Effect of Tire Pressure on Flexible Pavement Response and Performance

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The effects of tire pressure on flexible pavement response and performance were evaluated using data from the first phase of research at the FHWA Pavement Testing Facility. The Accelerated Loading Facility testing machine was used to simulate traffic loading. The response evaluation included measuring surface deflections, surface strains, and strains at the bottom of the asphalt layer for various combinations of load and tire pressure. The data showed little effect due to tire pressure at all load levels. The performance evaluation included an evaluation of differences in rutting and cracking for two test sections trafficked with the same load but different tire pressures. The data showed increased rutting and cracking for the section trafficked with the higher tire pressure; however, this section was thinner and trafficked at a higher temperature than the low tire pressure section. Based on postmortem evaluations of the two sections and an analysis of pavement strains using layer theory, the increased rutting was due mainly to the higher temperature. On the basis of classical fatigue models, the increased cracking was found to result primarily from the combined effects of higher pavement temperature and thinner pavement structure.

In recent years, the effects of increased truck tire pressures on flexible pavement performance have become a subject of great concern. Various researchers have used analytical methods to attribute decreased fatigue life, increased rutting, and accelerated serviceability loss to the effects of increased tire pressure (*1–3*). This paper presents an analysis of the impact of tire pressure on flexible pavement response and performance on the basis of data collected during the first phase of research at the FHWA Pavement Testing Facility (PTF).

The Pavement Testing Facility is an outdoor, full-scale pavement testing laboratory located at the Turner-Fairbank Highway Research Center in McLean, Virginia. The purpose of the PTF is to quantify the performance of full-scale test pavements under accelerated loading. The facility comprises the Accelerated Loading Facility (ALF) test machine; two 200-ft-long, instrumented asphalt concrete test pavements; and a computer-controlled data-acquisition system.

The ALF, shown in Figure 1, simulates one-half of a dual-tire single axle, and can apply loads ranging from 9,400 to 22,500 lb. The test wheels travel at 12 mi/hr over 40 ft of pavement. To simulate highway traffic, the loads are applied in one direction and are normally distributed about a 48-in. wheelpath.

Each test lane is divided into four sections for a total of eight test sections. Cross sections for the two lanes are shown in Figure 2. Typical Virginia Department of Transportation (DOT) materials were used in the pavements. The wearing and binder courses consist of crushed aggregate and AC-20 asphalt. The crushed aggregate base is dense graded, and contains a high amount of fines, approximately 50 percent passing the No. 8 sieve. The subgrade is classified as an AASHTO A-4(0) soil.

The pavement instrumentation and data-acquisition system form an integral part of the PTF. The pavement instrumentation consists of thermocouples and moisture cells at various depths in the pavement, strain gauges at the bottom of the asphalt binder, and a linear variable differential transformer (LVDT) for dynamic surface deflection. Signals from the various instruments are directed through signal conditioning equipment to analog to digital converters mounted in a personal microcomputer. Software was developed to collect environmental and pavement response data as part of the routine operation of the PTF.

The effects of tire pressure on flexible pavements were evaluated in two ways. First, deflections and strains for various combinations of load and tire pressure were measured and compared. Second, rutting and cracking for two test sections trafficked with the same load but different tire pressures were analyzed. The remainder of this paper describes these two evaluations.

PAVEMENT RESPONSE EVALUATION

Experimental Design

The objective of the pavement response experiment was to compare pavement responses for various combinations of load and tire pressure for two types of tires. The experiment consisted of measuring surface deflection, surface strain, and strain at the bottom of the asphalt layer for three load levels, three tire pressures, and two tire types. Table 1 summarizes the experimental design. The experiment was conducted on Lane 2 of the PTF in July 1987 and Lane 1 in December 1987.

Instrumentation

The pavement instrumentation included an LVDT to measure surface deflections and strain gauges at the surface and the bottom of the asphalt layer. The LVDT was mounted to a reference beam placed adjacent to the test pavement and

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FIGURE 1 Accelerated Loading Facility testing machine.

