field and research studies have shown that the rutting of crushed aggregate base courses contributes significantly to overall rutting of flexible pavements. The Probabilistic Distress Models for Asphalt Pavements (PDMAP) study also indicated that the compressive stress of the asphalt layer interface was a significant variable in the development of surface rutting (6). The effect of inflation pressure and axle load on the compressive stress at the asphalt layer interface was investigated for the bias, radial, and wide-base radial single tires (Figures 8, 9, and 10).

The effect of inflation pressure was then greatest for pavements with 2 in. of asphalt layer. The maximum variation, approximately 10 percent, was under the wide-base radial single tire. The effect of inflation pressure was as low as 1 percent for asphalt layers with thicknesses of 4, 6, and 8 in.

The effect of axle load on the compressive stress was present for all tires and pavement thickness combinations. The increase in compressive stress was on the order of 15 percent for an asphalt layer of 2 in. and was gradually reduced to about 5 percent for asphalt layer of 8 in.

Under the bias and wide-base radial single tires and for certain load and inflation pressure combinations, the compressive stress under a 2-in. asphalt surface may be greater than the inflation pressure. For example, the compressive stress under the 2-in.-thick asphalt layer for the bias tire showed values of 100 and 110 psi under an axle load of 22,000 lb and inflation pressures of 75 and 100 psi, respectively.

The compressive stresses under the wide-base radial single tire were at 125, 140, and 160 psi for an axle load of 20,000 lb with inflation pressures of 105, 130, and 145, respectively. The compressive stresses under the radial tire were always lower than the inflation pressure for all combinations. This observation indicates that heavily loaded bias and wide-base radial tires are more critical to pavements with thin asphalt layer than are radial tires.

Effect of Tire Type on Tensile Strain

By observing the typical contact pressure distributions for the bias, radial, and wide-base radial single tires in Figure 1, the

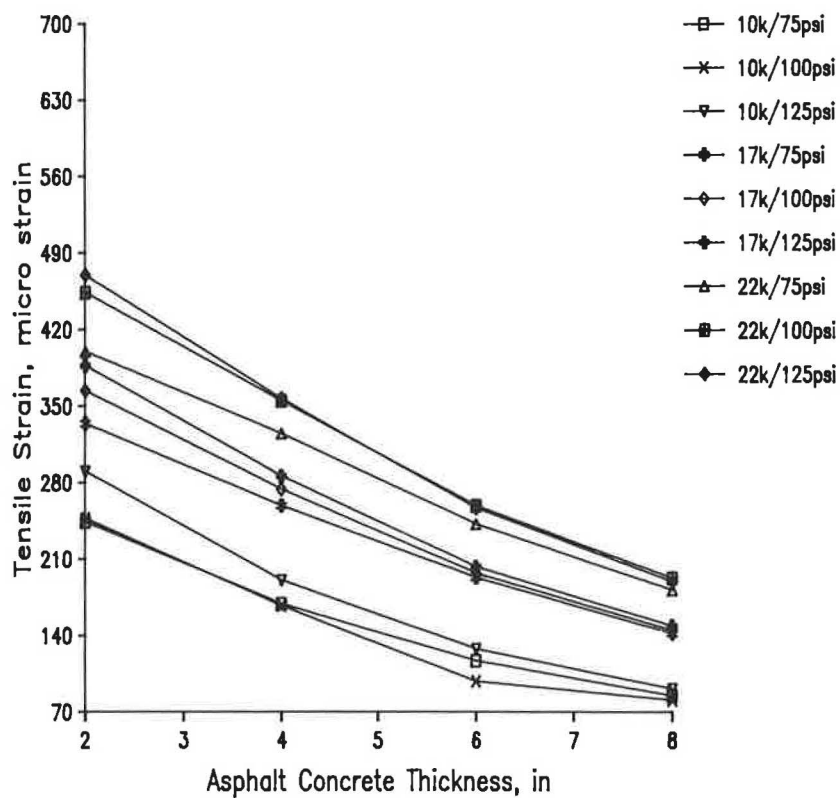


FIGURE 2 Effect of tire pressure and load on the tensile strain at the bottom of asphalt layer for dual bias tires.

