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16. Abstract

This report includes the results of an analytical study of the effects of automobile tire loads on thin asphalt pavements over flexible bases. Two different ways of calculating the tire contact pressure were used and the strains induced in the pavement structure were evaluated. The uniform pressure tire model assumes that the tire contact pressure is equal to the tire inflation pressure. The Tielking tire model is a finite element computer program that models the tire as a shell of revolution and calculates the contact pressure distribution by using the tire carcass properties and the tire load.

The contact pressure distributions were used in ILLIPAVE to calculate the strains at various locations in a pavement having a surface of thickness ranging from 1 to 4 inches and moduli ranging from 50 to 800 Ksi. A granular base 8 inches thick with 2 different moduli was over a subgrade soil with a modulus of 10 Ksi. The results were analyzed and the findings indicate that automobile tire loads can lead to fatigue failure and rutting problems for certain combinations of surface thickness - moduli over weak bases. The best performance occurred when stiff bases were used.

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EFFECTS OF AUTOMOBILE TIRE LOADS
ON THIN FLEXIBLE PAVEMENTS

by

Freddy L. Roberts

Roberto Urruela

and

Mikael P. J. Olsen

Research Report 345-2F
Research Study Number 2-8-83-345
Performance Considerations and Specifications
of Hot-Mix Asphaltic Concrete

Sponsored by

Texas State Department of Highways and Public Transportation
in cooperation with
U. S. Department of Transportation, Federal Highway Administration

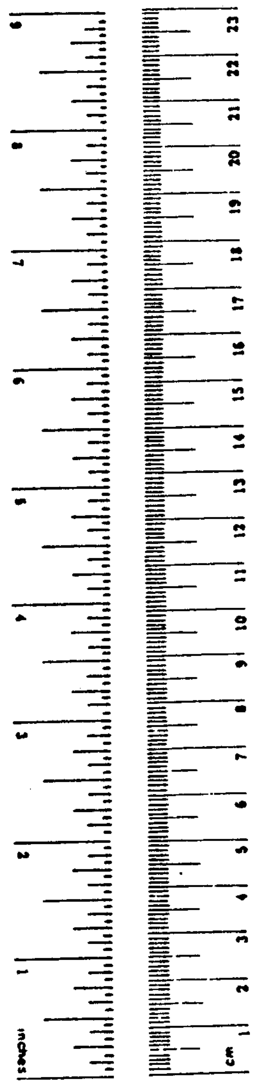
April 1987

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas

METRIC CONVERSION FACTORS

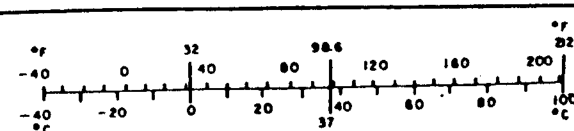
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This is the second and final report dealing with the conditions of use, construction, and specifications of hot mixed asphalt concrete materials used in thin, flexible pavements. This report is an extension of the first report with an emphasis on the effect of automobile tire loads on strains in thin asphalt concrete pavements over flexible bases. Just as in the first report, the analysis in this report is concentrated on an evaluation of strain in thin asphalt concrete pavements and in defining the material property combinations that show strains too large to ensure adequate performance.

This report was completed with the assistance of many people. Special appreciation is extended to Drs. Robert L. Lytton and Thomas Tielking for their help with the computer modeling and to Messrs. James L. Brown and Robert L. Mikulin of the Texas State Department of Highways and Public Transportation for their encouragement and constructive criticism. Appreciation is also extended to the secretarial staff of the Materials, Pavements, and Construction Division of TTI who prepared the manuscript materials. The support of the Federal Highway Administration, Department of Transportation, is gratefully acknowledged.

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Roberto Urruela
Mikael P.J. Olsen

SUMMARY

This report summarizes the results from an analytical study to determine the material properties and thicknesses of asphalt surface layers needed to provide adequate resistance to fatigue cracking for thin flexible pavements being subjected to automobile tire loads. The analytical study includes the effects of an important parameter not generally considered in these studies: the tire contact pressure distribution.

Results indicate that the effects of tire inflation pressure on strain are very important. These results show that surface materials which served adequately when automobile loads are assumed to be applied at 26 psi contact pressure can fail when very high repetitions of automobile tire loads are actually applied at a contact pressure of 65 psi. The contact pressure distributions used in the study were developed from a finite element computer program that models the tire using its constituent elements. The contact pressure distributions were for a typical radial automobile tire that carried two different loads of 800 and 1320 pounds per tire. These contact pressure distributions were then used to evaluate the effect of surface and base properties and thicknesses. The results indicate that (1) thick and stiff granular bases provide the best protection for the subgrade soil, especially for thin surfaces, (2) that current asphalt materials can serve adequately if stiff bases are used and if surface thicknesses around 2-inches are avoided, and (3) on weak bases the thin, very flexible surfaces or the thick, very stiff surfaces provide the best opportunity for achieving a reasonable fatigue life.

IMPLEMENTATION STATEMENT

Based on the findings from this study it is apparent that thin layers of conventional asphalt concrete materials should be used with caution on granular bases. Flexible pavements with surfaces around 2-inches thick combined with weak granular bases should probably not be used at all.

Evaluations of the results from this study show that for flexible pavements over unbound, granular bases the surface thickness and stiffness combinations affect the tensile strains significantly and that bituminous surfaces of

(1) 1-inch or less should be very flexible and placed on very stiff bases,

(2) 2 to 4-inches should be stiff and strong and placed on stiff bases, and

(3) around 2-inches should probably not be placed on weak bases since the strains are very high and early cracking is expected.

In considering the use of 1 to 3-inch bituminous surfaces, careful consideration should be given to the number of loads to be applied by trucks since a relatively small number of these loads can lead to premature failure even though the automobile loads can be handled adequately. Therefore, the results of this project indicate that intermediate surface thicknesses should be used only after a careful analysis of each pavement structure to ensure that overstressing of the surface does not occur.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure | Page

CHAPTER I

INTRODUCTION

Most studies of the effect of wheel loads on thin flexible pavements have exclusively considered truck tire loads which usually make up less than 10 percent of the traffic. The automobile tire load has been considered to cause minor damage compared to the truck tire load, especially since the AASHO Road Test findings.

The purpose of this study is to take a closer look at the response of thin flexible asphalt pavements subjected to passenger car tire loads by modeling the tire using two different models, the Tielking tire model and the uniform pressure model. These tire models describe the intensity of the pressure distribution and the area of the surface over which the load is applied. With the uniform pressure model, the tire load is represented as a uniform pressure equal to the inflation pressure which is spread over a circular area with no lateral shear stresses produced by the tire rolling on the surface. Studies conducted by the tire industry have shown that the contact pressure is not uniform but rather has a unique shape, depending on the type and structure of the tire. The Tielking tire model reflects more accurately the effect of the tire carcass on the contact pressure distribution at the roadway surface.

The first part of this report describes the computer programs used in this study along with the two tire models used to estimate the interaction between the tire and the road surface.

The second part of the report consists of the study results which included tire pressure and tire load effects as well as thickness and modulus effects on strain in thin flexible pavements. These strains are used to estimate the fatigue and rutting life of a thin flexible pavement subject to passenger car tire loads.

CHAPTER II

LAYERED SYSTEM CONCEPTS

Pavement designers are making increased use of theoretical structural analysis techniques. A major reason is the ease of use and availability of computer programs. There are, however, a number of potential pitfalls involved in using these techniques including input data reliability, a tendency to use the analysis as an end in itself rather than as a tool, a tendency to blindly use computer programs as "black boxes" with complete trust in the results, and, perhaps, a lack of experience and appreciation of the sensitivity of the design factors and their effect on results. Even though these programs are a great help in making pavement design more fundamental in nature, the pitfalls should be clearly recognized.

The theoretical layer methods allow the engineer to calculate stresses, strains and deflections at selected points in the pavement structure. The stresses and strains most often considered are the vertical compressive stress at the top of the subgrade and the horizontal tensile strain at the bottom of the asphalt layer.

The following input information is required in order to conduct an elastic layered structural analysis of a flexible pavement:

1) wheel load and tire pressure
2) modulus of each layer material, and of the subgrade
3) Poisson's ratio of each layer material (the ratio of lateral displacement to vertical displacement)

Currently, there are a number of computer models available to perform structural analysis including ELSYM5, CRANLAY, PLANE, BISAR, ILLIPAVE, etc. (1).

The ILLIPAVE (2,3) computer program was selected primarily for two reasons:

1) non-uniform tire contact pressure distributions had to be accepted as input in order to successfully model tire contact pressure distributions, and

2) the modulus of non-stabilized pavement layers had to be modeled as stress sensitive materials.

In this computer program, the pavement is modeled as a three-dimensional pavement section by using a two-dimensional half-space of a cylindrical finite solid as shown in Figure 1. This rectangular half-space is then divided into a set of rectangular elements connected at their nodal points as shown in Figure 2.

One of the significant features of the ILLIPAVE finite element model of pavement analysis is the ability to incorporate both nonlinear and linear stress-strain behavior of component pavement materials (Figure 3).

Loading in ILLIPAVE is specified using the surface contact pressure and the radius of the loaded area. The loading is of the "flexible plate" type, i.e., a uniform circular contact pressure. The ILLIPAVE input was modified to allow a non-uniform pressure distribution to be calculated and input directly as nodal forces (1).

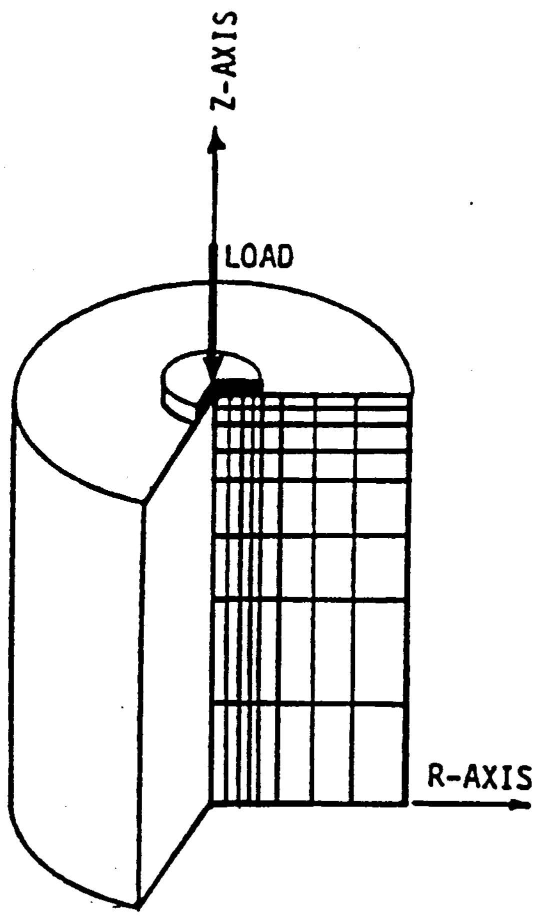


Figure 1

Cylindrical pavement configuration

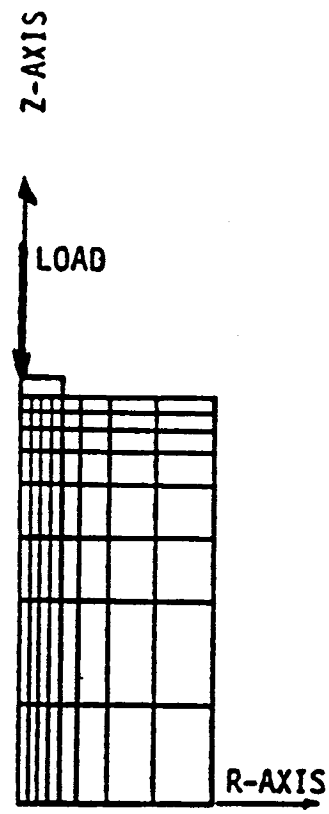


Figure 2

Rectangular half space of an axisymmetric solid

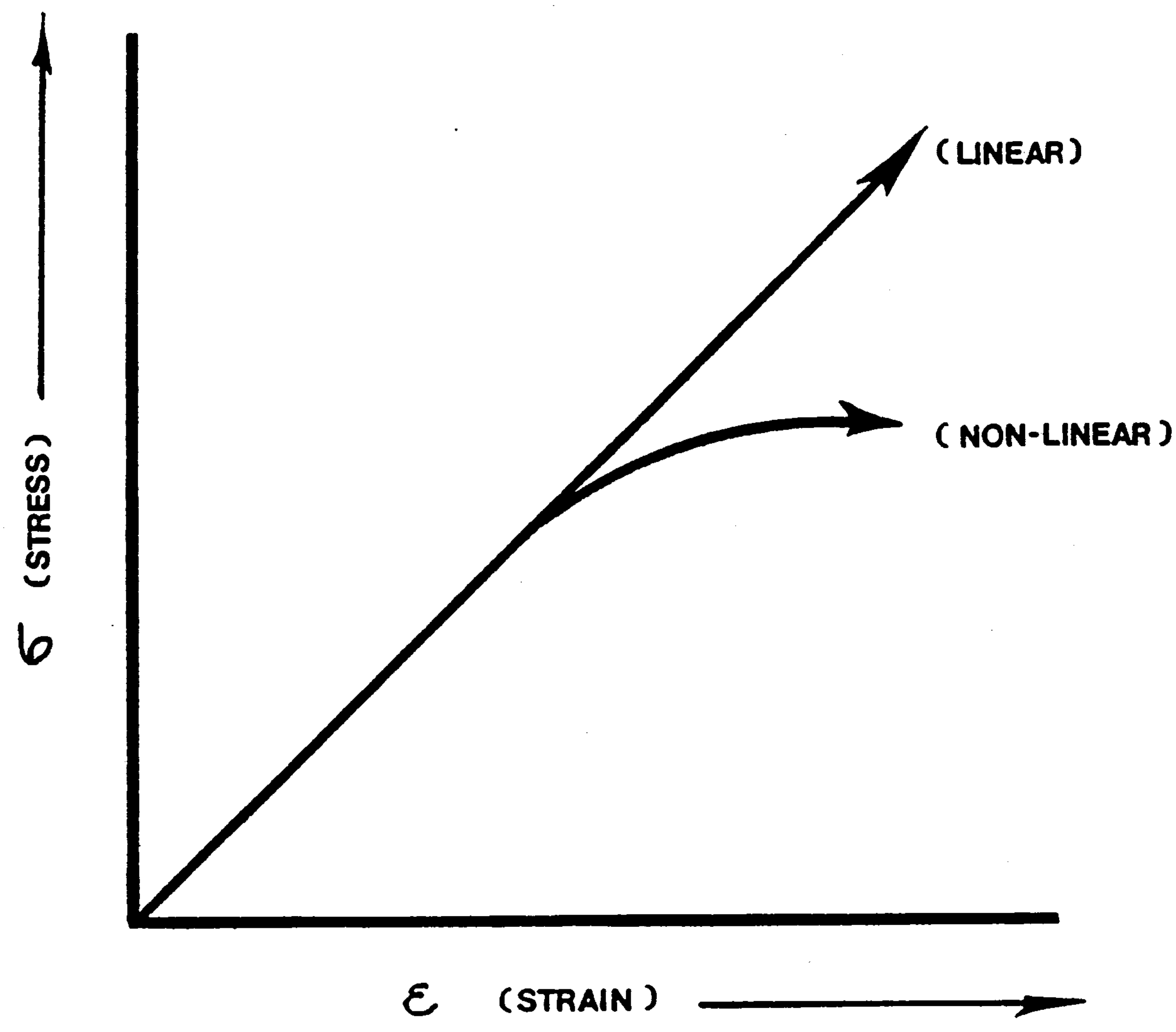


Figure 3. Stress-strain behavior of pavement materials.