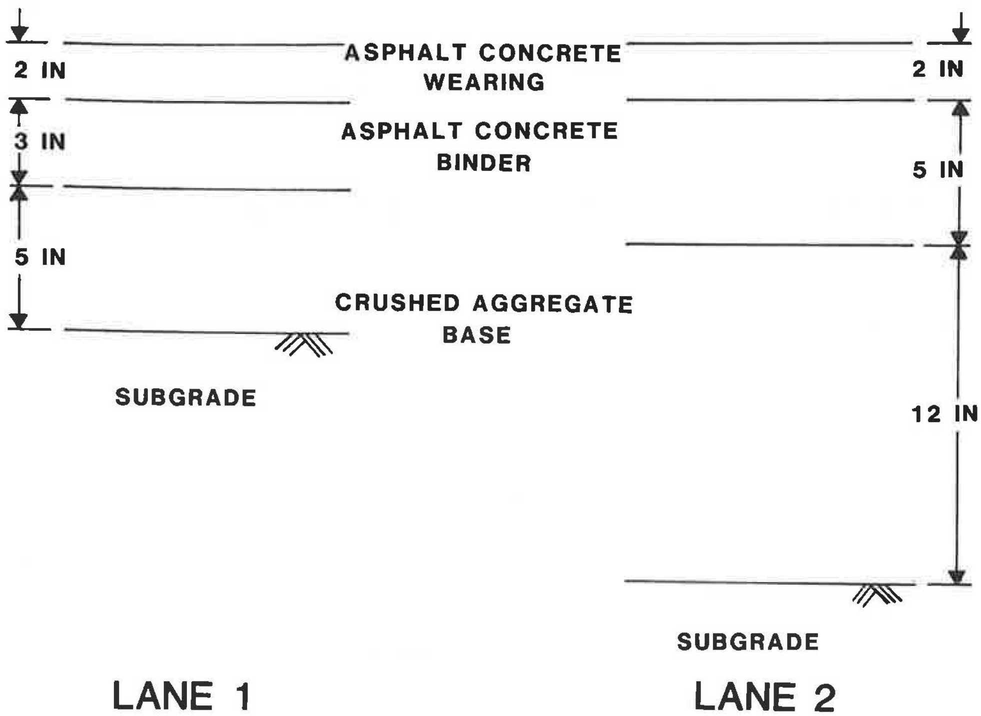

FIGURE 2 Pavement Testing Facility pavement cross sections.

TABLE 1 EXPERIMENTAL DESIGN

	Tire Pressures (psi)					
	Radial			Bias Ply		
Load (lb)	76	108	140	76	108	140
9,400	X	X	X	X	X	X
14,100	X	X	X	X	X	X
19,000	X	X	X	X	X	X

measured the pavement deflection 27 in. from the center of the dual wheels.

Surface strains were measured with 2-in. gauge length bonded foil resistance strain gauges. The gauges were installed in shallow slots cut in the pavement surface. Surface strains were measured in the transverse direction both between the dual wheels and under the center of one tire.

Strains at the bottom of the asphalt layer were measured using strain gauges installed at the interface between the asphalt binder and the crushed aggregate base during construction. These gauges consisted of a strain gauge encapsulated in a plastic strip. The plastic strip was anchored in the asphalt by two transverse beams attached to the ends of the strip. The resulting strain gauge formed an **H** shape (*4*). The strains at the bottom of the asphalt layer were measured in the longitudinal direction under the inside edge of one of the dual tires.

Response curves for the various instruments were obtained by using the PTF data-acquisition system to monitor the instruments as the ALF wheels traversed the pavement. For each response measurement, a temperature profile for the asphalt layer was obtained using thermocouples installed adjacent to the response instrumentation.

Results

Typical response curves for deflection and strain are shown in Figure 3. Of particular interest is the response curve for longitudinal strain at the bottom of the asphalt layer. This response curve shows a strain reversal when the load passed over the gauges. As the load approached the gauges, compressive strains were induced at the bottom of the asphalt layer. When the load was over the gauges, tensile strains occurred, and finally, compressive strains were once again induced as the load moved away from the gauges.

In analyzing the data, only the peak responses were considered. These responses and the corresponding pavement temperatures are summarized in Tables 2 and 3 for tests conducted on Lanes 1 and 2, respectively. Figures 4, 5, and 6 compare peak responses for surface deflection, surface strain, and strain at the bottom of the asphalt layer using data from the Lane 2 tests. The Lane 1 data show similar effects. These comparisons showed that the effect of tire pressure on the measured responses was small. Increasing the tire pressure from 76 to 140 psi increased the measured responses only 2 to 10 percent. On the other hand, increasing the load from 9,400 to 19,000 lb increased the measured responses 200 to 400 percent. Additionally, the data do not show any consistent trends with respect to tire type. For Lane 2 at the higher load levels, the bias ply tires resulted in higher strains than the radial tires. This effect was probably due to temperature, rather than tire type. The average pavement temperatures during the bias ply tests at these loads were from 6° to 10°F higher than those during the corresponding radial tire tests. Laboratory resilient modulus data show that this temperature difference would result in a 100,000-psi decrease in the resilient modulus for the asphalt layer.