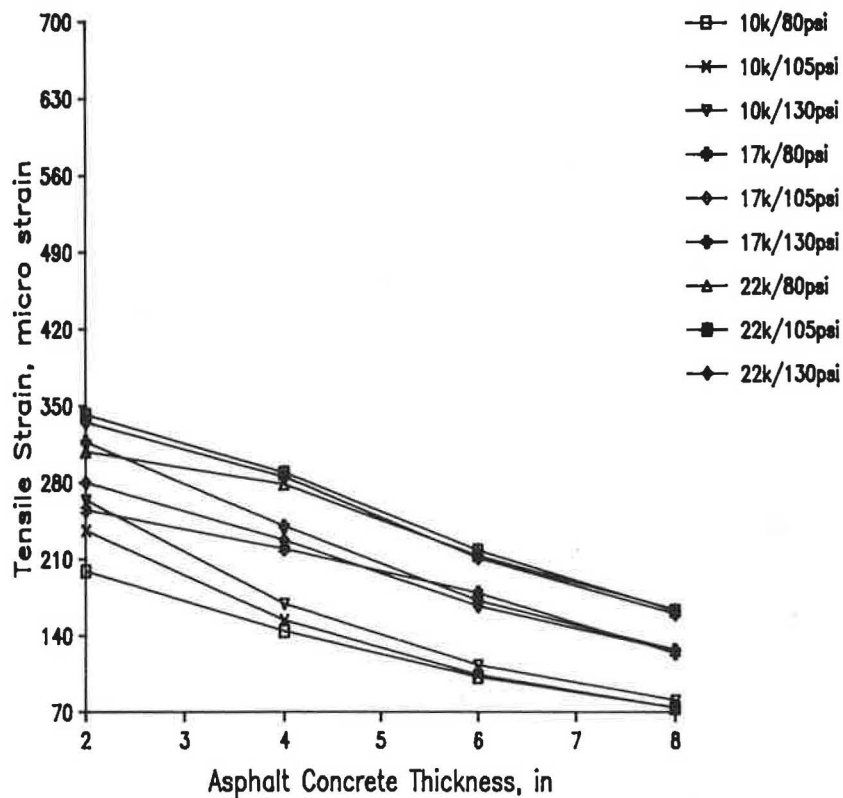


FIGURE 3 Effect of tire pressure and load on the tensile strain at the bottom of asphalt layer for dual radial tires.

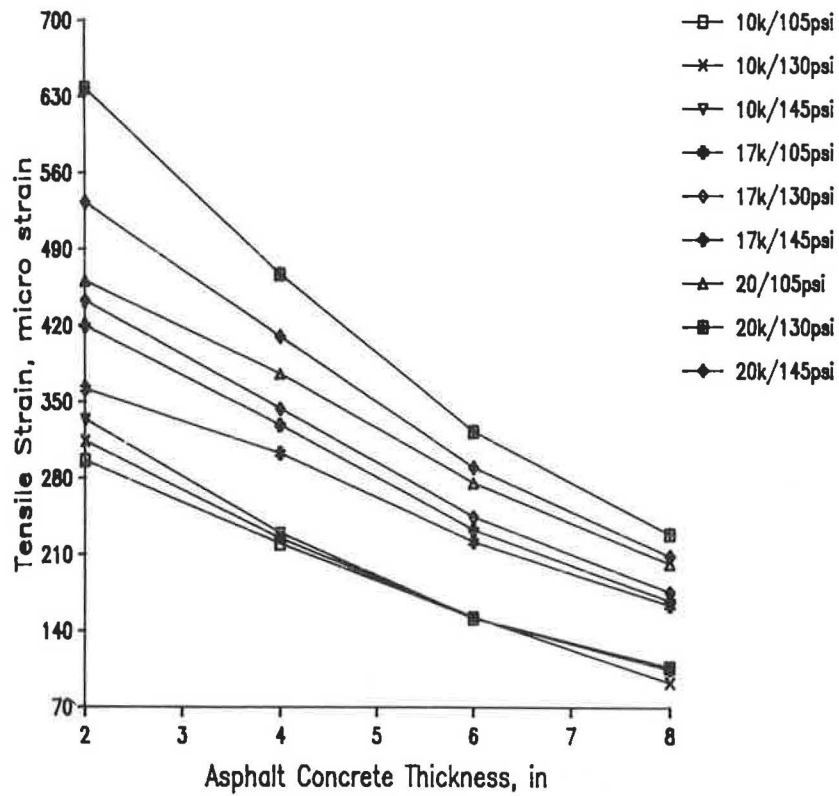


FIGURE 4 Effect of tire pressure and load on the tensile strain at the bottom of asphalt layer for single wide-base radial tire.

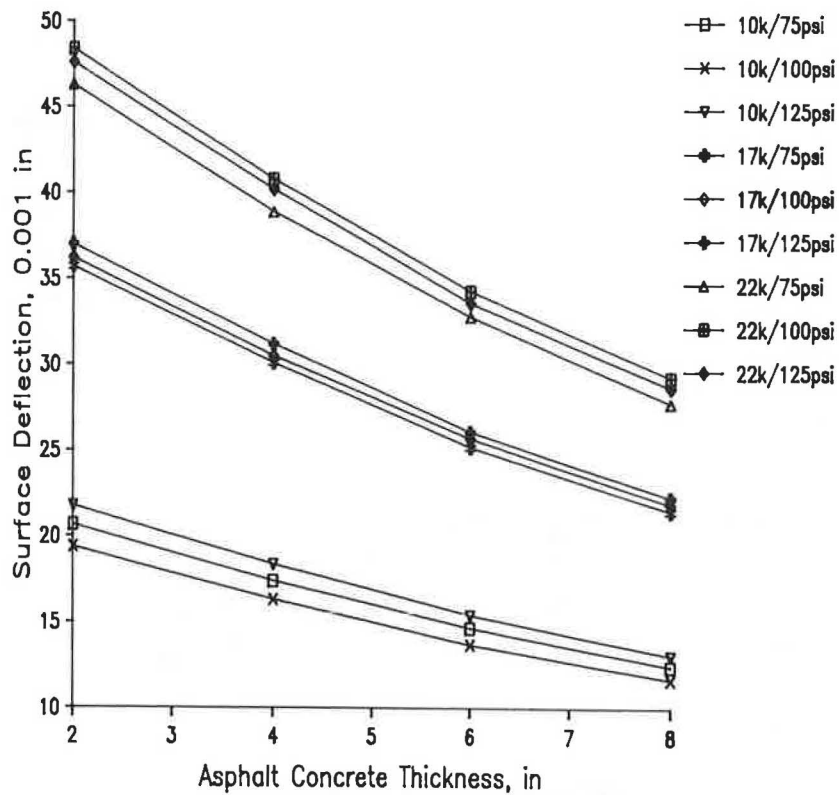


FIGURE 5 Effect of tire pressure and load on the pavement surface deflection for dual bias tires.