CHAPTER III

TIRE MODELS

Historically, initial analysis of the state of stress on solid bodies involved the use of a point load applied to a uniform elastic material of semi-infinite extent; later analysis techniques included striploads of finite width and infinite length. As analysis of pavement systems became more sophisticated, the pavement was considered to have more than one layer and also began to include a model of the tire as a circle of uniform vertical pressure with no surface shear forces. In more recent years, highway engineers have begun to use finite element models developed for tire carcass analysis to define the stress conditions that occur at the tire-pavement interface.

Tielking Tire Model

The finite element tire model used in this study was originally developed for the Federal Highway Administration as part of an analytical and experimental investigation of tire-pavement interaction (4). The program was developed to provide the capability for calculating the distributions of sliding velocity and normal pressure at the tire-pavement contact interface. Tielking (4) chose a relatively general, nonlinear, finite element shell of revolution computer program to be the foundation for the finite element tire model. A Fourier transform procedure was developed and incorporated into the finite element program, giving this tire model the unique capability of calculating the contact boundary and interface pressure distribution for a specified tire deflection.

The shell elements used in the tire model are orthotropic. A material property subroutine was developed to generate orthotropic moduli from cord to rubber property data and geometric data describing the ply structure in the tire carcass. Although the shell elements are homogeneous orthotropic, they are sensitive to details of the carcass design including tire materials and geometry.

The tire is modeled by an assemblage of axisymmetric curved shell elements. The elements are connected to form a meridian of arbitrary curvature and are located at the carcass midsurface. Figure 4 shows the assembly of 22 elements along the midsurface of a G78-14 tire. A cylindrical coordinate system is used, with r, w, and z indicating the radial, circumferential, and axial directions respectively. Each element forms a complete ring which is initially axisymmetric with respect to z. The elements are connected at nodal circles (numbered in Figure 4).

The elements are homogeneous orthotropic with a set of moduli specified for each individual element. The orthotropic moduli for each element are determined by the ply structure surrounding the element.

The finite element is clamped at the edges (node 22 in Figure 4), pressurized, and rotated to induce centrifugal force loading. It is then brought into contact with a rigid, frictionless surface perpendicular to the plane of symmetry (the specified loaded radius, R), measured from the z-axis. The internal pressure, the angular velocity, and the loaded radius are the only operating variables specified prior to calculating contact deformation and pressure in the contact region. Reference 4 describes the mathematical procedures used to calculate the contact pressure distribution and deformation of the tire deflected against the pavement.

The deflected shape of a nylon tire meridian passing through the center of the contact pressure is plotted in Figure 5 for a tire deflection of 0.9 inches. The calculated tire load is 850 lbs. for a deflection of 0.9 inches.

This finite element tire model is believed to be the first to have the capability of calculating the contact pressure distribution in the footprint of a deflected tire. Such a capability is important because contact pressure has a profound influence on all aspects of tire performance. The finite element tire model permits analytical investigations of the effects of tire design variables on contact pressure distribution.

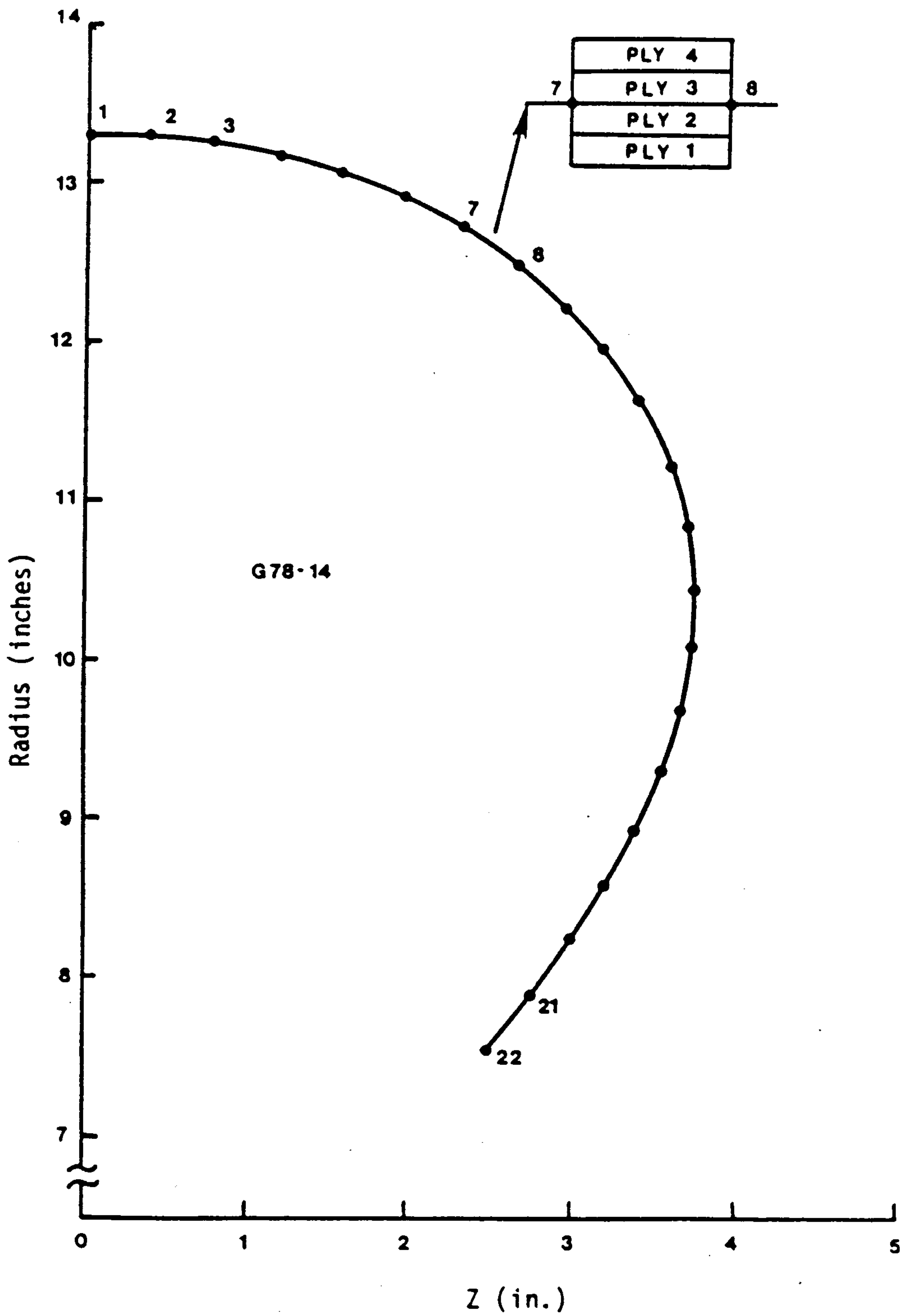


Figure 4. Finite elements positioned on the G78-14 tire carcass mid-surface.

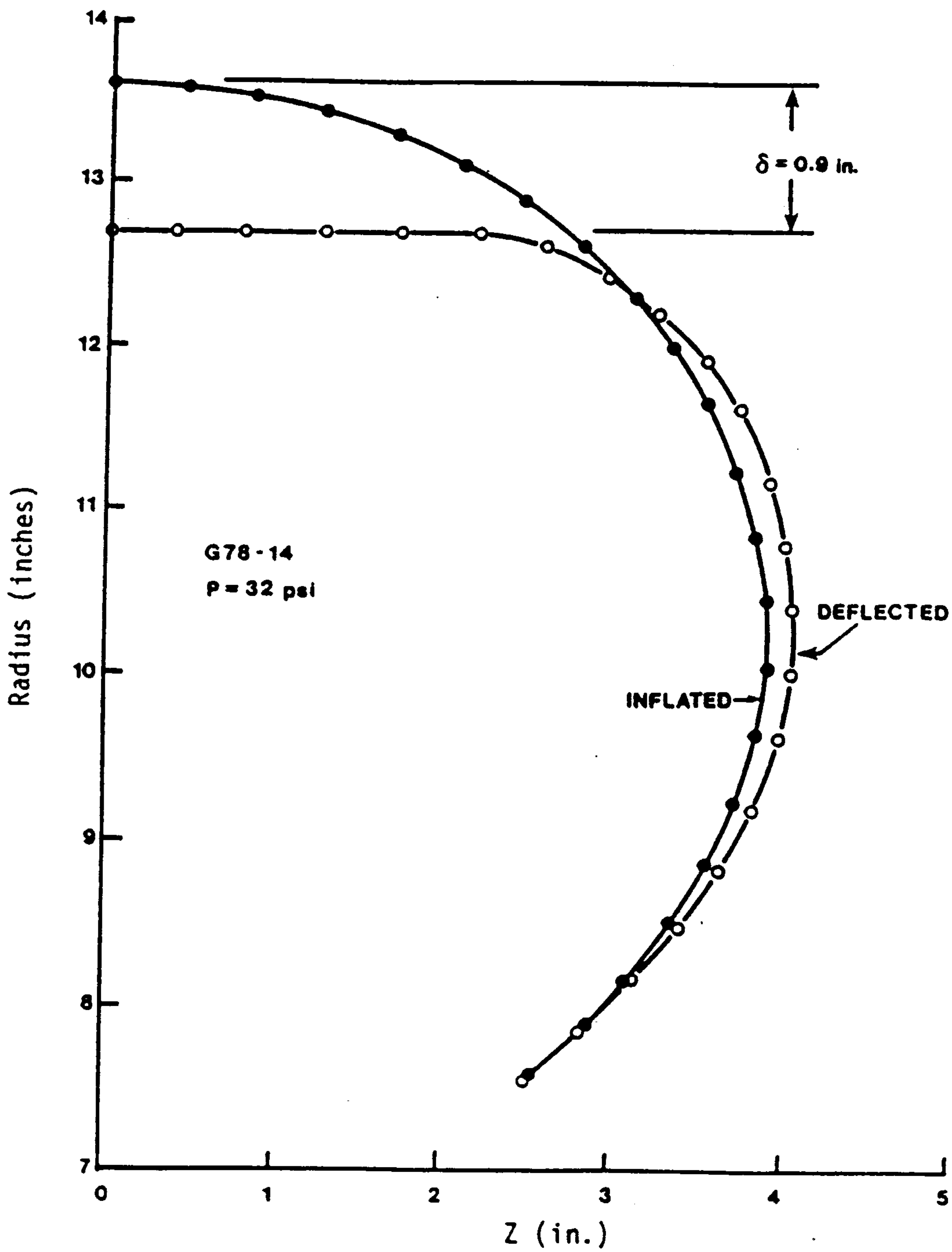


Figure 5. Deflected shape and tire contact pressure distribution results from finite element tire model for a G78-14 tire.

The rolling tire results are calculated by superimposing the angular velocity of the rolling tire on the solution for static contact against a frictionless surface. The sliding velocities of points in the contact region are calculated as outlined in Reference 4. The sliding velocity and the normal contact pressure determine the friction coefficient at each point in the footprint. The resultant braking, driving, and steering shear forces respond to tire operating variables such as inflation pressure, tire load, and slip angle through the influence of these operating variables on the distribution of sliding velocity in the footprint. Tire side forces are similarly obtained by summing the lateral shear forces in the contact region.

Uniform Pressure Model

Early models of tires as circles with uniform vertical pressure did not include the effect of tire construction and lateral shear forces were not included in the analysis; only the inflation pressure and the total tire load were considered important. The tire inflation pressure was assumed to be constant and the radius of the circular tire print calculated as:

$$R = \sqrt{P/\pi p}$$

R = radius of the circular uniform contact pressure, in inches.

P = total tire load, in pounds.

p = inflation pressure, psi.

Notice that the tire contact pressure is assumed to be equal to the inflation pressure. This assumption is true only if the tire basically behaves as an inner tube, i.e., if the tire itself has almost no structural stiffness. Since Tielking and others have shown that the tire does have a structure and that this structure significantly affects the pressure transmitted to the contact surface, a portion of this study includes comparisons between computer runs made using contact pressures from both the uniform and Tielking tire models.

CHAPTER IV

STUDY PARAMETERS AND RESULTS

Study Parameters

Several computer runs were made with ILLIPAVE by varying the surface characteristics such as thickness and elastic modulus and by varying the base modulus.

The surface thicknesses included were 1,2,3, and 4 inches. Taking into consideration the soil types, temperature ranges and moisture levels within the different regions of the state, a range of material properties was selected for typical surface, base, and subgrades. The following set of material property combinations and layer thicknesses were included in the study.

Surface:

- Thickness: 1,2,3, and 4 inches
- Elastic Moduli: 50, 200, 400 and 800 Ksi.
- Poisson's Ratio: 0.3
- Density 145 pcf.

Base:

- Thickness: 8 inches
- Elastic Moduli: 30 and 60 Ksi.
- Poisson's Ratio: 0.4
- Density: 135 pcf

Subgrade:

- Thickness: infinite
- Elastic Modulus: 5 Ksi
- Poisson's Ratio: 0.45
- Density: 120 pcf.

The tire selected for the study was a P205/75R14 radial passenger vehicle tire with an inflation pressure of 26 psi. Two different magnitudes of tire load were used: 1320 and 800 pounds. These two loads correspond to the maximum rated load and a fairly typical tire load on a lightly loaded vehicle.

Study Results

In this study two tire models were used, the Tielking tire model and the uniform pressure model, to analyze the effect of radial passenger-car tires on thin asphalt pavements. The uniform pressure model is used to contrast the effect on the expected life of pavements of using what has previously been assumed in pavement design calculations with the more realistic results of the Tielking tire model. The contact pressure distributions developed using the Tielking tire model are shown in Figures 6 and 7. Figure 6 contains the contact pressure distribution from front to back of the tire along the path of the vehicle. Figure 7 shows the transverse pressure distribution across the middle of the tire. These plots show very strikingly the difference between the predictions from Tielking's model and the uniform pressure model which assumes that the inflation pressure is the same as the contact pressure. To model the tire pressure distribution for 26 psi inflation pressure, the tire load was divided by the loaded area from Tielking's analysis producing an average tire contact pressure of 65 psi. This average contact pressure was used in all of the comparisons of results of the computer runs using the 26 psi contact pressure.