PAVEMENT PERFORMANCE EVALUATION

During the first phase of research at the PTF, two test sections, Lane 2, Section 3 (Test 2-3), and Lane 2, Section 2 (Test 2-2), were trafficked with the same load but different tire pressures. The wheel load was 19,000 lb and the tire

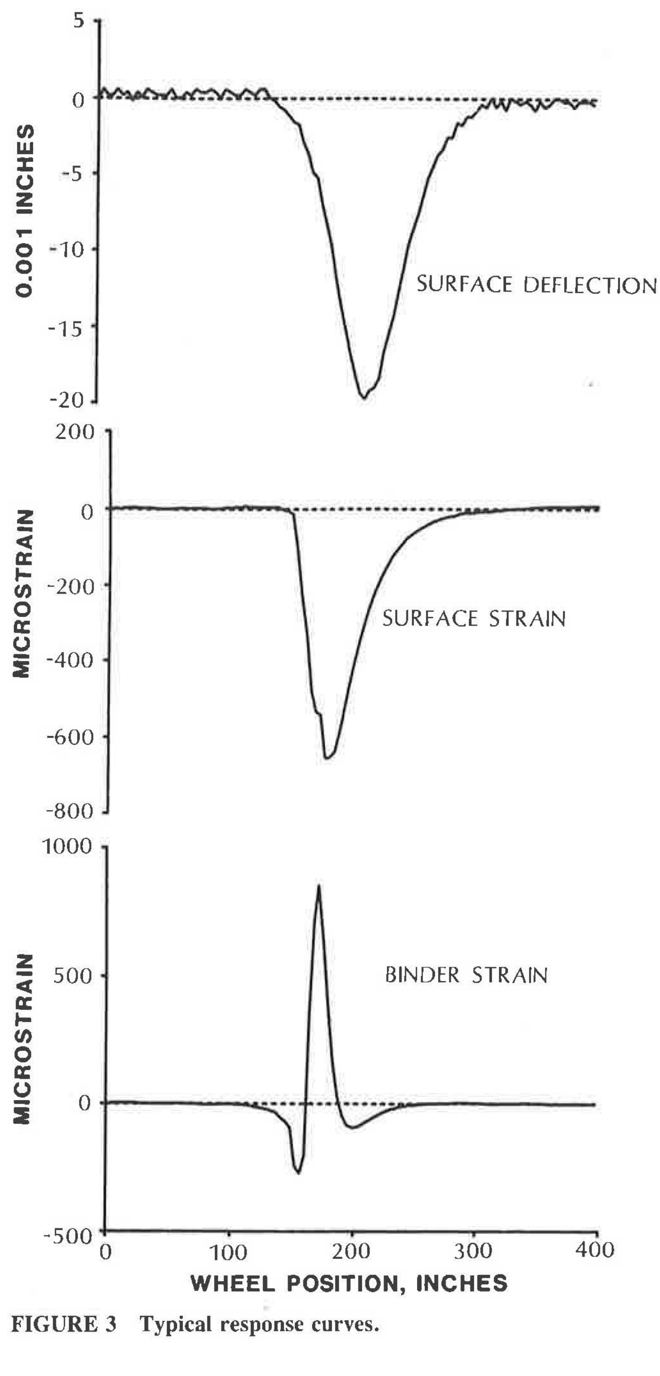

FIGURE 3 Typical response curves.

TABLE 2 SUMMARY OF PAVEMENT RESPONSE DATA FOR LANE 1

Tire Type	Load (lb)	Pressure (psi)	Temp. (F)	Surface Deflection (0.001in)	Surface Between (micro)	Strain Under (micro)	Binder Strain (micro)
Radial	9,400	76	41.8	8.2	--	-231	212
Radial	9,400	108	42.0	8.1	--	-152	194
Radial	9,400	140	42.1	10.9	--	-201	111
Radial	14,100	76	40.7	14.6	--	-233	292
Radial	14,100	108	40.4	15.1	--	-349	267
Radial	14,100	140	40.8	15.7	--	-294	284
Radial	19,000	76	39.4	26.8	-314	-514	351
Radial	19,000	108	39.4	26.6	-310	-510	377
Radial	19,000	140	39.3	25.3	-306	-514	381
Bias	9,400	76	39.5	10.8	-148	-208	159
Bias	9,400	108	38.9	14.1	-179	-279	123
Bias	9,400	140	38.7	14.1	-168	-276	185
Bias	14,100	76	39.0	18.7	-253	-374	249
Bias	14,100	108	38.8	18.9	-242	-380	277
Bias	14,100	140	38.8	19.0	-248	-372	257
Bias	19,000	76	38.0	26.4	-322	-506	363
Bias	19,000	108	38.6	26.3	-321	-487	374
Bias	19,000	140	38.5	26.3	-330	-519	375

Note "-" denotes compression.
"--" denotes data unavailable.

pressures were 100 psi and 140 psi for Test 2-3 and Test 2-2, respectively. This section describes an evaluation of the effect of tire pressure on rutting and cracking for these two test sections.