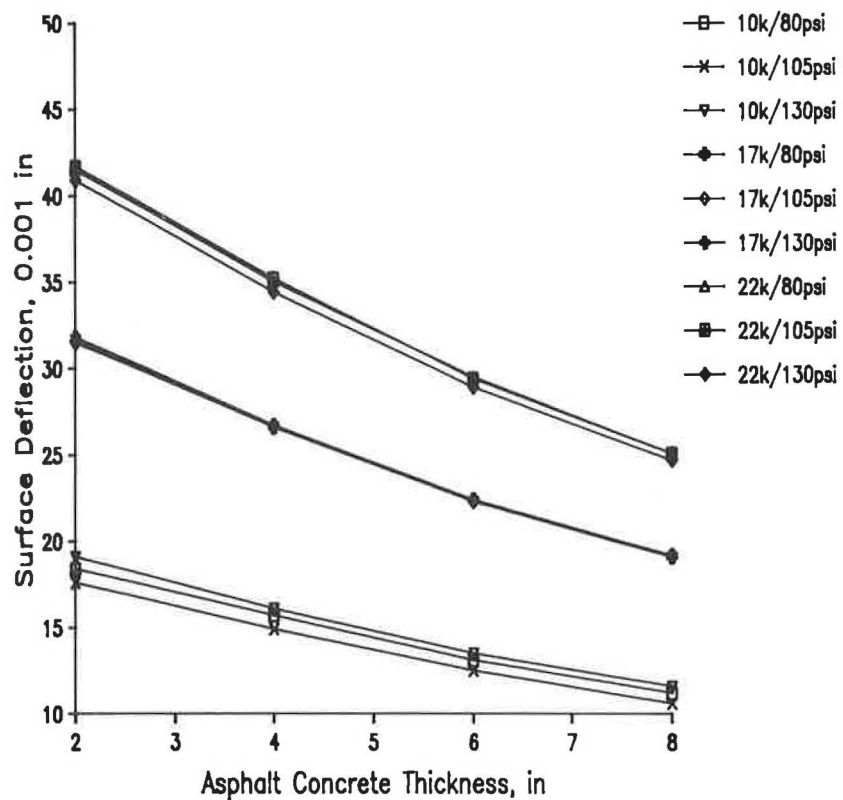


FIGURE 6 Effect of tire pressure and load on the pavement surface deflection for dual radial tires.

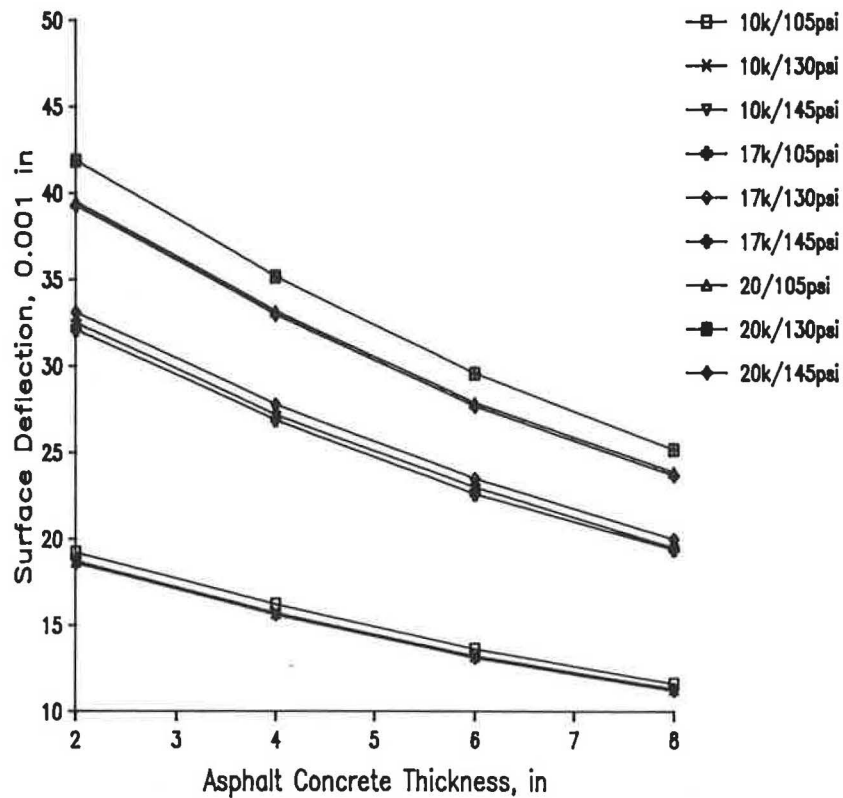


FIGURE 7 Effect of tire pressure and load on the pavement surface deflection for single wide-base radial tire.