To assess the difference in the effect of the tire models on pavement strains, several types of comparisons have been made using results from ILLIPAVE computer runs. These comparisons include plots to show the effects of tire pressure on horizontal tensile strains in the surface as well as the effects of layer modulus and thickness on strains in the pavement.

Additional analyses include the evaluation of the effects of the tensile strains on predicted fatigue damage and an assessment of the effects of the compressive strains on the permanent deformation in the pavement.

Tire Pressure Effects

A series of computer runs was made and the results were used to analyze the effects of tire pressure on thin pavements using both the Tielking and the uniform tire models. To describe the effects of

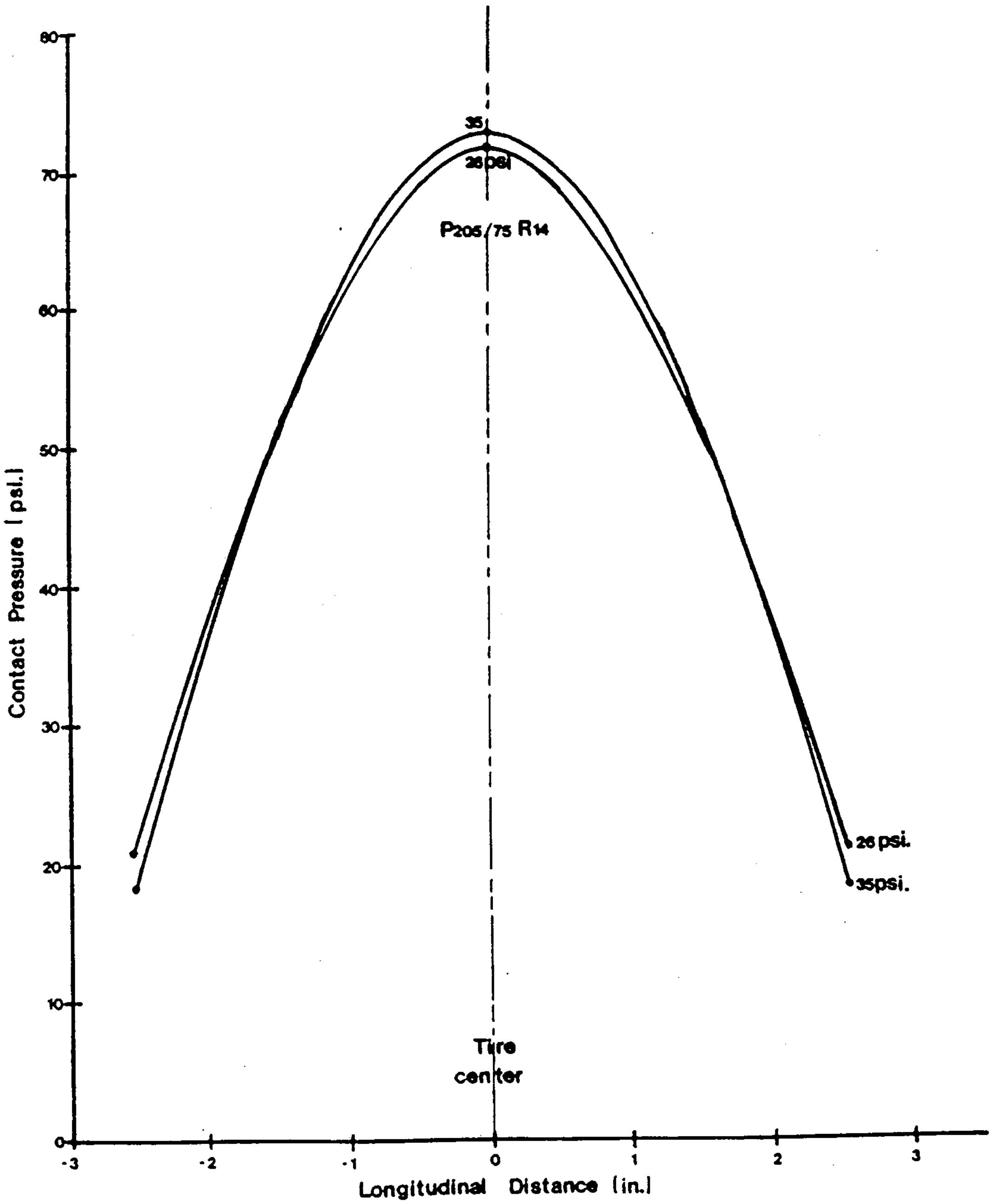


Figure 6. Effect of inflation pressure on footprint pressure distribution of radial passenger car tires.

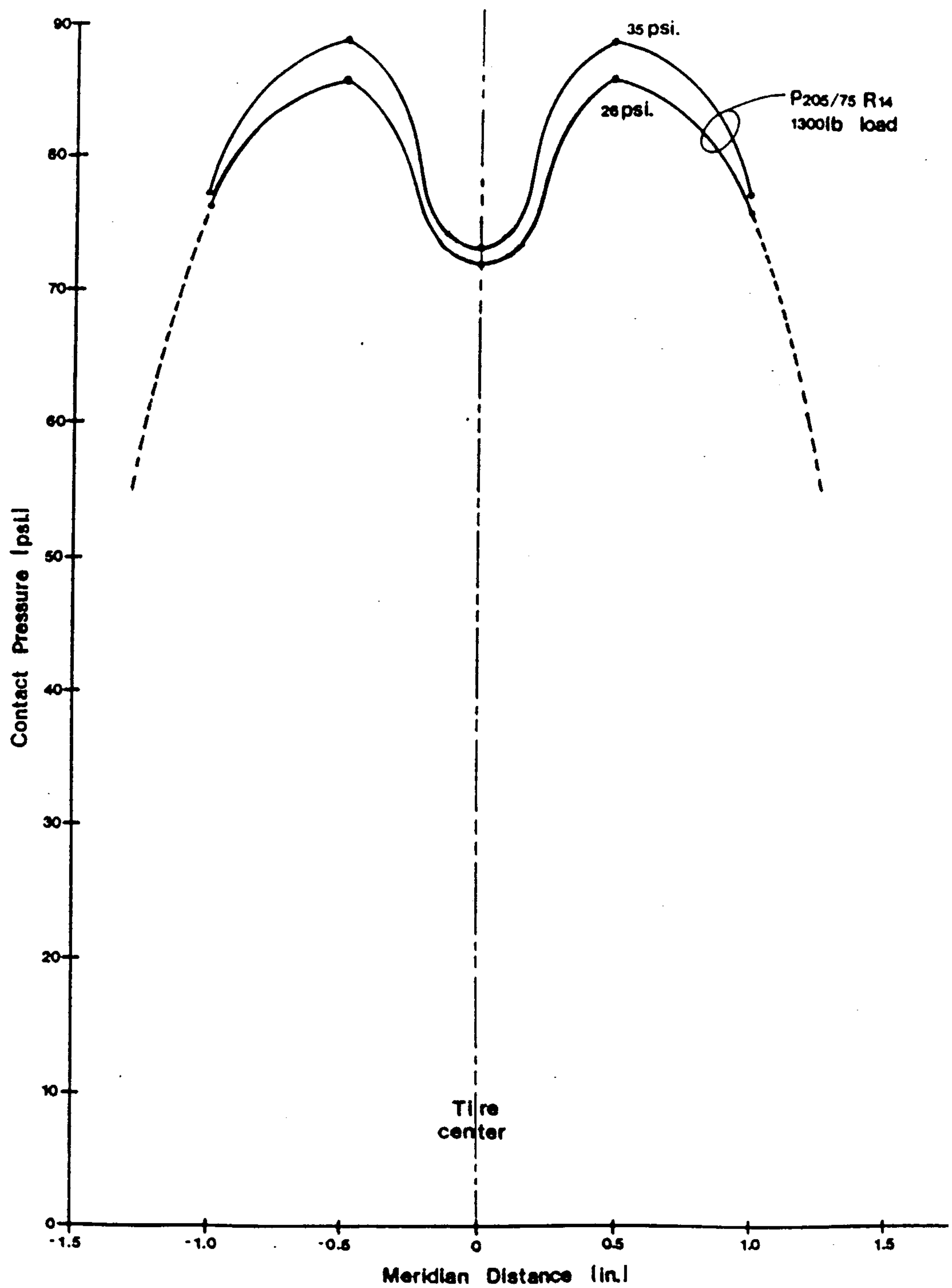


Figure 7. Effect of inflation pressure on footprint pressure distribution of radial passenger car tires.

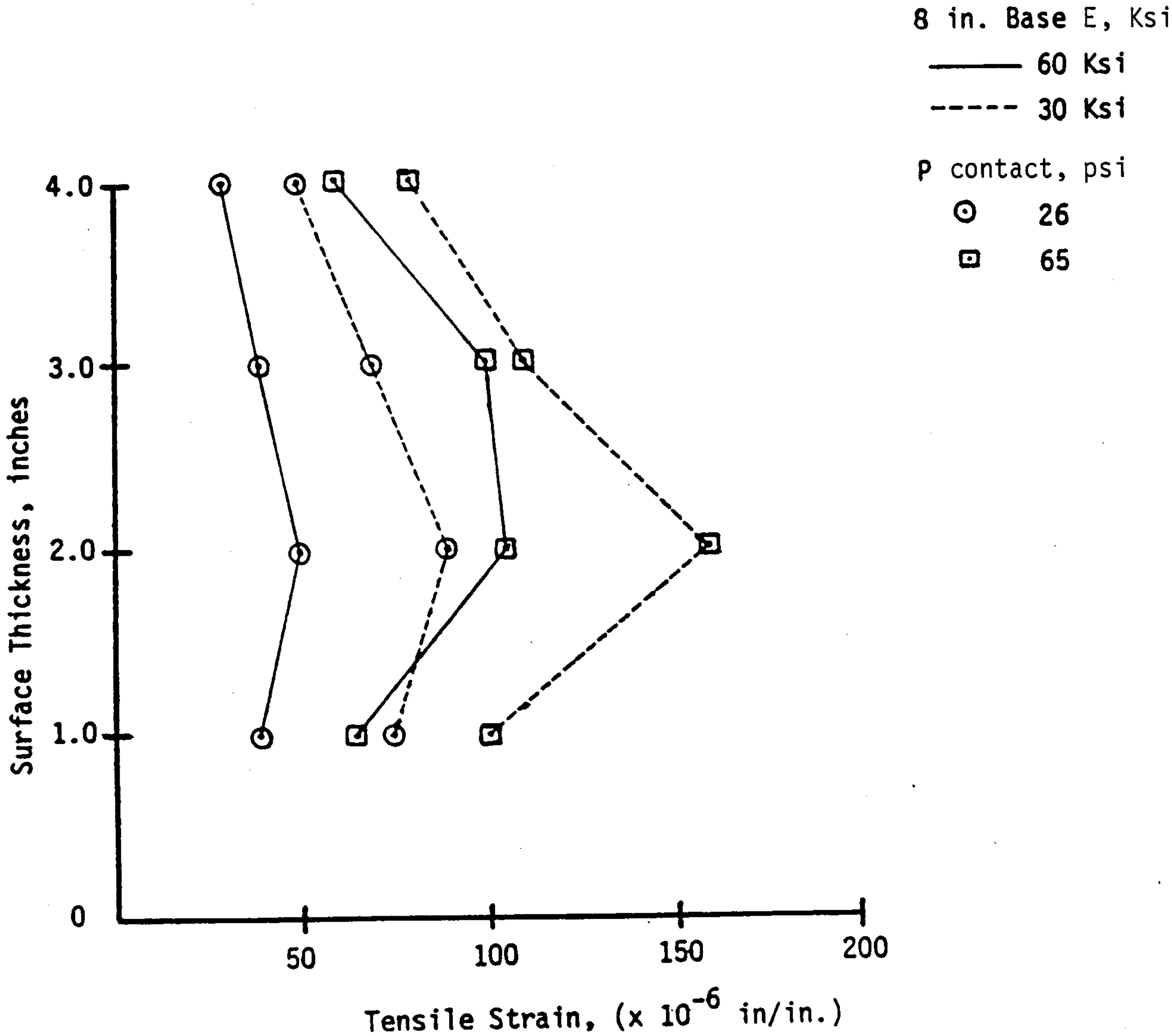


Figure 8. Effect of tire pressure on tensile strain at the bottom of a surface with a modulus of 400 Ksi for a P205/75R passenger tire load of 1320 Lbs.