Test Conditions

Load and tire pressure were carefully controlled during these tests. Pavement performance, however, may have been significantly affected by other test conditions including environment and construction variability which could not be controlled. These test conditions were quantified as outlined below to aid in the interpretation of the rutting and cracking data.

Temperature and moisture conditions have a significant impact on flexible pavement performance. The stiffness of asphalt concrete is affected by temperature, and the stiffness of subgrade soils and granular base materials is affected by moisture. Test 2-3 was conducted from January 8 to June 6, 1987, and Test 2-2 was conducted from June 18 to November 24, 1987. To quantify the thermal conditions during testing, daily maximum and minimum air temperatures were obtained from the National Oceanic and Atmospheric Administration weather station at Dulles International Airport, which is located 25 miles west of the PTF. Average air temperatures calculated from this data are shown in Figure 7.

The average air temperature for the first half of Test 2-2 was approximately 80°F, compared to only 40°F for the first half of Test 2-3. Moisture cells, oven-dried samples, and back-calculated moduli from periodic falling weight deflectometer (FWD) tests were used to track moisture content changes. These three methods indicated that moisture equilibrium was reached before trafficking Test 2-3, and moisture conditions remained constant throughout Tests 2-3 and 2-2 (7).

TABLE 3 SUMMARY OF PAVEMENT RESPONSE DATA FOR LANE 2

Tire	Load (lb)	Pressure (psi)	Temp. (F)	Surface Deflection (0.001in)	Surface Between (micro)	Strain Under (micro)	Binder Strain (micro)
Radial	9,400	76	82.9	5.6	-224	-306	331
Radial	9,400	108	81.7	--	-214	-287	287
Radial	9,400	140	82.2	6.6	-249	-259	307
Radial	14,100	76	79.2	--	-351	-500	508
Radial	14,100	108	78.4	--	-343	-456	504
Radial	14,100	140	78.8	--	-367	-503	553
Radial	19,000	76	78.6	20.3	-527	--	664
Radial	19,000	108	78.3	22.9	-479	--	673
Radial	19,000	140	78.4	22.8	-496	--	699
Bias	9,400	76	85.6	8.0	-224	-287	357
Bias	9,400	108	86.5	7.9	-238	-242	285
Bias	9,400	140	82.9	9.5	-323	--	385
Bias	14,100	76	85.6	14.0	-447	--	617
Bias	14,100	108	84.9	14.3	-474	--	655
Bias	14,100	140	85.1	15.1	-503	--	712
Bias	19,000	76	88.5	19.9	-609	--	857
Bias	19,000	108	88.0	20.1	-662	--	885
Bias	19,000	140	89.4	20.0	-663	--	870

Note "-" denotes compression.

"--" denotes data unavailable.

Thickness and density are two construction variables that have a significant impact on flexible pavement performance. The structural capacity of a pavement is influenced directly by the thickness of the component layers, and density affects the stiffness of paving materials. Pavement layer thicknesses were obtained by differential leveling during construction. Table 4 presents average layer thicknesses for Tests 2-3 and 2-2. Both the asphalt concrete and the crushed aggregate base were approximately 0.5 in. thinner in Test 2-2 than Test 2-3.

In-place densities of the subgrade soil and crushed aggregate base were measured with a nuclear density gauge during construction. The asphalt concrete wearing and binder densities were obtained using cores from untrafficked areas of each section. Table 5 presents average layer densities for Tests 2-2 and 2-3. These data indicate the materials in both test sections were well compacted. The air void content of the asphalt layers and the density of the crushed aggregate base and subgrade were slightly higher in Test 2-2 than in Test 2-3.

The overall effect of the construction variability was evaluated using nondestructive testing. Deflections for each layer were measured with a falling weight deflectometer. The deflection at the middle of the loading plate was used in conjunction with layer theory to calculate a composite modulus. This composite modulus is a measure of the structural capacity of the pavement. Table 6 presents average composite moduli for FWD tests conducted at the surface of each layer. These data show Test 2-2 initially had a lower structural capacity than Test 2-3.

In summary, Test 2-2 represents a worst-case condition. In addition to the higher tire pressure, the pavement temperature during testing was also higher, and the initial structural capacity was lower than Test 2-3.