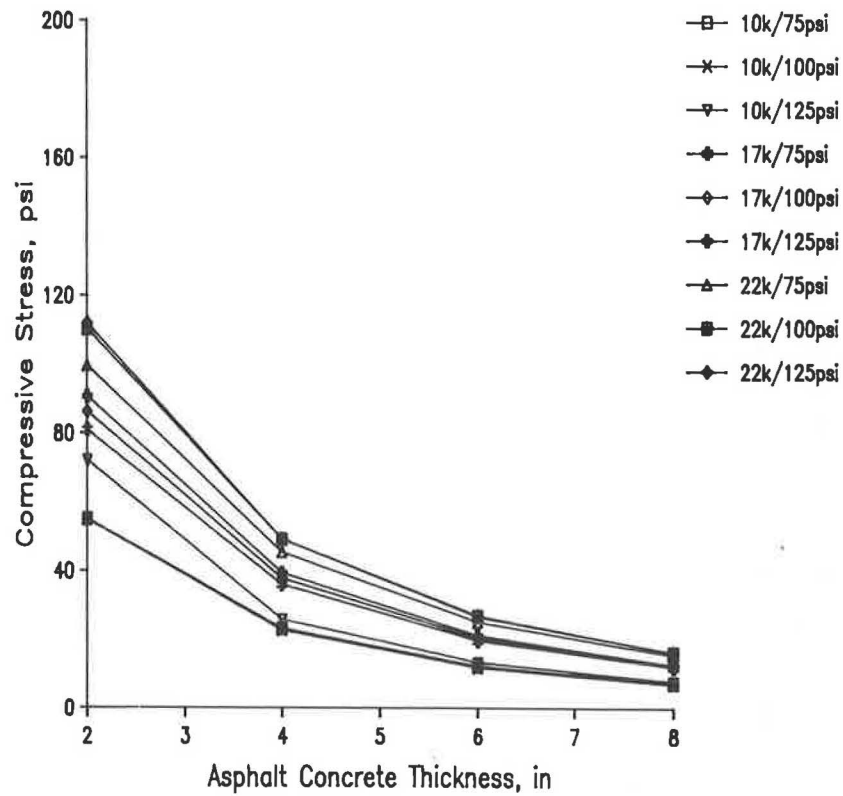


FIGURE 8 Effect of tire pressure and load on the compressive stress at the asphalt layer interface for six dual bias tires.

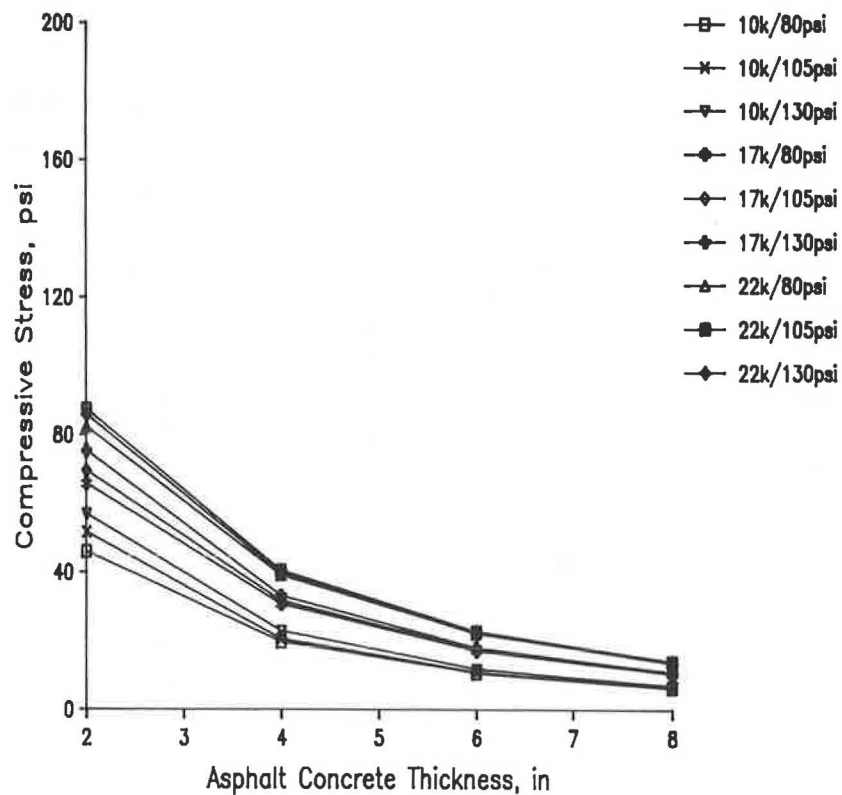


FIGURE 9 Effect of tire pressure and load on the compressive stress at the asphalt layer interface for six dual radial tires.

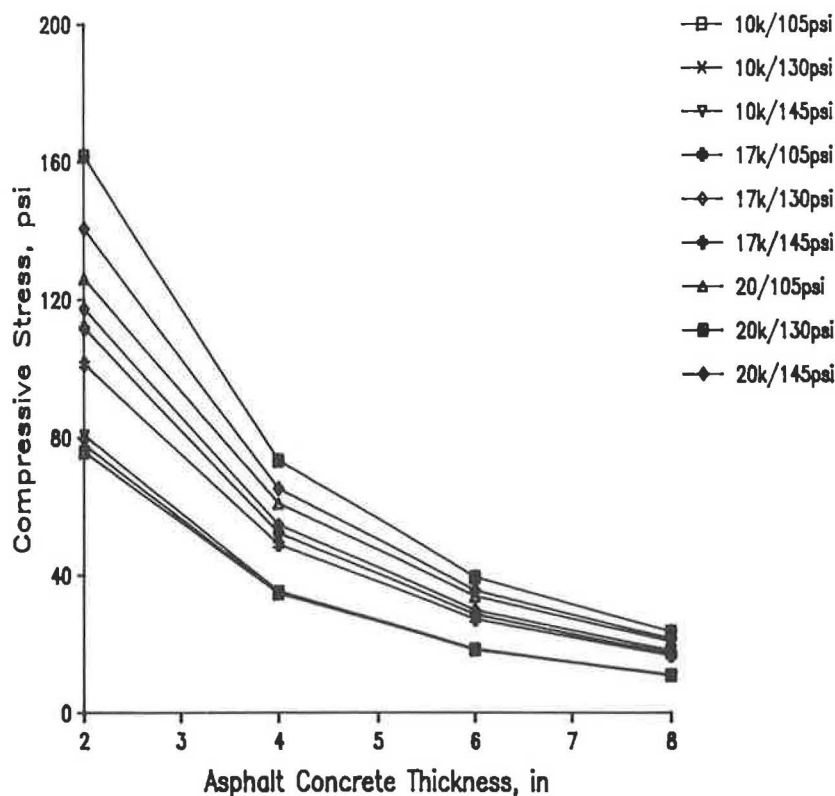


FIGURE 10 Effect of tire pressure and load on the compressive stress at the asphalt layer interface for six single wide-base radial tires.