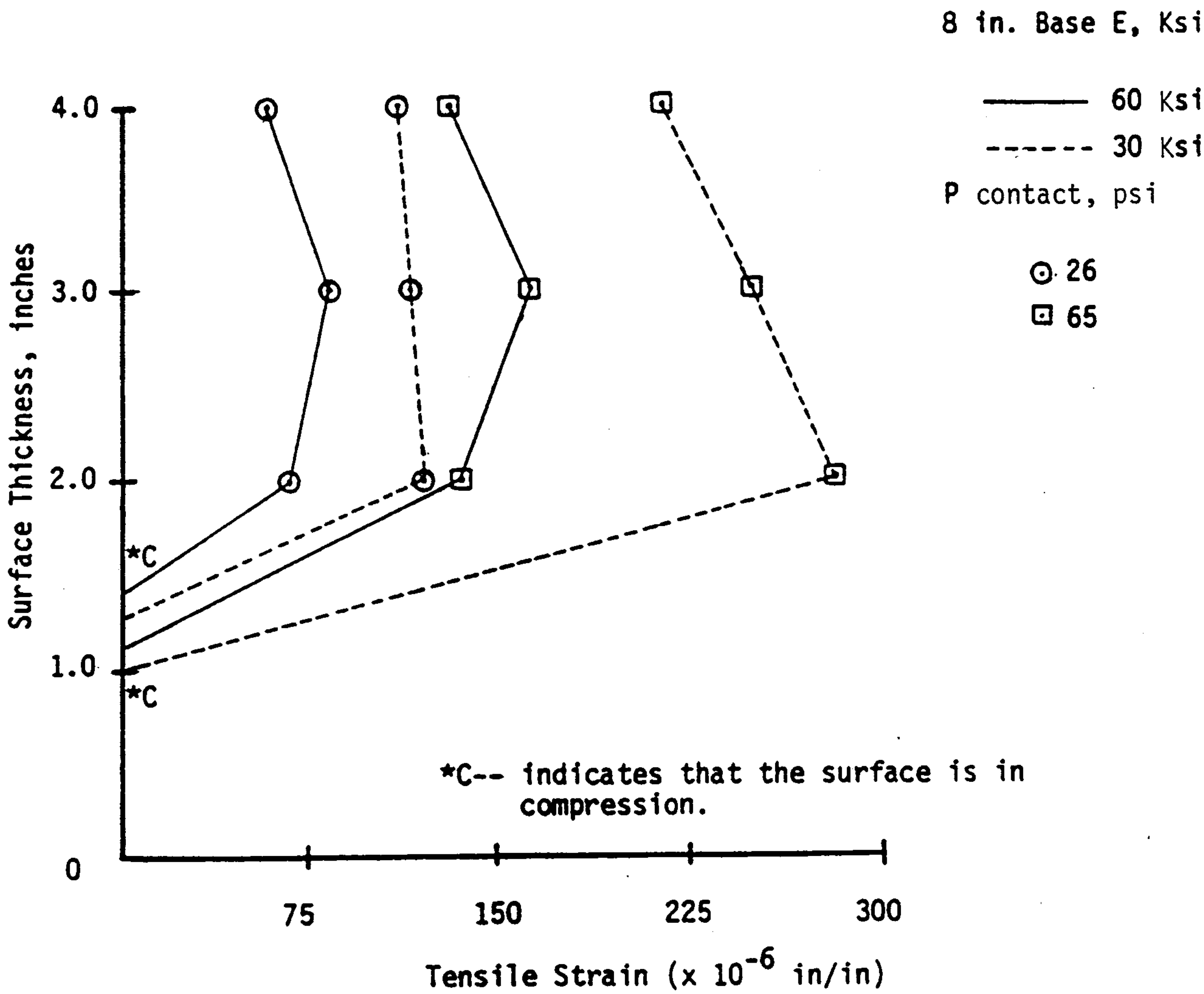


Figure 9. Effect of tire pressure on tensile strain at the bottom of the surface with a modulus of 50 Ksi for a P205/75R passenger tire load of 1320 lbs.

automobile tire pressure on tensile strains at the bottom of the surface, Figures 8 and 9 have been prepared. Figure 8 shows the change in tensile strain for a surface of varying thickness and with a modulus of 400 Ksi

There is an increase in tensile strain as the tire contact pressure increases for both the weak and strong base as shown in Figure 9. Notice in Figure 8 that a 26 psi contact pressure on a 1 inch thick surface with a weak base causes a higher strain than the same pavement under a 65 psi tire pressure but with a stronger base. This demonstrates the importance of providing an adequate base.

For the 60 Ksi base the strains are increased by approximately 100% as the tire pressure model is changed from the 26 psi uniform to the 65 psi Tielking model results and almost as much for the 30 Ksi base, Figure 8. Notice that as the surface thickness decreases from 2 inches to 1 inch all the tensile strains at the bottom of the surface decrease and are moving toward compression.

Comparisons between plots in Figures 8 and 9 show the effect of reducing the surface modulus on tensile strain. Notice that as the surface becomes thinner and the surface modulus decreases, the differences in tensile strains between Figures 8 and 9 are greater. Figure 9 also shows that the thin, low surface moduli combinations experience compression at the bottom of the surface.

If both the surface and base modulus are low, these passenger wheel loads will lead to rapid fatigue failure because the tensile strains are quite high. For the very low modulus surface, Figure 9, the change in contact pressure shown by the 2 models produces strains that are about twice as high for the Tielking model as for the uniform model for both base moduli. Notice that for all cases, when the surface thickness is only 1 inch, the strain at the bottom of the surface is in compression.

Tire Load Effects

With the trend of the automobile industry to build lighter and more efficient cars, two different magnitudes of tire loads were used in this study. The highest load was that for the maximum rated tire load and the second was for a more typical value for vehicular loading.

To describe the effect of automobile tire load on tensile strains at the bottom of the surface, Figures 10 and 11 have been prepared. Figure 10 shows the effect of tire load and pressure on different surface thicknesses having a surface modulus of 400 Ksi over an 8 inch base with a modulus of 30 Ksi. The figure shows that at 26 psi contact pressure the tensile strain increases by about 20 to 25 micro-inches per inch when the tire load is increased from 800 lbs to 1320 lbs. However, for 65 psi contact pressure, increasing the load substantially increases the strain, with increases ranging from 30 to 50 micro-inches per inch. Figure 11 shows similar trends as those shown in Figure 10, the primary difference is that the change in strain due to increased load is lower because the base modulus is higher.

As seen in Figure 11, there is little difference in the tensile strains for the 4 inch surface carrying a tire load of either 800 or 1320 at 26 psi contact pressure. Notice too that the strains are about the same for a 1 inch surface subjected to the two tire loads at both contact pressures. This means that the major effects on tensile strains due to tire loads increments occur for the pavement surface thicknesses between 1 and 4 inches.

Layer Modulus and Thickness Effects

To show the effects of combinations of different surface modulis and thicknesses, base moduli and inflation pressures on strains in the pavement structure, a series of figures was prepared. This analysis is divided into three categories in order to evaluate the effects of surface modulus and thickness on:

1) tensile strains at the bottom of the surface,
2) compressive strains at the top of the subgrade, and
3) tensile strains at the top of the surface.

The two primary distresses considered in this part of the analysis are fatigue and rutting. To evaluate the occurrence of these distresses, the tensile strain in the bottom of the surface is used to evaluate fatigue damage and the compressive strain at the top of the subgrade is used to evaluate rutting.

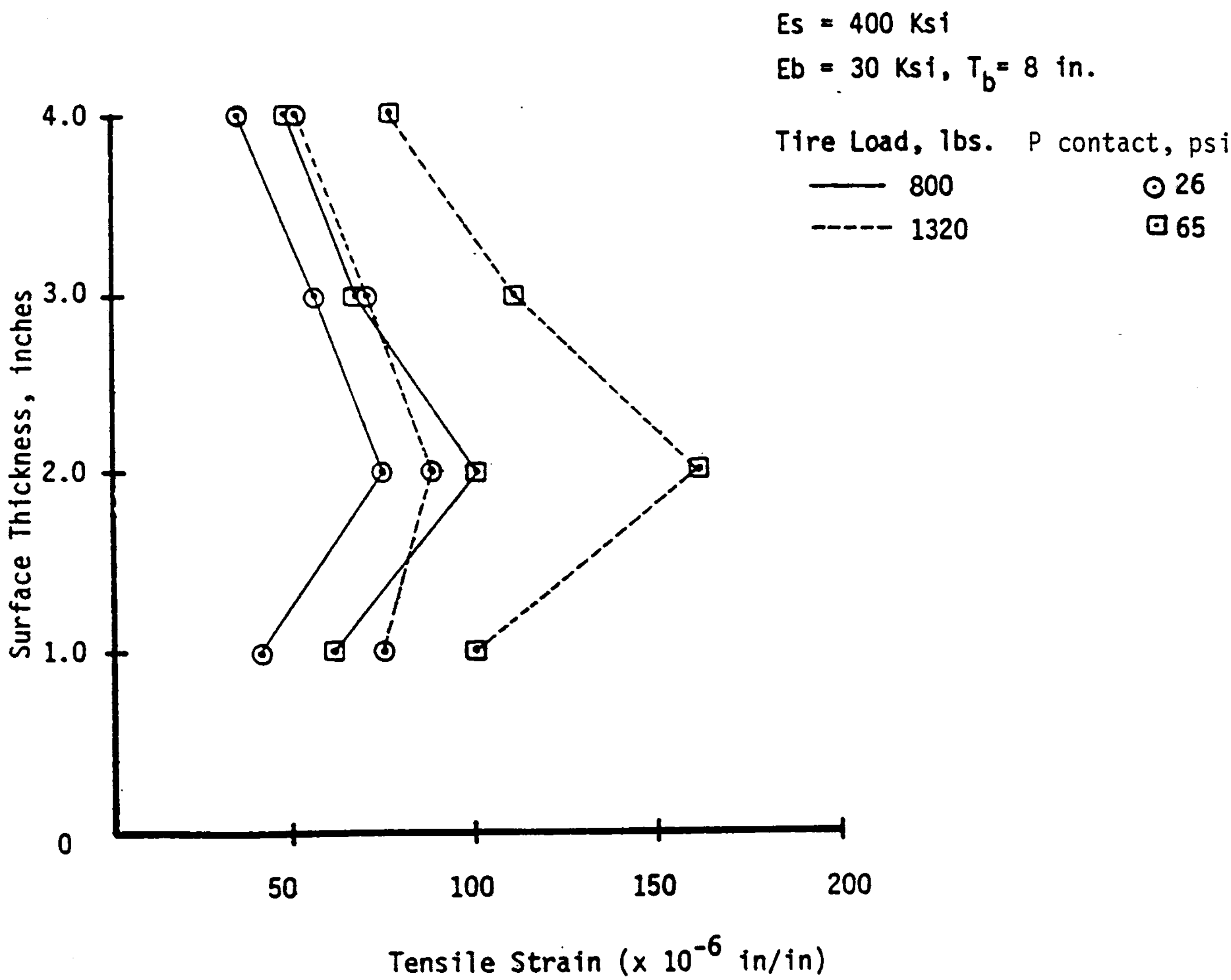


Figure 10. Effect of tire load on tensile strains at the bottom of the surface with a modulus of 400 Ksi and a base modulus of 30 Ksi.

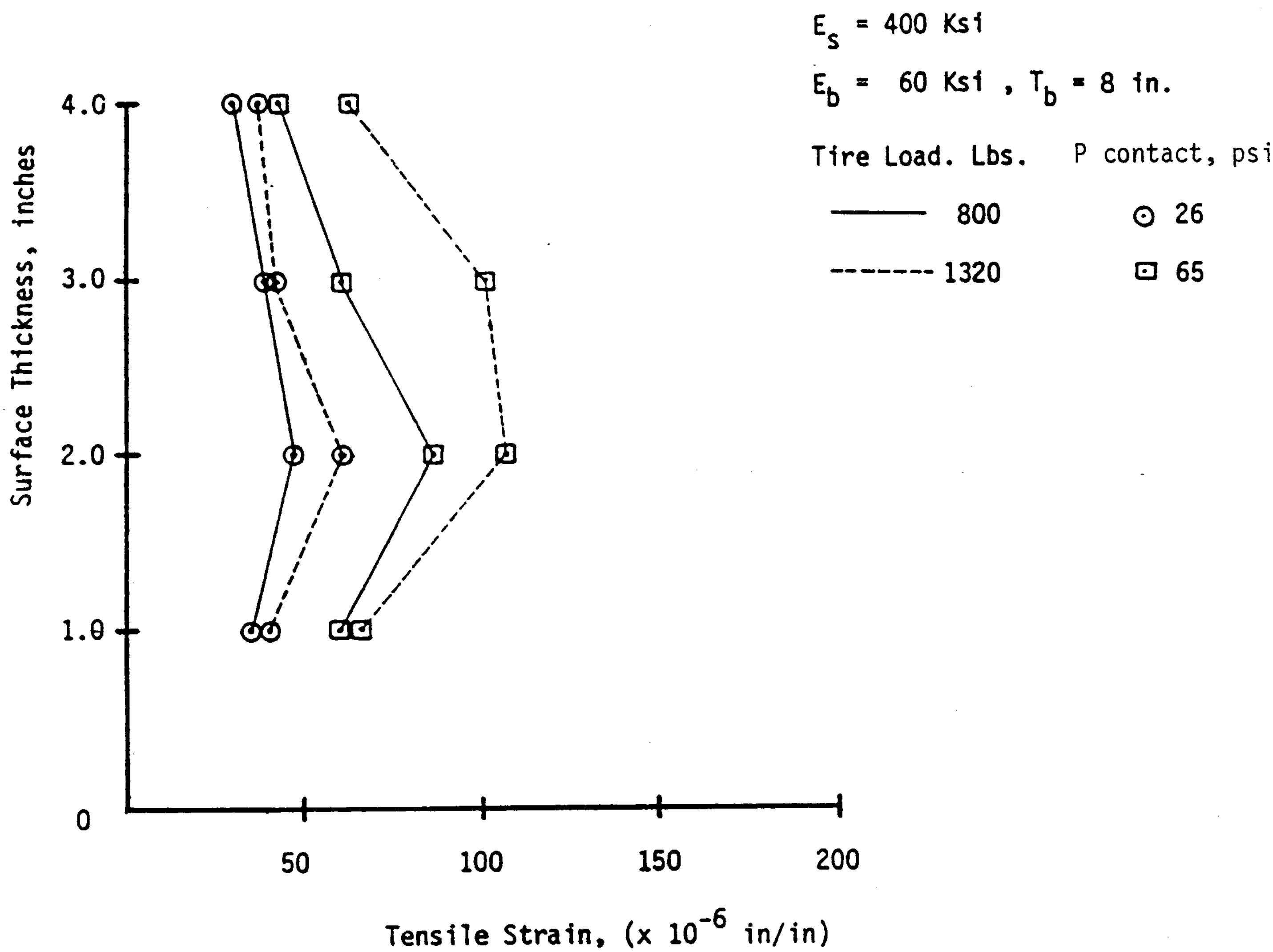


Figure 11. **Effect of tire load on tensile strains at the bottom of the surface with a modulus of 400 Ksi and a base modulus of 60 Ksi.**

Tensile Strain at Bottom of Surface. To control the extent of fatigue damage, the tensile strains at the bottom of the surface must be kept fairly low, the exact level depending on the total traffic and the characteristics of the pavement structure and especially the stiffness and thickness of the surface layer.