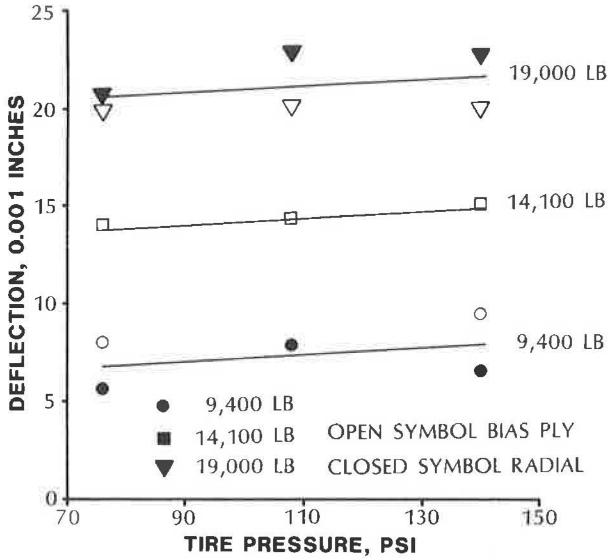

FIGURE 4 Effect of tire pressure on surface deflection for Lane 2.

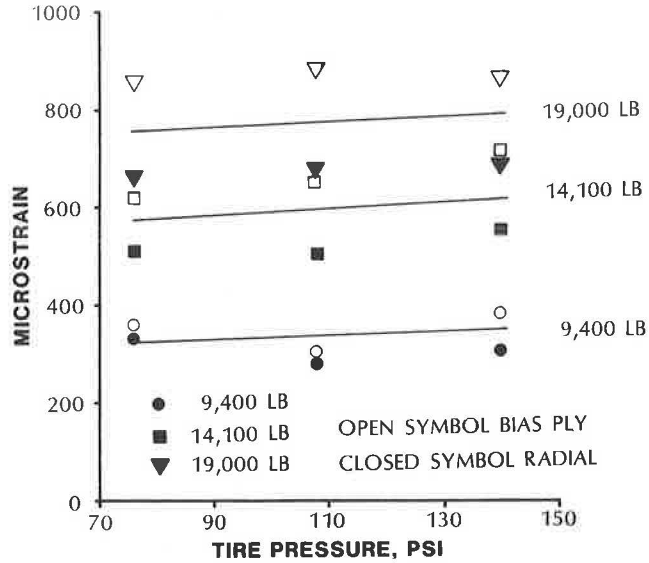

FIGURE 6 Effect of tire pressure on strain at the bottom of the asphalt layer for Lane 2.

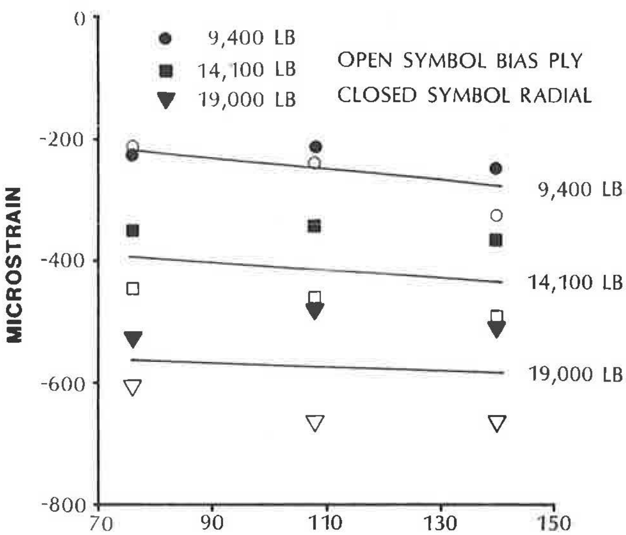

FIGURE 5 Effect of tire pressure on surface strain for Lane 2.

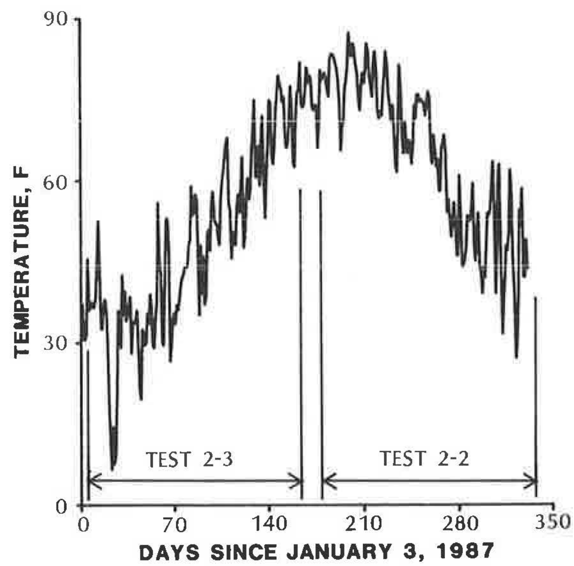

FIGURE 7 Average air temperatures during Tests 2-2 and 2-3.