differences among tire types are readily distinguished. The first part of the research showed that the effect of inflation pressure was pronounced only when the asphalt layer was 2 in. thick. For pavements with asphalt layers 4, 6, and 8 in. thick, the effect of inflation pressure became less pronounced. However, the effect of axle load was found to be significant under all tires and asphalt layer thicknesses. The tensile strain, surface deflection, and compressive stress at the asphalt layer interface were very sensitive to any increase in the axle load.

The second part of this study was to investigate the effect of axle load on the pavement response under each tire and how it compared with the response under other tires. The operating inflation pressure for each tire was used: 105, 100, and 130 psi for bias, radial, and wide-base radial single tires, respectively.

Figure 11 shows the results of tensile strain studies for asphalt thicknesses of 2, 4, 6, and 8 in. The strains under the dual-fitting radial tires were the lowest for all axle loads and asphalt thicknesses. Strains under the dual-fitting bias tires were 35 percent higher than under the radial tire for an asphalt layer thickness of 2 in., and 25 percent higher for asphalt layer thicknesses of 4, 6, and 8 in. The strains under the single-fitting wide-base radial tire were 50 percent higher than the radial tire for all asphalt layer thicknesses. This observation was expected because the wide-base radial single tire has a higher load-per-tire ratio than both radial and bias tires.

Effect of Tire Type on Surface Deflection

The results of the surface deflection study (Figure 12) showed that the bias tires had the highest surface deflection for all

asphalt layer thicknesses. The surface deflections under the radial and the wide-base radial single tires were very close, especially under the heavily loaded cases. The surface deflections under the bias tire were 20 and 15 percent higher than those under the radial and wide-base radial single tires, respectively. The bias tires had the lowest tire deflection among the three tires, indicating that the bias tires were the stiffest and would, therefore, create the highest surface deflections.

Effect of Tire Type on Compressive Stress

The results of the compressive stress study are shown in Figure 13. The trends in the compressive stress data are similar to the strain data. The stresses under the radial tires were the lowest for all asphalt layer thicknesses and axle load levels. The stresses under the wide-base radial single and bias tires were 25 and 50 percent higher, respectively, than stresses under the radial tires.

CONCLUSIONS

The response of flexible pavements was investigated under various conditions of tire pressures, tire types, and axle loads. The tire parameters, including footprints, net contact area, contact pressures, and tire deflections, were evaluated through a laboratory testing program. The set of tested tires included the commonly used radial and bias tires and the wide-base radial single tire, which is used widely in Europe but has only limited use in the U.S.