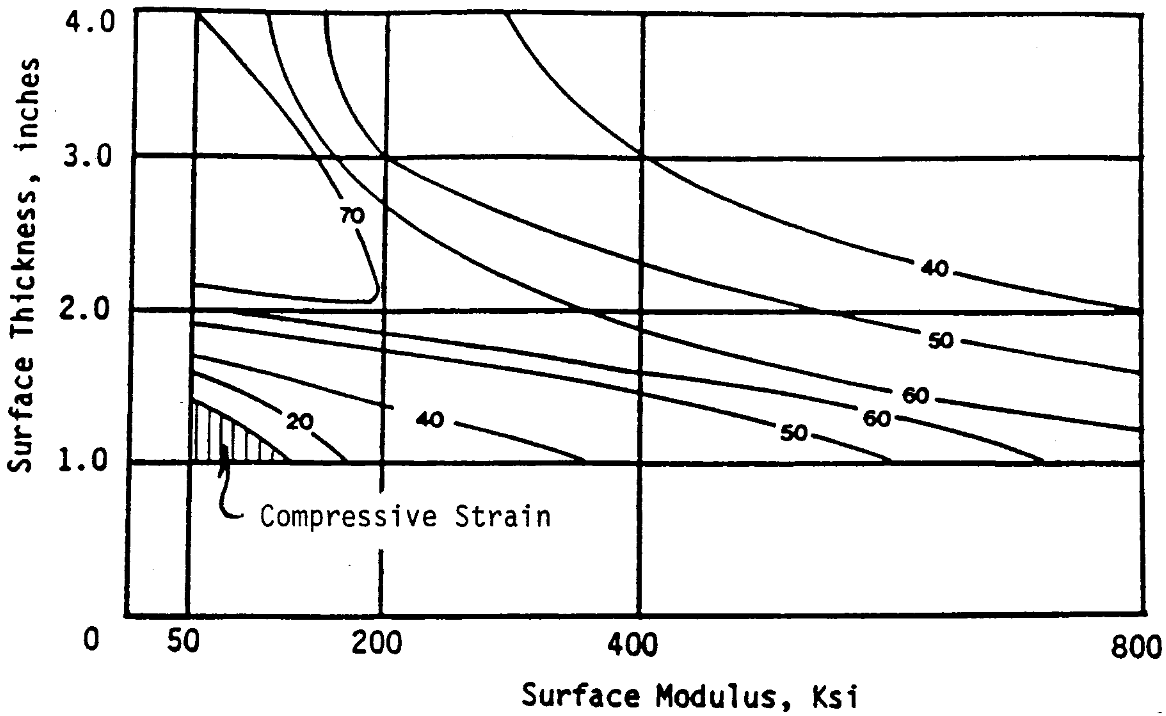
A set of figures was prepared to show the different horizontal tensile strain as a function of surface thickness and modulus for various combinations of tire load and contact pressure. Figure 12 shows the changes in strain produced by increasing the tire contact pressure from 26 to 65 psi for a constant tire load of 1320 pounds. In general, the tensile strains tend to increase as the contact pressure increases. The lowest strains occur in the upper right and lower left corners of the figures with the highest strains occuring generally in the middle and upper left portions of the figures. Figure 13 shows the horizontal tensile strains for the same pavement structure subjected to a tire load of 800 pounds. Comparisons between Figure 12 and 13 show that increasing the load increases the horizontal tensile strains for both tire contact pressures. The difference in tensile strains is not so significant due to the high moduli of the strong base layer.

Figure 14 and 15 are similar to the previous plots except that the base layer has a low modulus. Observe in Figure 14 the effect of increasing the tire contact pressure on the tensile strains is similar to that shown in Figure 12. The percentage increases in the strain are about the same for increases in contact pressure in both Figures 12 and 14.

Comparisons of data in Figures 14 and 15 indicate the effect of incrementing tire load on this particular pavement structure. Again, the lowest strains occur in the upper right and lower left corners of both figures and the highest strains occur in the middle and upper left at the low moduli, thicker surface combinations.

Vertical Subgrade Compressive Strain. Vertical compressive strains have been used as pavement design criteria to indicate whether the total pavement structure above the subgrade is thick enough to protect the subgrade from excessive vertical strain that leads to permanent deformation. A series of figures was prepared to show the effects of

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

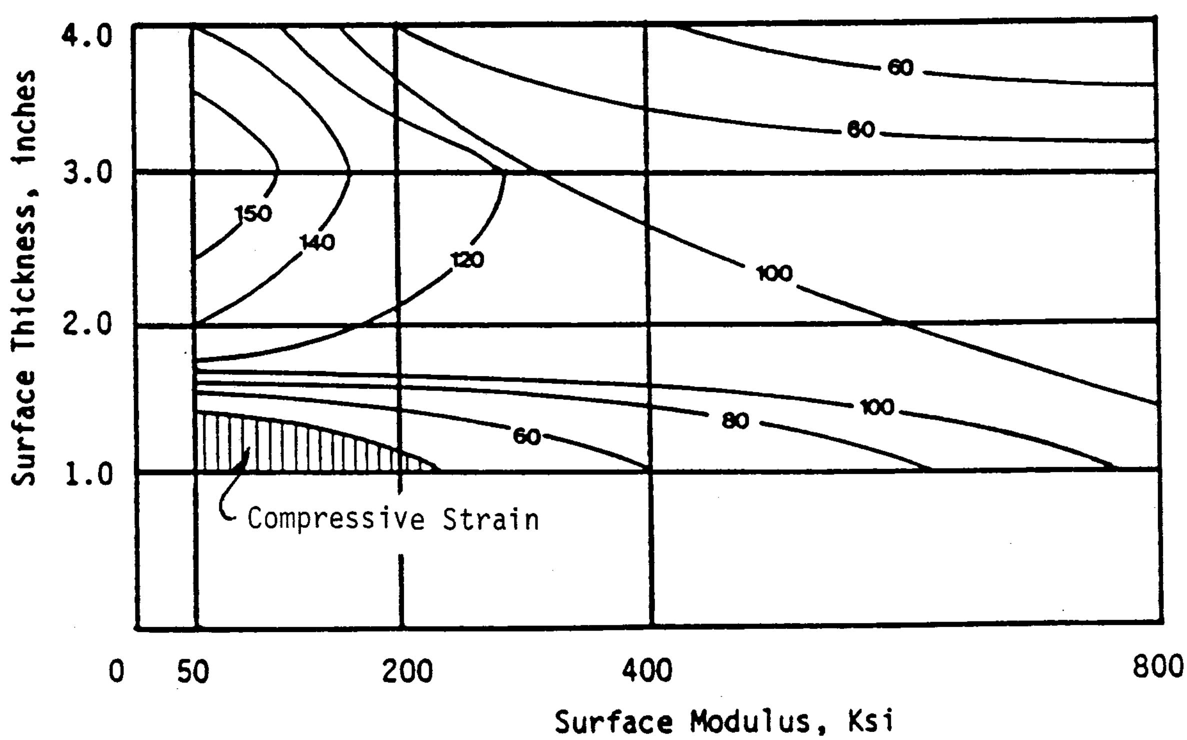


Figure 12. Tensile micro-strain contours at the bottom of the surface for a 60 Ksi base modulus and a tire load of 1320 lbs.

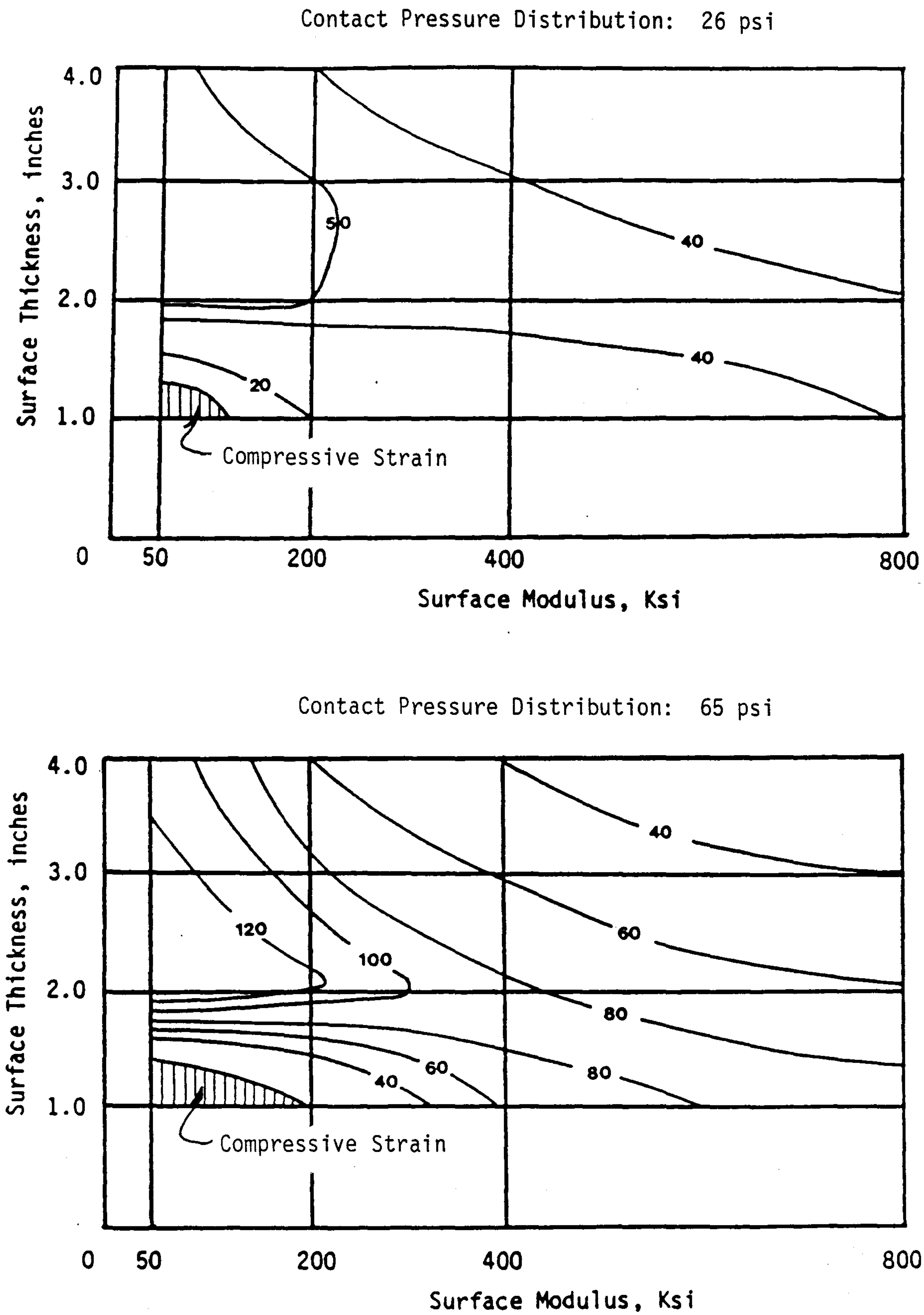
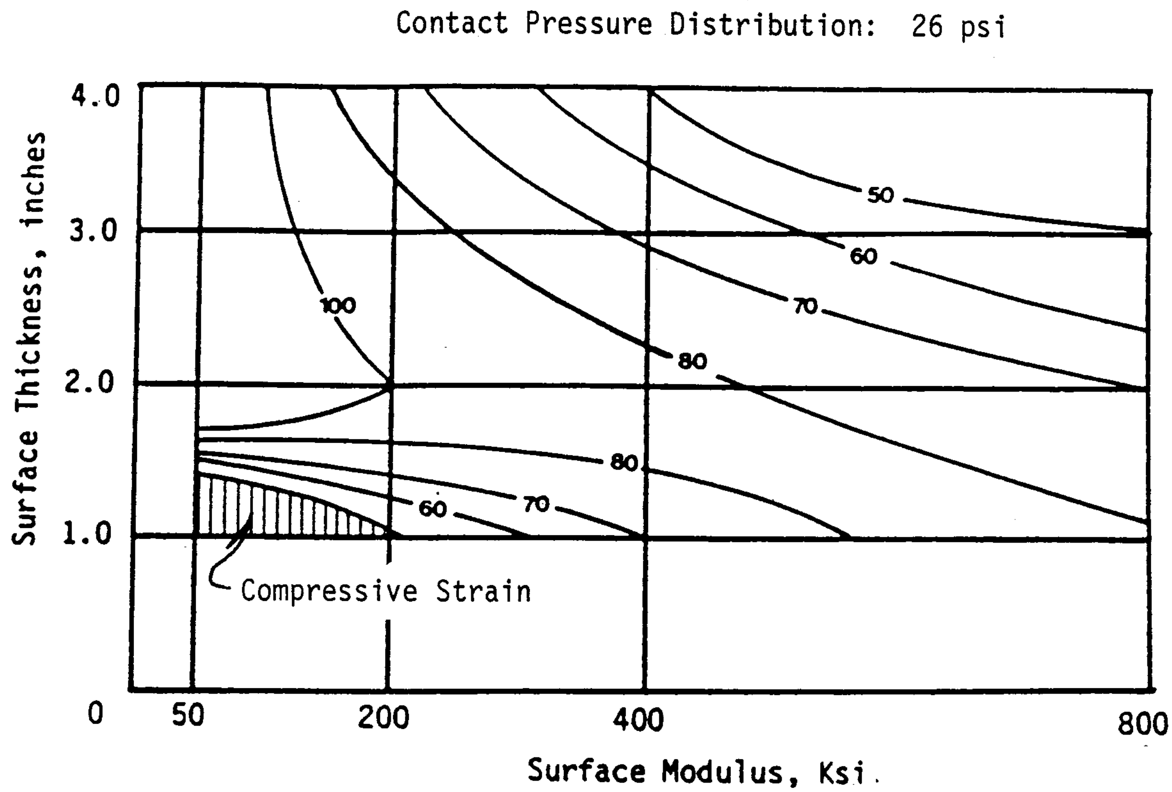


Figure 13. Tensile micro-strain contours at the bottom of the surface for a 60 Ksi base modulus and a tire load of 800 lbs.