Results

At the PTF, rutting and cracking data were collected periodically during trafficking. Rutting was obtained by differential leveling at 10 locations along each test section. At each location, the elevation of the pavement surface was measured every 6 inches across the pavement to produce a transverse profile. To eliminate initial surface irregularities from the rut depth data, profiles obtained before trafficking were used as references. Subsequent profiles were subtracted from the appropriate reference to calculate rut depths.

A manual procedure was also used to measure cracking. On a regular schedule, a clear plastic sheet was placed over the test section and the cracks were traced onto the plastic. Different color markers were used each time a crack survey was performed. The test section was then divided into eight 4-ft long by 6-ft wide subsections. The length of cracking in each subsection was measured with a map wheel, and the surface area of AASHTO Class 2 and Class 3 cracking was estimated.

Comparisons of average rutting and cracking for Tests 2-3 and 2-2 are presented in Figures 8 and 9. The comparisons show Test 2-2 had significantly higher rutting than Test 2-3, and cracking began much sooner in Test 2-2. These effects were the result of the higher tire pressure, higher temperature, and thinner pavement structure in Test 2-2.

Analysis

After each test section failed, a postmortem evaluation was conducted in an area of the test section exhibiting average

TABLE 4 AVERAGE PAVEMENT THICKNESSES

	Thickness (in.)	
Layer	Test 2-2	Test 2-3
Asphalt concrete	6.8	7.3
Crushed aggregate base	11.2	11.8
Total	18.0	19.1

rutting and cracking. This evaluation consisted of excavating each layer of the pavement, and obtaining profiles, density measurements, and samples for laboratory testing. The findings of these evaluations were used in conjunction with layer theory to estimate the relative influence of tire pressure, temperature, and thickness on the observed rutting and cracking.

Profiles obtained from the postmortem evaluations indicated that the majority of the rutting in Tests 2-3 and 2-2 occurred in the crushed aggregate base. This rutting is generally governed by the vertical compressive strain at the top of the crushed aggregate base. The ELSYM5 computer program was used to calculate this strain for various temperatures using the load, pavement thicknesses, and tire pressures from the PTF tests.

Moduli for the asphalt concrete at different temperatures were obtained from Figure 10, which shows the modulus-versus-temperature relationship for the PTF asphalt concrete, based on indirect tension tests on cores removed from the pavement shortly after construction. The moduli of the crushed aggregate base and subgrade were assumed constant at 20,000 psi and 8,000 psi, respectively.

Figure 11 presents the calculated vertical compressive strains at the top of the crushed aggregate base. These data show temperature had the greatest effect on this strain. Assuming an average pavement temperature of 40° and 80°F for the first half of Tests 2-3 and 2-2, respectively, temperature accounted for 66 percent of the increase in the calculated strain at the top of the crushed aggregate base. Tire pressure accounted for 18 percent of the increase, and the 0.5-in. difference in asphalt thickness accounted for the other 12 percent.

Thus, the difference in rutting between Tests 2-3 and 2-2 was due mainly to the higher temperature during Test 2-2. Test 2-2 was trafficked in the summer and fall under relatively high pavement temperatures, while Test 2-3 was trafficked in the winter and spring under much lower pavement temper-

TABLE 6 AVERAGE COMPOSITE MODULI

	Composite Moduli (ksi)	
Layer	Test 2-2	Test 2-3
Subgrade	7.0	8.4
Base	12.0	15.4
Wearing	41.5	49.4

TABLE 5 AVERAGE LAYER DENSITIES

	Test 2-2	Test 2-3
Subgrade		
Average Dry Density, pcf	125.0	119.5
AASHTO T180 Max. Dry Density, pcf	121.7	121.7
Crushed Aggregate Base		
Average Dry Density, pcf	149.3	146.2
AASHTO T180 Max. Dry Density, pcf	152.4	152.4
Lower Lift Binder		
Average Density, pcf	158.3	158.0
Average Air Voids, %	4.3	4.4
Upper Lift Binder		
Average Density, pcf	155.9	161.1
Average Air Voids, %	5.7	2.6
Wearing		
Average Density, pcf	153.8	154.9
Average Air Voids, %	5.4	4.7

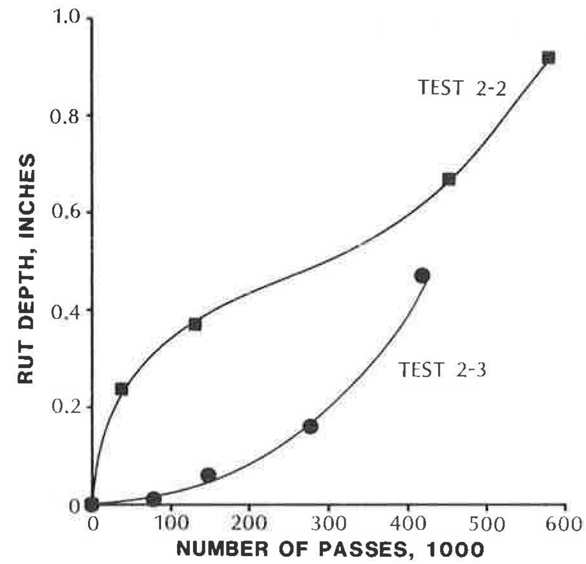

FIGURE 8 Average rutting for Tests 2-2 and 2-3.