Tire characteristics data showed linear relationships between

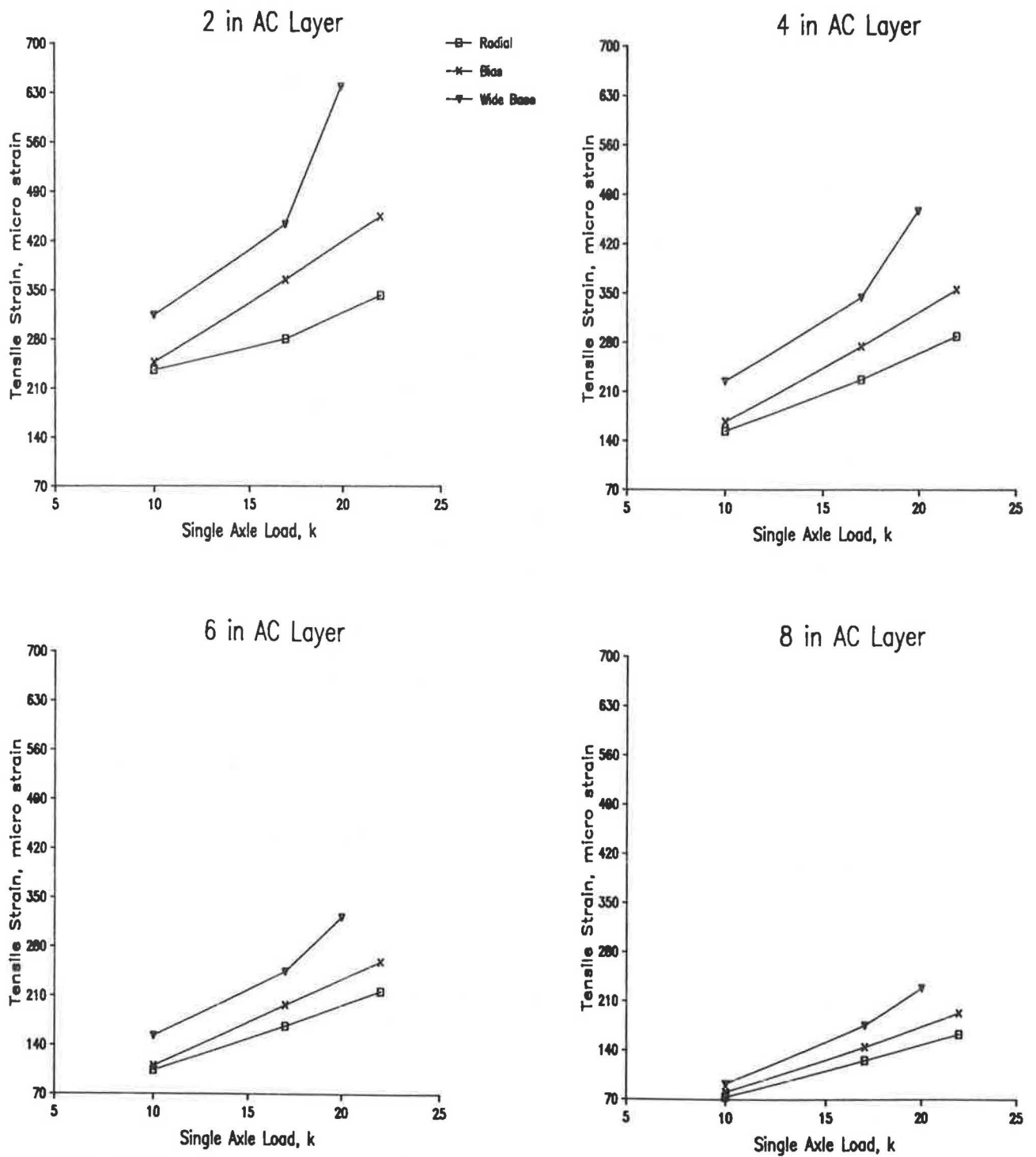


FIGURE 11 Effect of axle load and tire types on tensile strain at the bottom of four asphalt layer thicknesses.

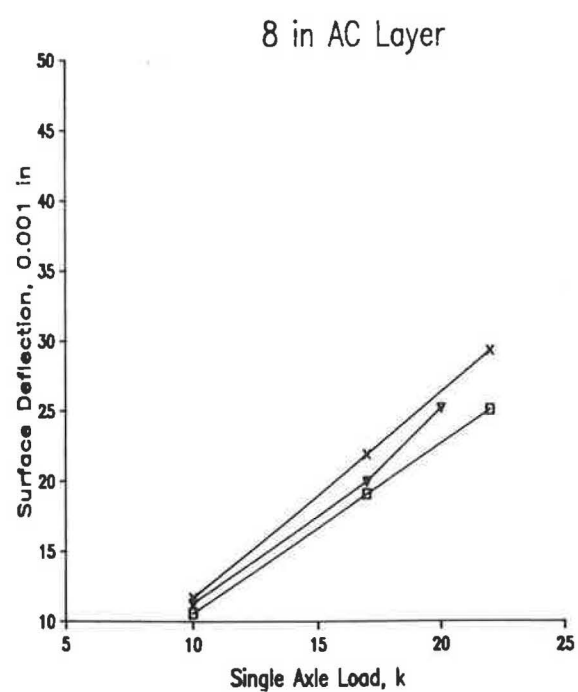
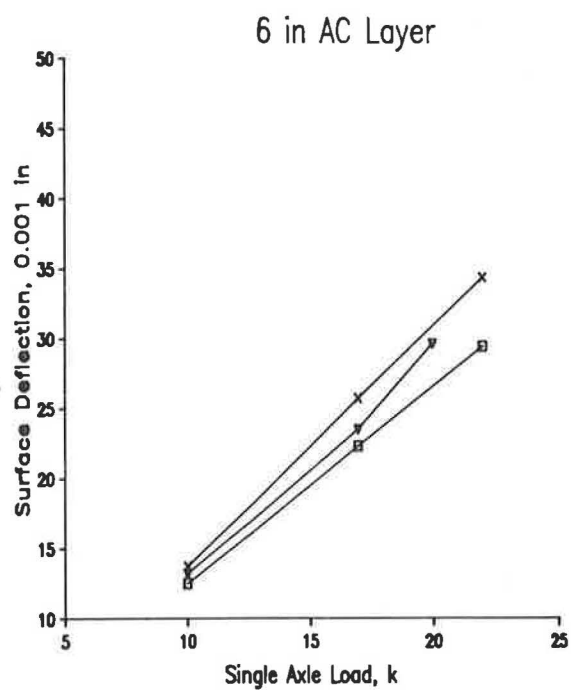
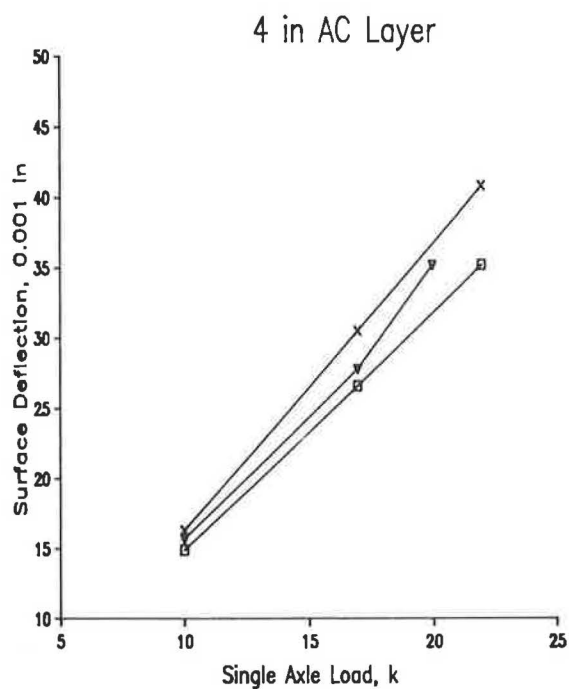
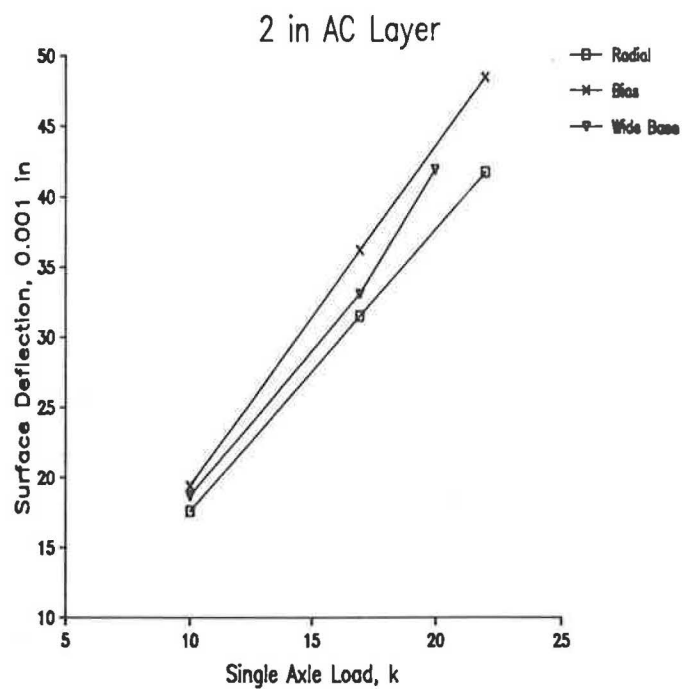