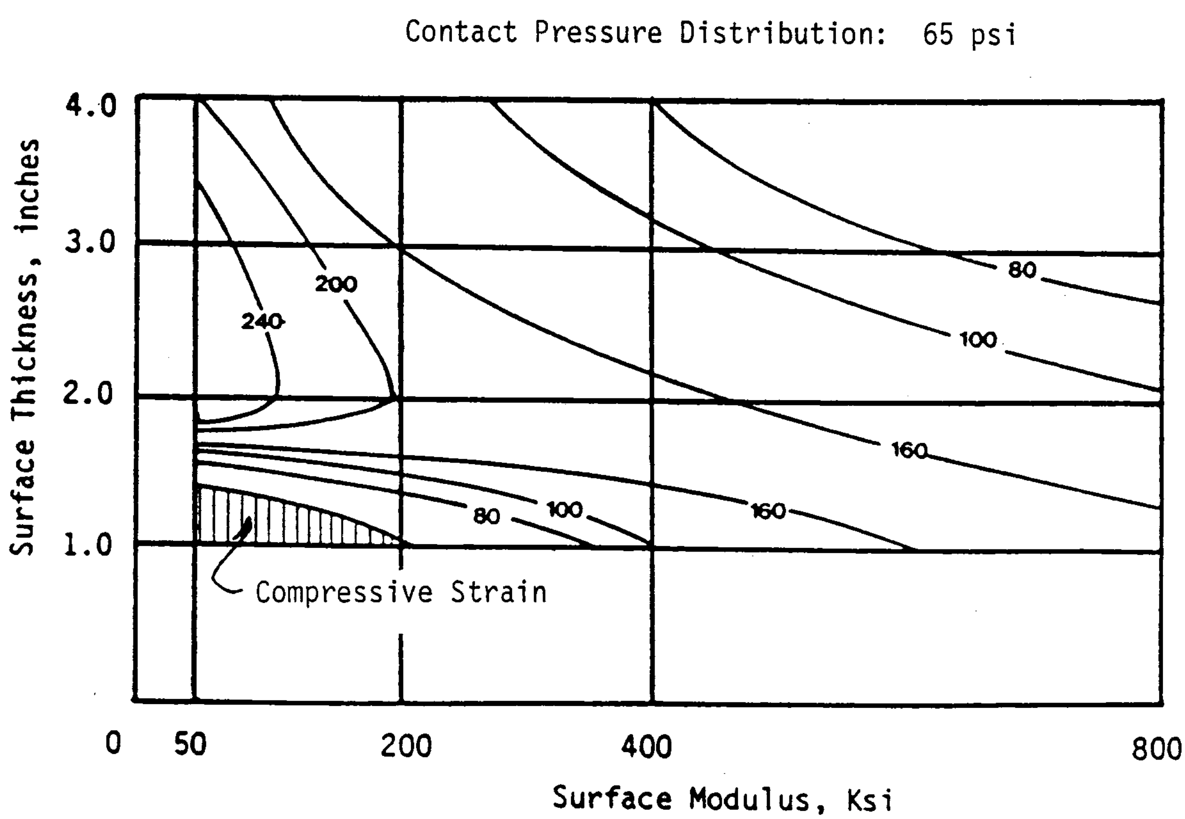
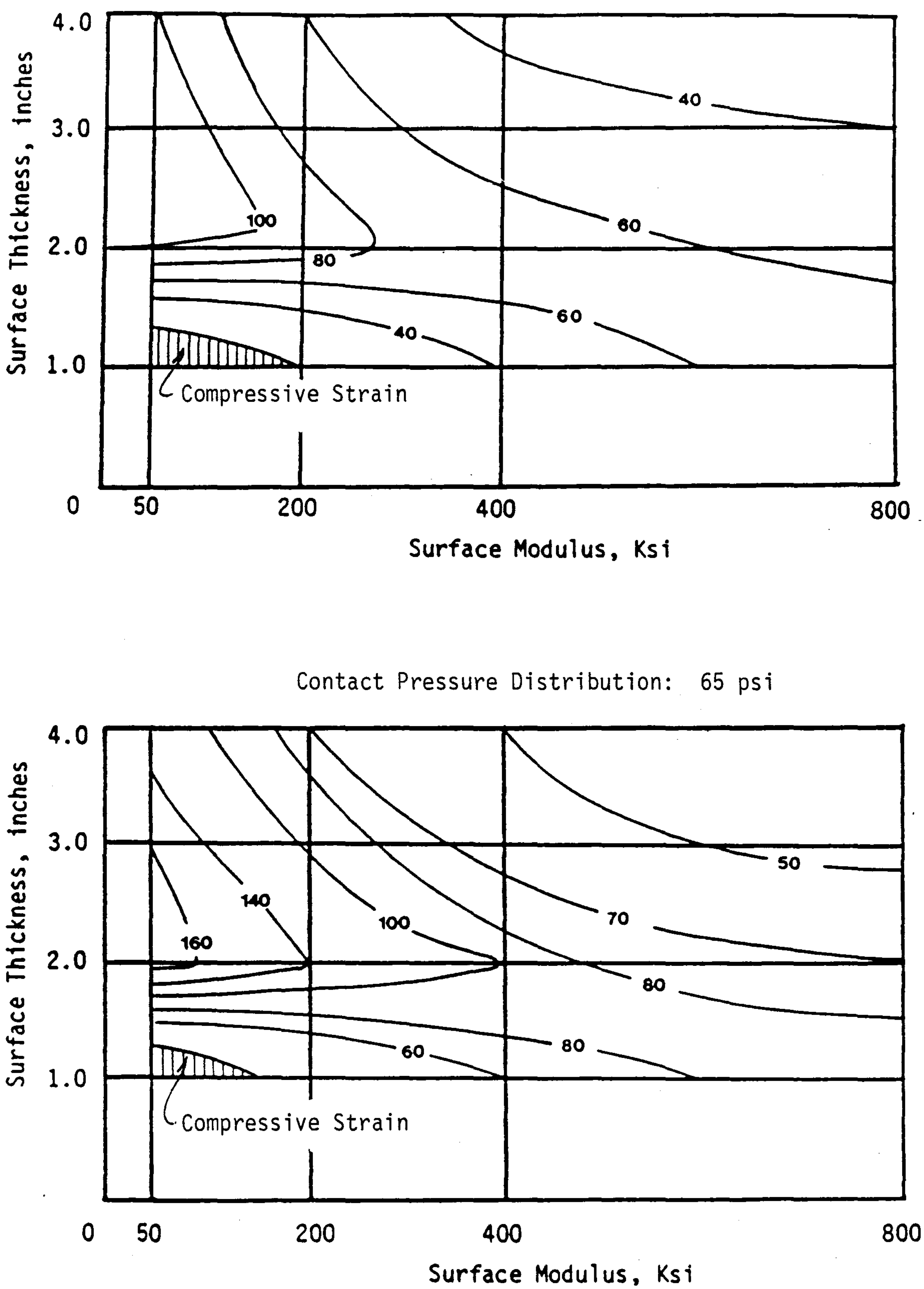


Figure 14. Tensile micro-strain contours at the bottom of the surface for a 30 Ksi base modulus and a tire load of 1320 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

Figure 15. Tensile micro-strain contours at the bottom of the surface for a 30 Ksi base modulus and a tire load of 800 lbs.

surface moduli and thicknesses, and tire loads and contact pressures on strains at the top of the subgrade.

The effect of tire contact pressure on vertical subgrade strain is not significant for the thicker, stiffer surfaces, in fact, the differences in strains in Figure 16 are about 20 micro-inches per inch for surfaces with greater than 2 inches having moduli of 400 Ksi or greater. However, when both surface thickness and modulus decrease, the strain differences are much larger for tire contact pressures between 26 and 65 psi.

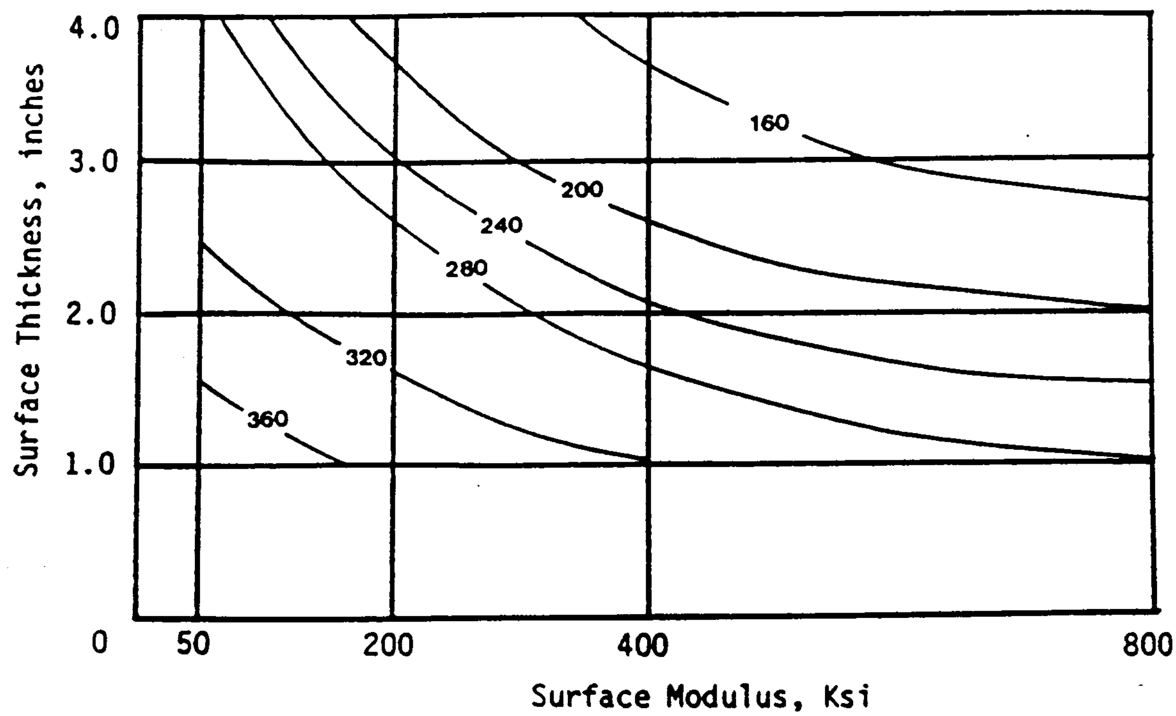
In comparing the results between Figure 16 and 18, a decrease in the base modulus slightly increases the strains for the thick, high modulus surfaces but substantially increases the strains for thin, low modulus surfaces.

Figures 17 and 19 contain plots of the vertical subgrade compressive strain for a tire load of 800 pounds, base moduli of 60 and 30 Ksi, and contact pressures of 26 and 65 psi. The effect of change in tire load on the subgrade strain can best be evaluated by comparing the results in Figure 16 with Figure 17 and the results in Figure 18 with Figure 19. These comparisons show that increasing the tire load has little effect on subgrade strain for the thick, stiff surfaces but has a substantial effect for the thin, flexible surfaces. This trend is true for both the 60 and 30 Ksi bases but the effect is much more pronounced for the 65 than for the 26 psi contact pressure.

Tensile Strain at the Top of the Surface. Tensile strains at the top of the surface are generally lower than those at the bottom. A previous report on this project (1) showed that when the surface modulus is less that 100 psi and the surface thickness is less than 1.5 inches, the maximum strains at the top of the surface are often larger than those at the bottom.

Notice in Figure 21 that increasing the tire contact pressure from 26 to 65 psi produces an increase in the tensile strains for the thin low modulus surfaces. The higher modulus combinations show no substantial change in strains with increase in contact pressure.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

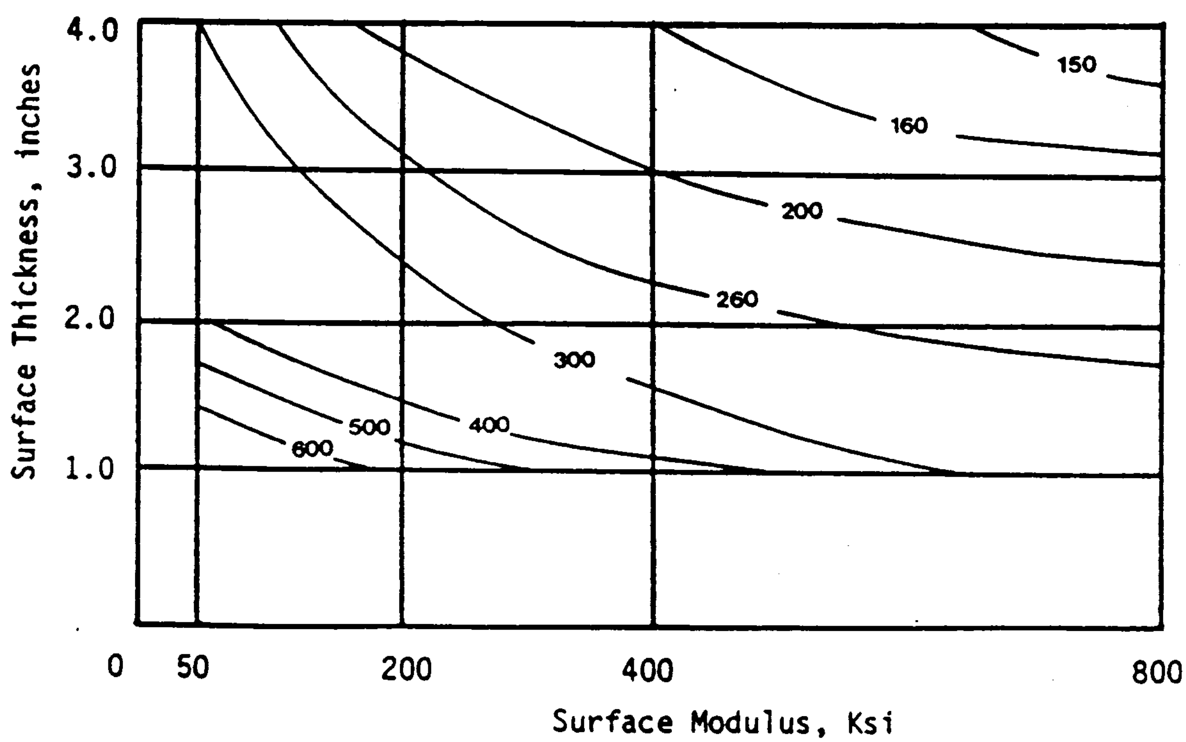
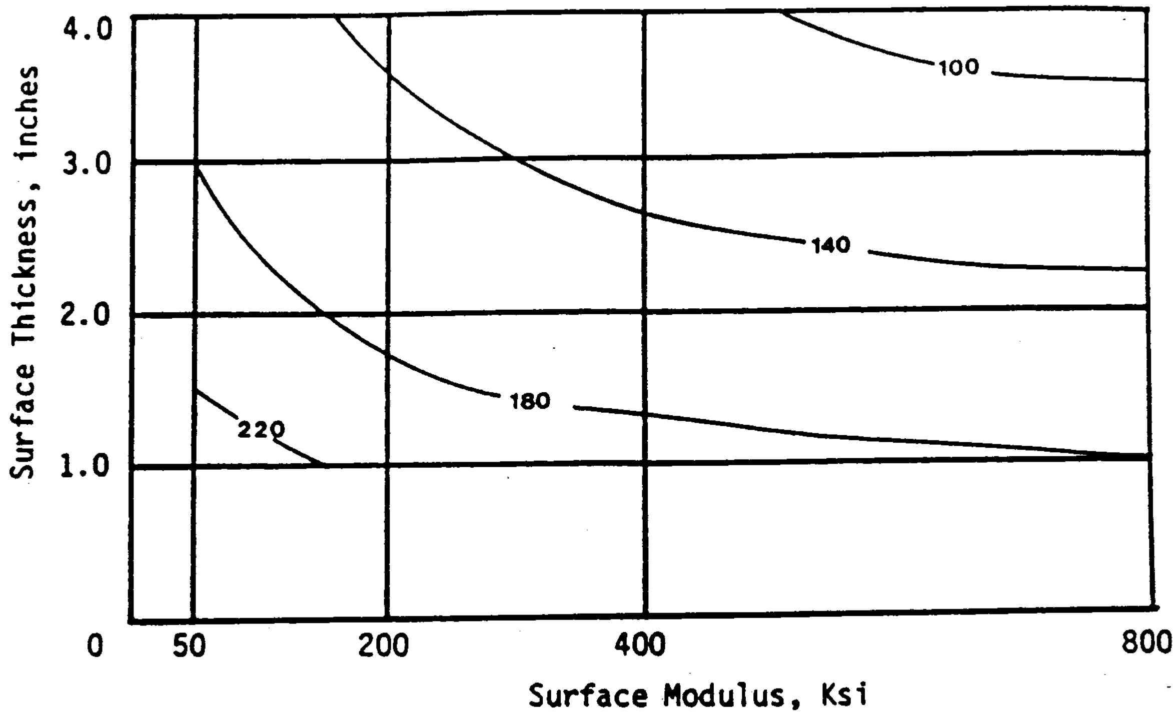