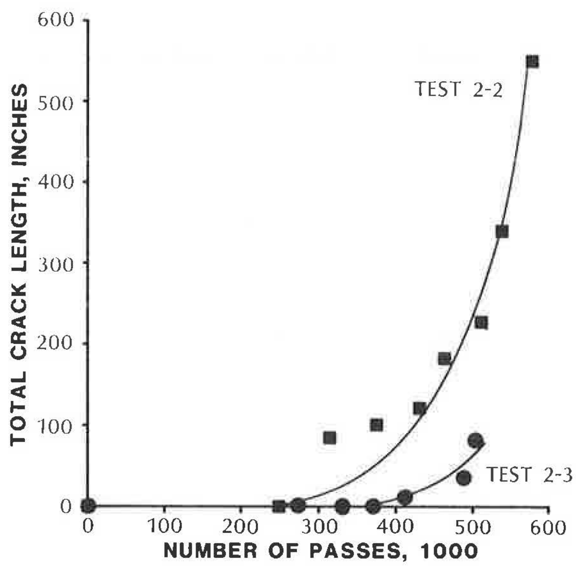

FIGURE 9 Average cracking for Tests 2-2 and 2-3.

atures. The vertical compressive strain at the top of the crushed aggregate base increased with increasing temperatures. At high temperatures, this strain was further increased by higher tire pressure, and decreasing asphalt thickness.

The failure mode for Tests 2-3 and 2-2 was fatigue of the asphalt concrete. This type of failure is generally governed by the tensile strain at the bottom of the asphalt layer. The ELSYM5 computer program was used to calculate this strain for various temperatures using the load, thicknesses, and tire pressures from the PTF tests. The moduli described in the rutting analysis were also used in this analysis. The fatigue damage caused by one repetition of the load for each test condition was calculated using Miner's Law and the following distress prediction model for fatigue cracking (*6*):

$$N_f = K_1 \left(\frac{1}{e_t}\right)^{3.29} \left(\frac{1}{E^*}\right)^{0.85}$$

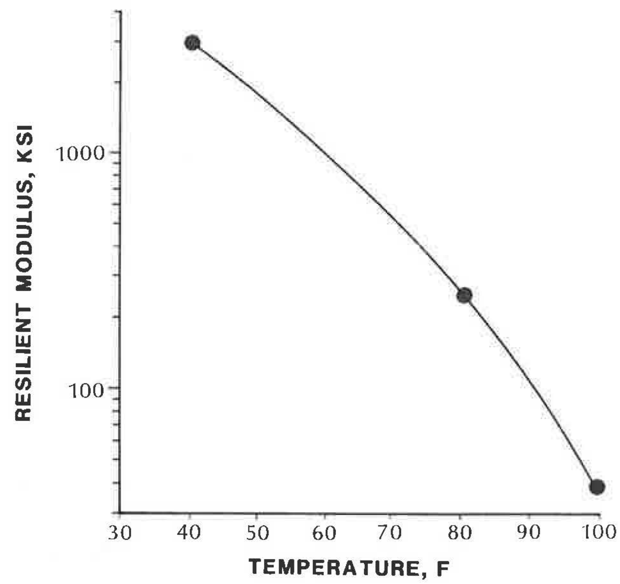

FIGURE 10 Resilient modulus versus temperature curve for PTF asphalt concrete.

where

N_f = fatigue life,
e_t = tensile strain at the bottom of the asphalt layer,
E^* = dynamic modulus of the asphalt layer, and
K_1 = constant.

Figure 12 presents this damage normalized with respect to 70°F, 100-psi tire pressure, and the thickness for Test 2-3. These data show the combined effects of temperature and difference in pavement thickness had the greatest effect on fatigue damage. Assuming average pavement temperatures of 40° and 80°F for Tests 2-3 and 2-2, respectively, temperature only accounted for 14 percent of the difference in expected fatigue damage. At the higher temperature, however, the 0.5-in. difference in asphalt thickness accounted for 53 percent of the difference in expected fatigue damage, while the increased tire pressure accounted for only 33 percent of the difference.