FIGURE 12 Effect of axle and tire type on the surface deflection for four asphalt layer thicknesses.

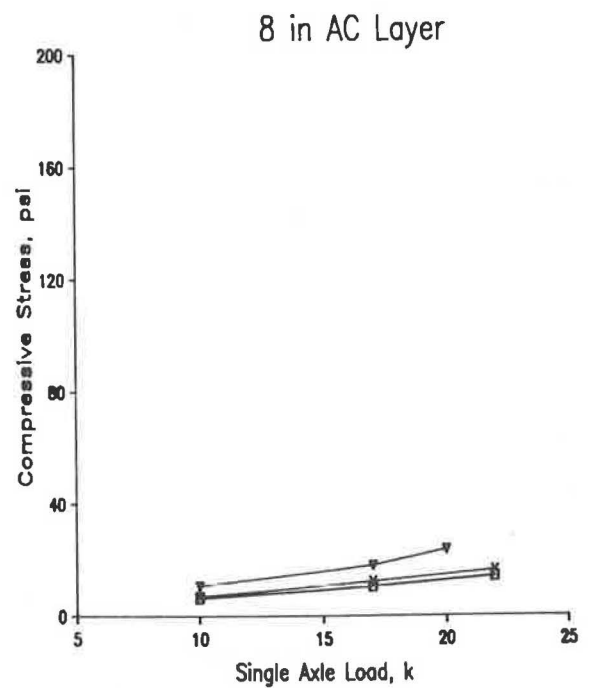
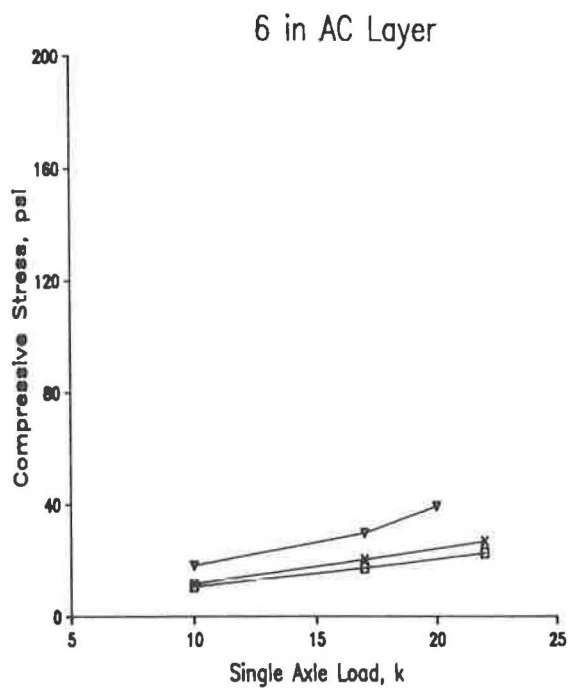
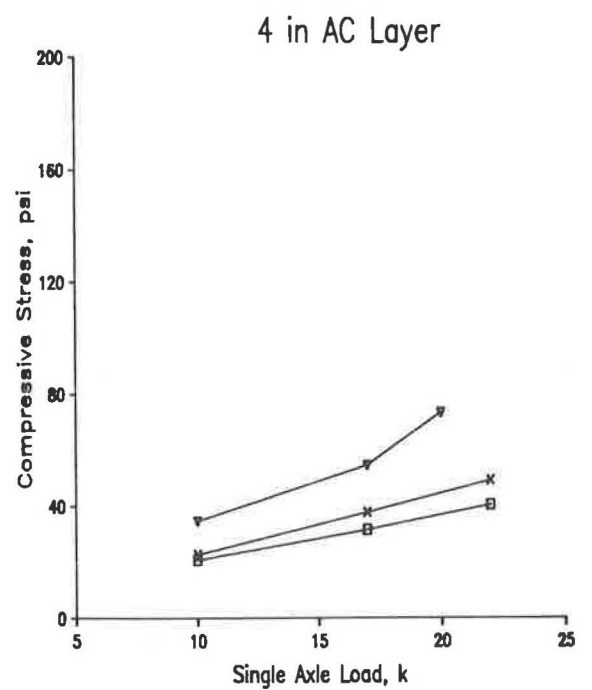
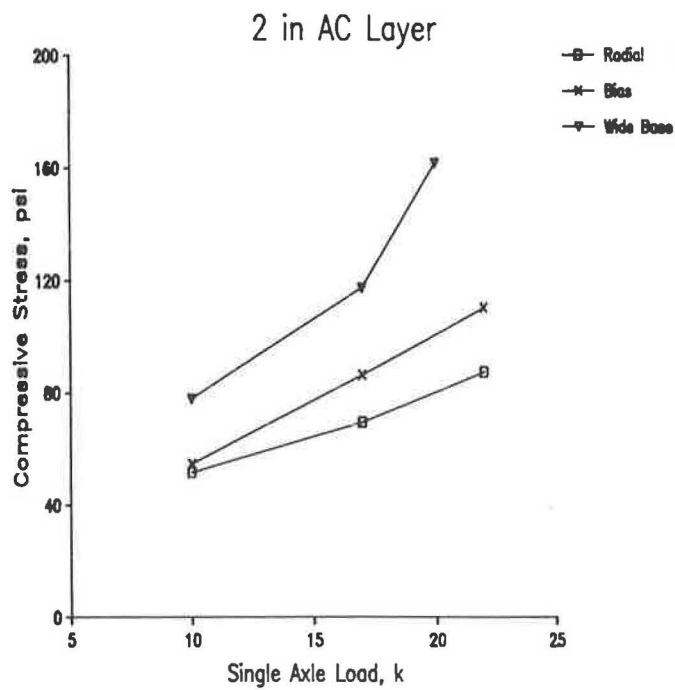