Figure 16. Compressive micro-strain contours at the top of the subgrade for a 60 Ksi base modulus and a tire load of 1320 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

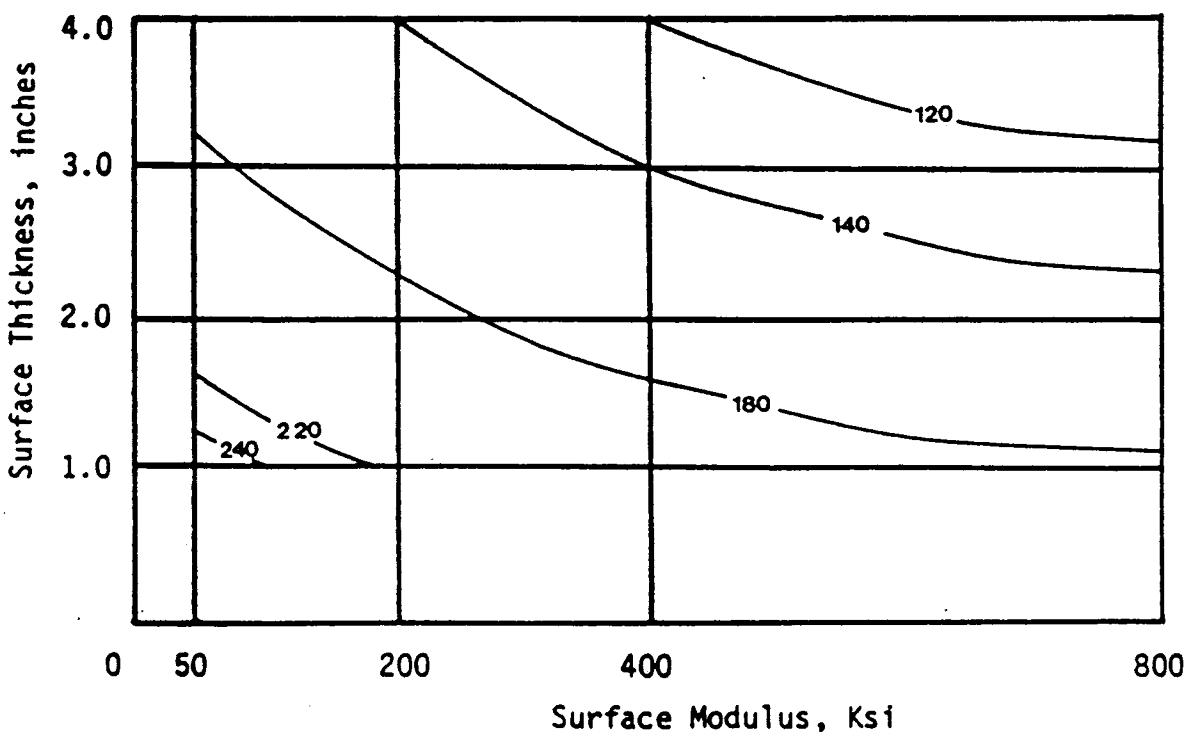
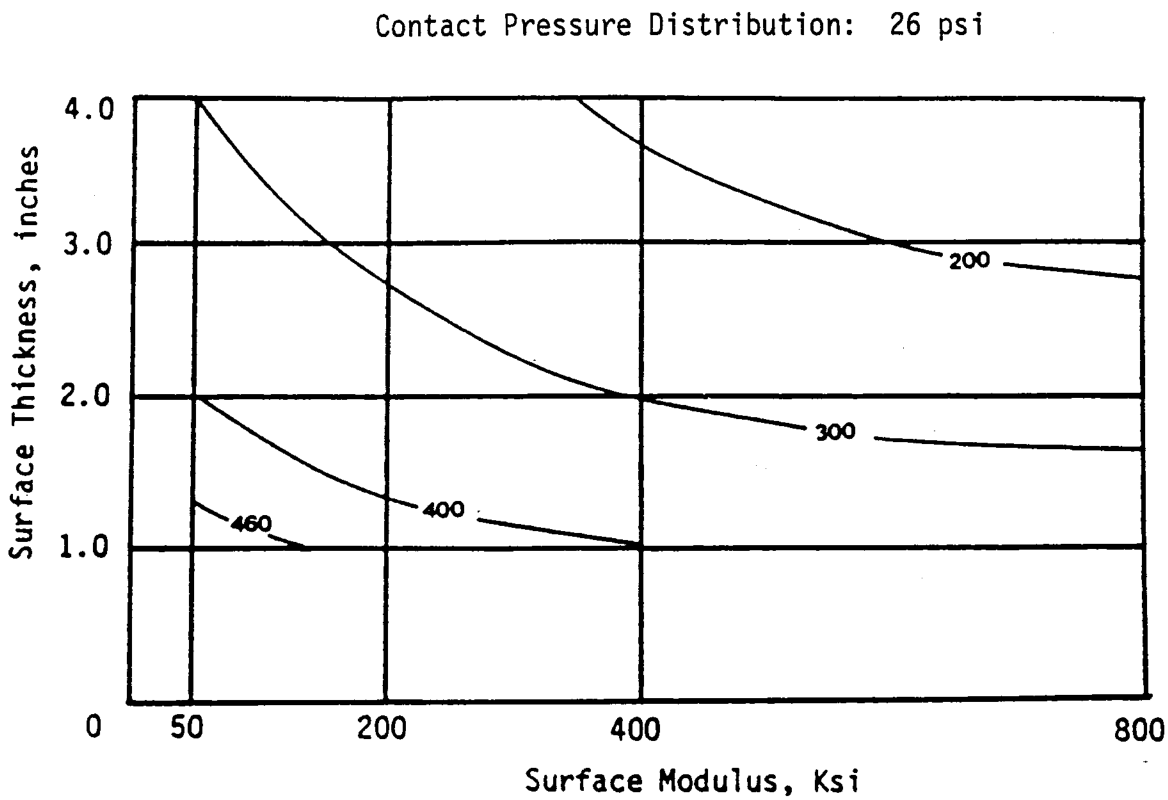


Figure 17. Compressive micro-strain contours at the top of the subgrade for a 60 Ksi base modulus and a tire load of 800 lbs.



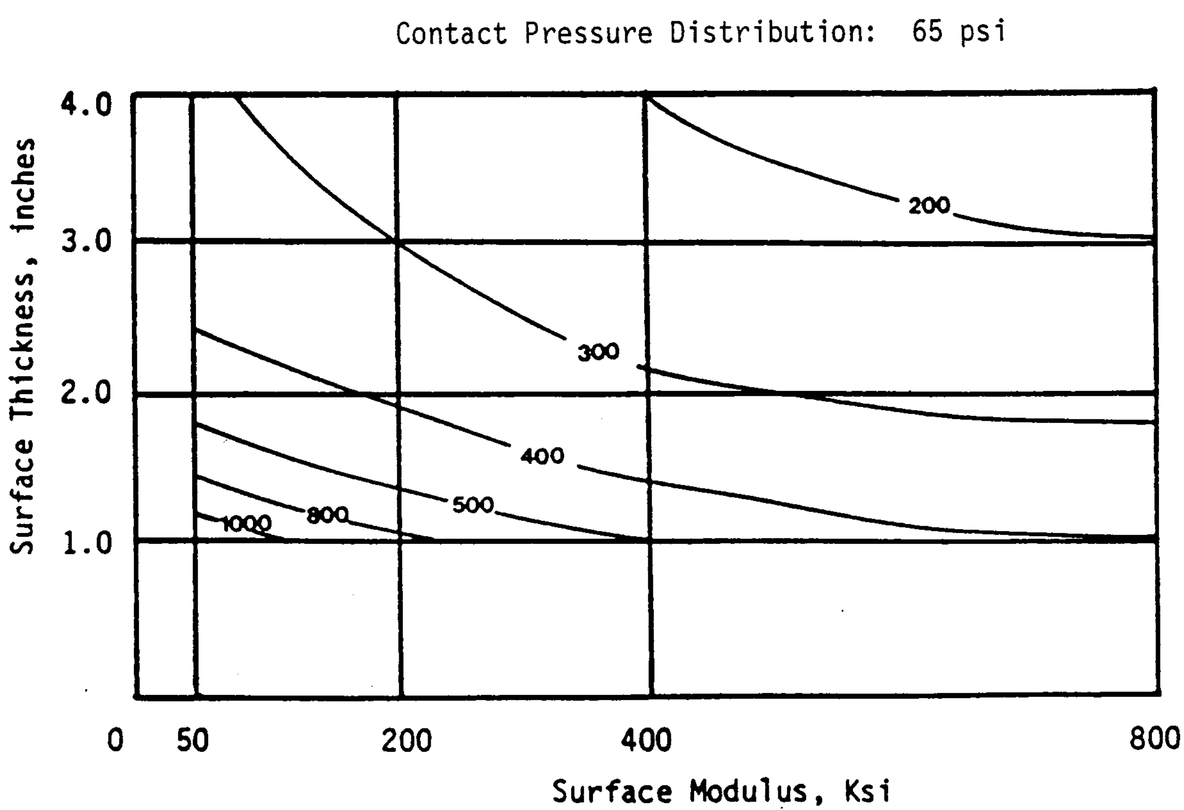
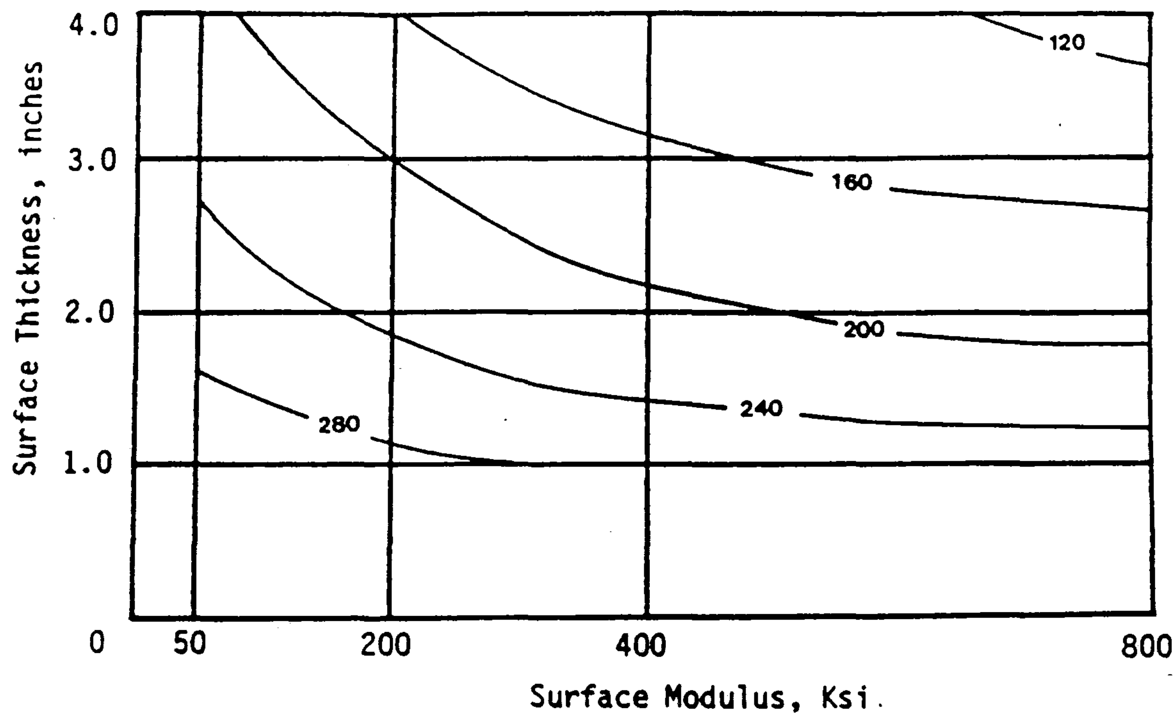


Figure 18. Compressive micro-strain contours at the top of the subgrade for a 30 Ksi base modulus and a tire load of 1320 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

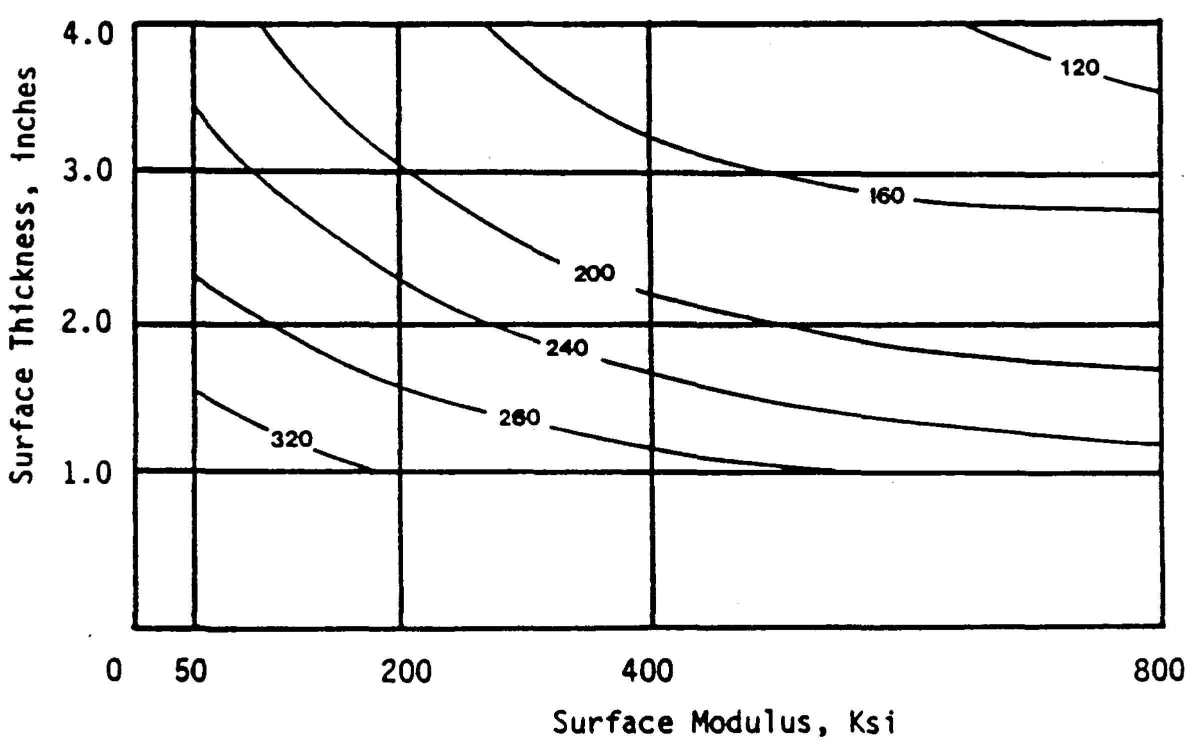


Figure 19. Compressive micro-strain contours at the top of the subgrade for a 30 Ksi base modulus and a tire load of 800 lbs.