Thus, the difference in cracking between Tests 2-3 and 2-2 was due mainly to the combined effects of high temperature and thinner pavement structure. This combination accounted for 67 percent of the difference in expected fatigue damage.

SUMMARY AND CONCLUSIONS

The effects of tire pressure on flexible pavements were evaluated in two ways. First, pavement responses, deflections, and strains for various combinations of load and tire pressure were measured and compared. Second, rutting and cracking for two test sections trafficked with the same load but different tire pressures were evaluated.

The response evaluation showed tire pressure had little effect on the measured responses at all load levels. Increasing the tire pressure from 76 to 140 psi accounted for only a 2- to 10-percent increase in surface deflection, surface strain, and strain at the bottom of the asphalt layer.

The performance evaluation showed increased rutting and

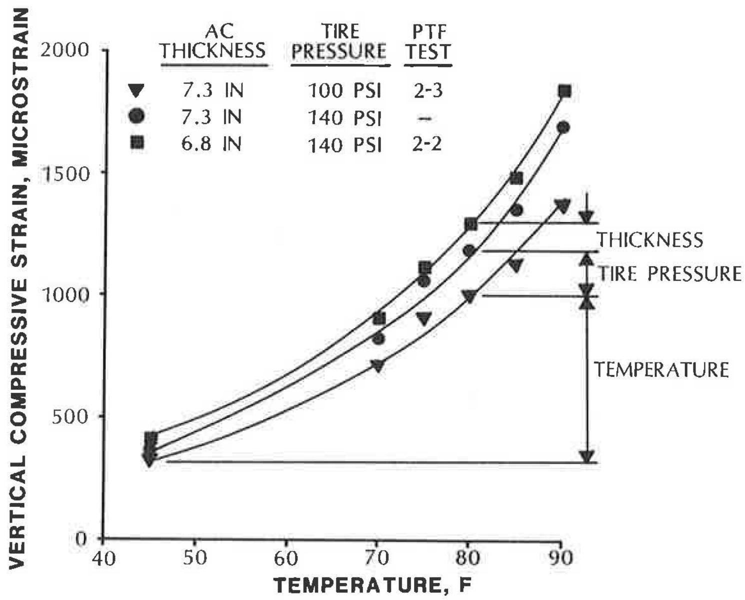

FIGURE 11 Vertical compressive strain at the top of the crushed aggregate base course based on ELSYM5.

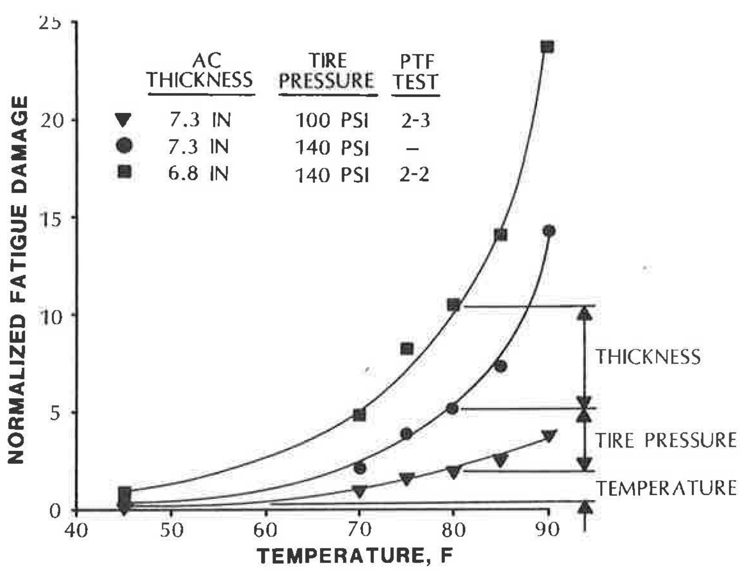

FIGURE 12 Expected fatigue damage.

cracking for the test section trafficked with the 140 psi tire pressure. However, this section was thinner and was trafficked at a higher temperature than the 100 psi test section. An analysis of pavement strains using layer theory showed the increased rutting resulted mainly from the higher temperature. A similar analysis showed the increased cracking resulted mainly from the combined effects of higher temperature and thinner pavement structure.

FUTURE RESEARCH

The PTF permits the study of pavement response and performance under controlled loading conditions. The facility, however, does not provide environmental control. The results of this study show that for the pavement sections studied, the effects of tire pressure on pavement performance were masked by differences in pavement temperature between the two tests. By moving the ALF between two test sections on a weekly basis, it may be possible to factor out the environmental effects. Various methods for moving the ALF are currently being studied. If a method proves feasible, a similar tire pressure study will be repeated at the PTF during a future phase of research.

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