FIGURE 13 Effect of axle load and tire type on the compressive strain at the asphalt layer interface for four thicknesses.

the amount of tire deflections and the net contact areas for all tire types and axle load levels. The contact pressure distributions were all nonuniform, with maximum contact pressures of 1.75 times the inflation pressures. The maximum contact pressures were obtained along the center rib for all three tires and the minimum contact pressures were obtained along the outside rib. The ratio of the maximum pressure to the minimum pressure became smaller as the axle load increased.

On the basis of laboratory contact pressure distributions, a pavement response study was conducted. Actual pressure distributions were used in a mechanistic solution to predict the response of flexible pavement under the various loading conditions. From the results, the following conclusions may be drawn:

- Inflation pressure affects the magnitude of the tensile strains and compressive stresses for pavements with asphalt layers 2 in. thick. The greatest effects of inflation pressure are found in the wide-base radial single tire under a 20,000-lb axle load.

- Surface deflection response is not significantly affected by inflation pressure for all tire types, axle loads, and asphalt thicknesses.

- The magnitude of the axle load is the predominant factor for all variations in the pavement response parameters. Any increase in the axle load is significant for all tire types, inflation pressures, and asphalt layer thicknesses.

- Under certain critical combinations of load and inflation pressure, the compressive stress at the 2-in.-thick asphalt layer interface with the base and wide-base radial single tires exceeds the values of the inflation pressure.

- The wide-base radial single tire produces the maximum tensile strains and compressive stresses under all combinations of axle loads and asphalt layer thicknesses.

- For the overall ranges of inflation pressures, axle loads, and asphalt layer thicknesses investigated in this study, the radial tire is the least damaging on the predicted flexible pavement response parameters.

REFERENCES

1. W. D. Cunigan and N. A. Ayoub. *Feasibility of Automatic Truck Tire Pressure Data Collection*. FHWA/TX/493-1F, Washington, D.C., November 1986, 43 pp.
2. F. L. Roberts, J. T. Tielking, D. Middleton, R. L. Lytton, and K. Tseng. *Effect of Tire Pressures on Flexible Pavements*. Report No. 372-1F, Texas Transportation Institute, College Station, Texas, 1986.
3. J. T. Tielking. A Finite Element Tire Model. *Tire Science and Technology*, Vol. 11, Nos. 1-4, 1983, pp. 50-63.
4. K. M. Marshak, W. R. Hudson, H. H. Chenn, C. L. Saraf, and R. B. Connel. *Effect of Truck Tire Inflation Pressure and Axle Load on Pavement Performance*. Report No. 386-2F, Center for Transportation Research, The University of Texas at Austin, Austin, Texas, 1985.
5. B. J. Rauhut and T. W. Kennedy. Characterizing Fatigue Life for Asphalt Concrete Pavements. In *Transportation Research Record 888*, TRB, National Research Council, Washington, D.C., 1982.
6. F. Finn, C. L. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah. *Development of Pavement Structural Subsystems*. NCHRP Report 291, TRB, National Research Council, Washington, D.C., Dec. 1986.
7. G. M. Dorman and C. T. Metcalf. Design Curves for Flexible Pavements Based on Layered System Theory. In *Highway Research Record 71*, HRB, National Research Council, Washington, D.C., 1965.
8. The Asphalt Institute. *Documentation of the Asphalt Institute's Thickness Design Manual*. Research Series No. 14 (RS-14), 7th ed., College Park, Md., 1964.

Publication of this paper sponsored by Committee on Flexible Pavement Design.