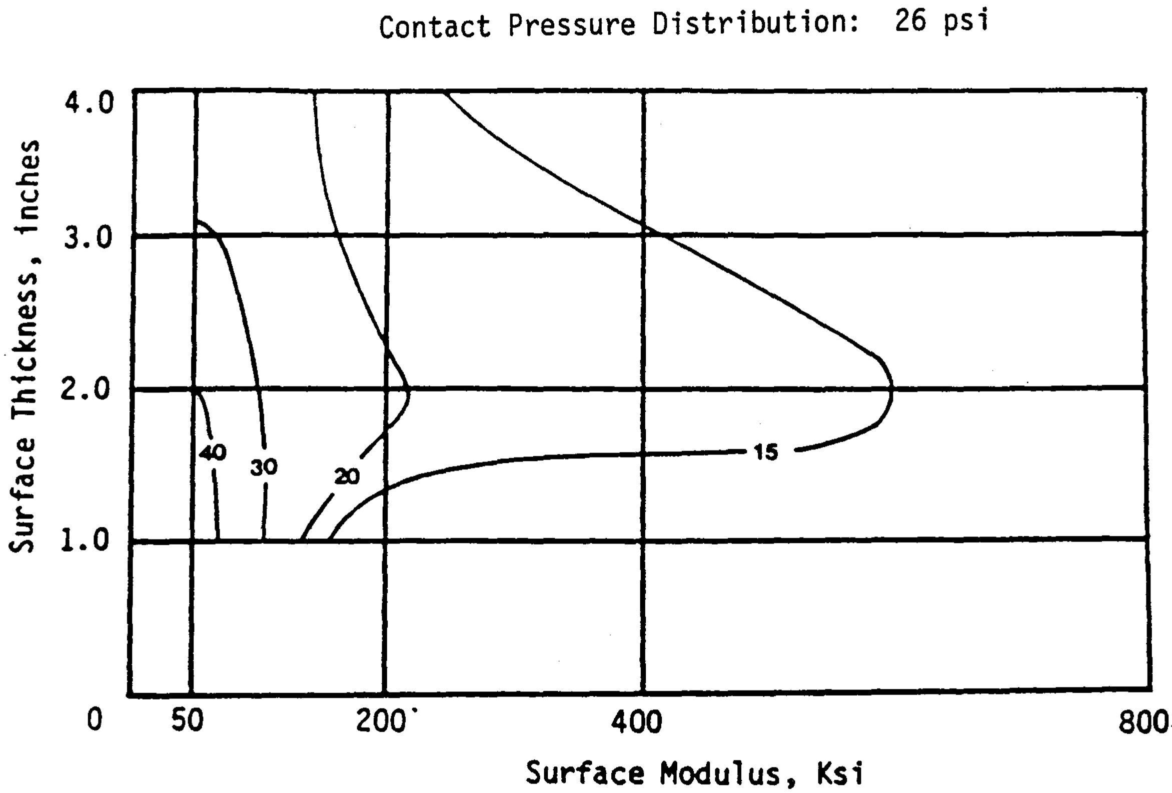
Figure 21 contains the same type of data as that in Figure 20 but for the 30 Ksi base. However, unlike the data in Figure 20, there is a substantial increase in the strain at the top of the surface for the higher contact pressure case. This indicates that for surfaces between 1 and 2 inches thick, that also have low moduli; the magnitude of the base modulus very significantly affects the strain. For the low contact pressure case, the base moduli produce no substantial differences in the strain at the top of the surface.

Figures 22 and 23 show the tensile strain at the top of the surface for the 800 pound tire load. It is interesting to notice that in Figure 22, increasing the tire pressure for the 60 Ksi base modulus does not substantially alter the tensile strain at the top of the surface for any of the surface modulus and thickness combinations; such is not the case for the 30 Ksi base, as shown in Figure 23. Increasing the tire contact pressure produces a significant increase in strain for the low moduli and thickness surfaces indicating again the need to provide strong bases to protect these pavement structures.

Fatigue Damage Effects

The calculated tensile strains at the top and bottom of the asphalt concrete surface are used to estimate the number of 18-Kip equivalent single axle loads (ESAL) applications until class 2 cracking occurs. Class 2 cracking is defined as fatigue cracking that has progressed to the point where cracks have interconnected to form a grid-type pattern (1). A pavement surface that has a class 2 cracking is assumed to have failed in fatigue. The cracks that exist still maintain some aggregate interlock and are so spaced that the surface layer is considered to retain some ability to support the load.

At the AASHO Road Test observations were made of surface condition and the number of load applications to failure for a variety of axle loads and pavement material combinations. These test sections covered a wide range of pavement thicknesses and the number of weighted 18-Kip single axle load applications required to produce class 2 cracking were measured. Material property data has been combined with field



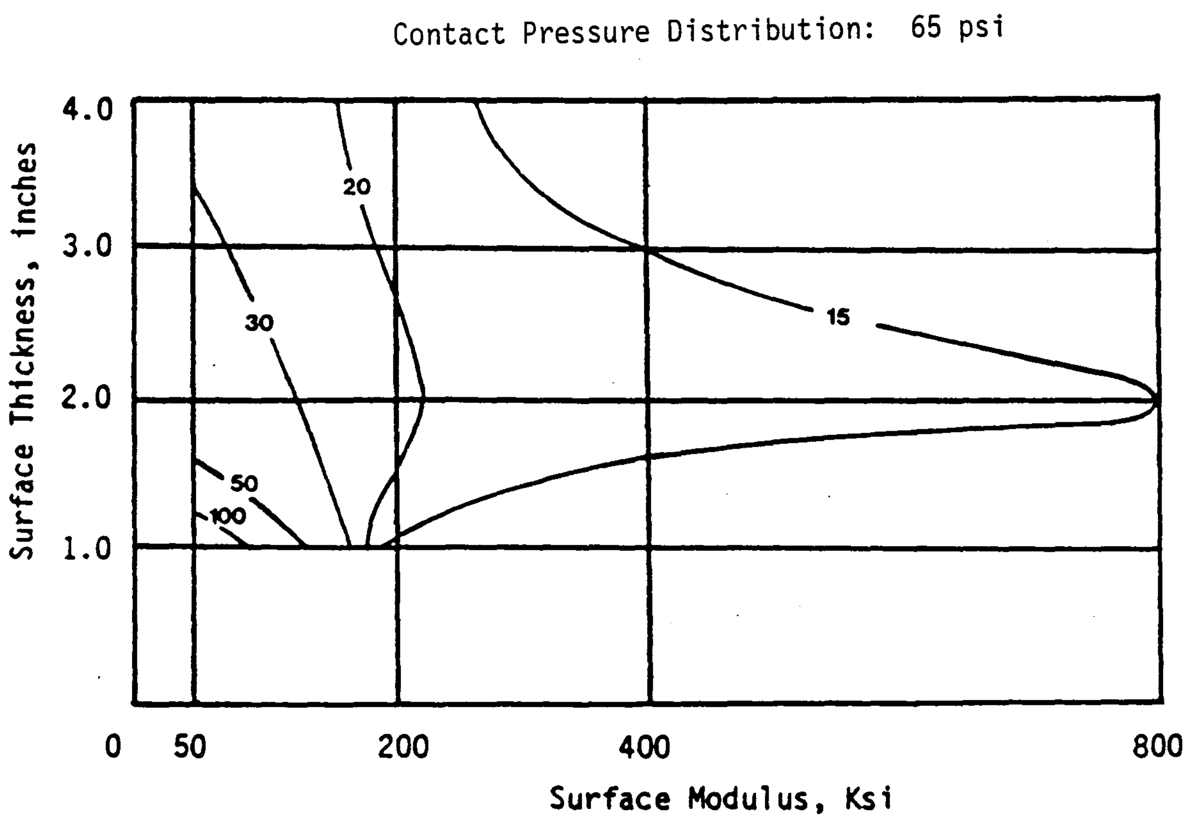
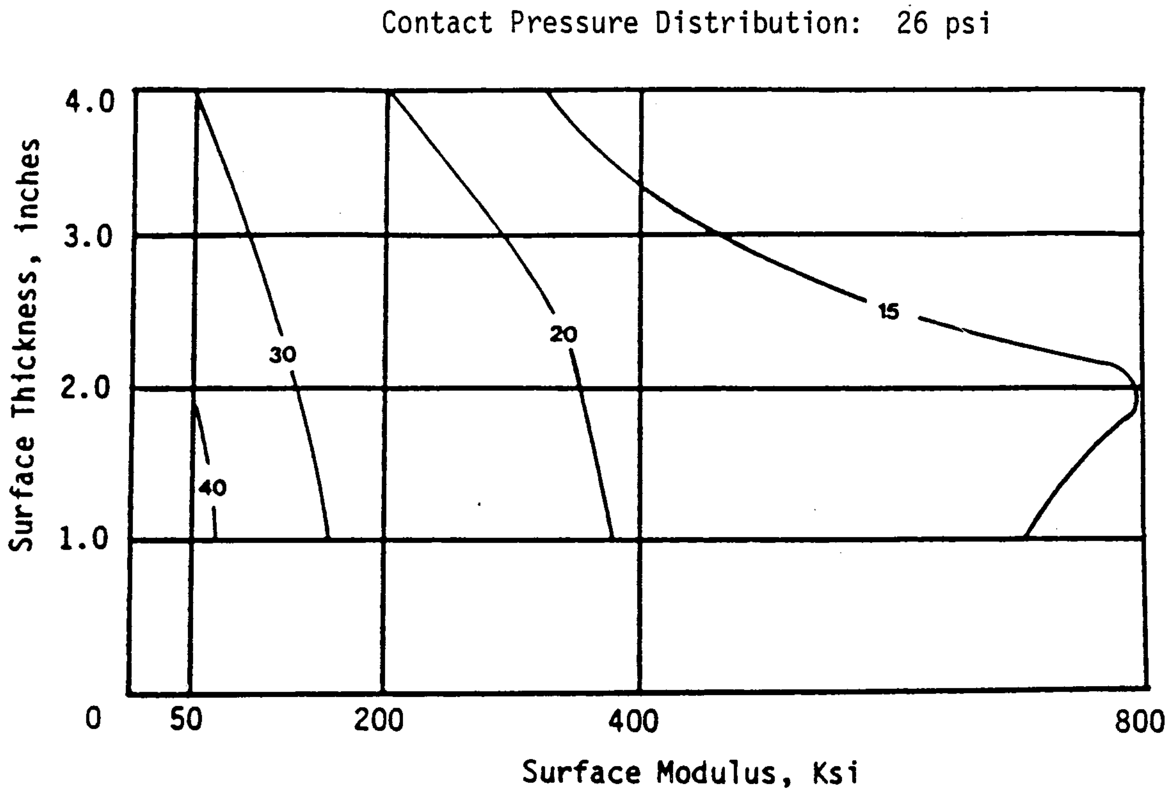


Figure 20. Tensile micro-strain contours at the top of the surface for a 60 Ksi base modulus and a tire load of 1320 lbs.



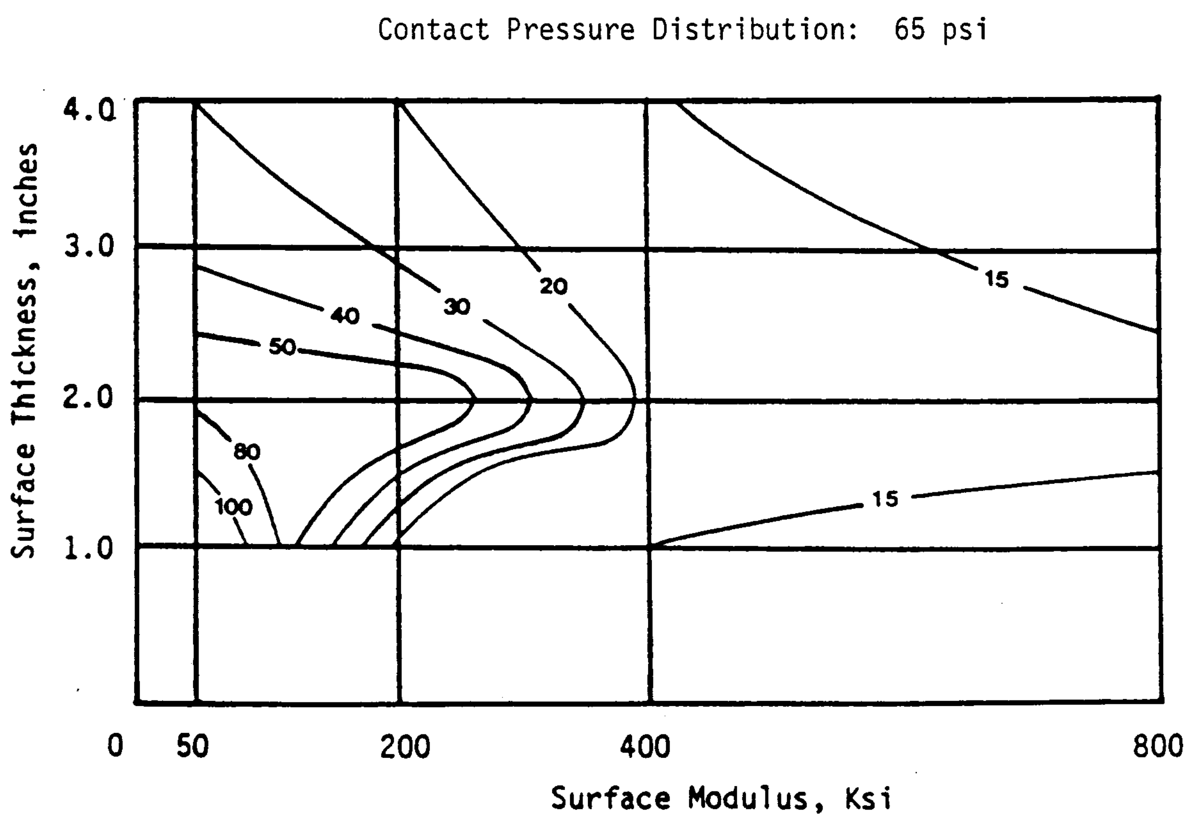
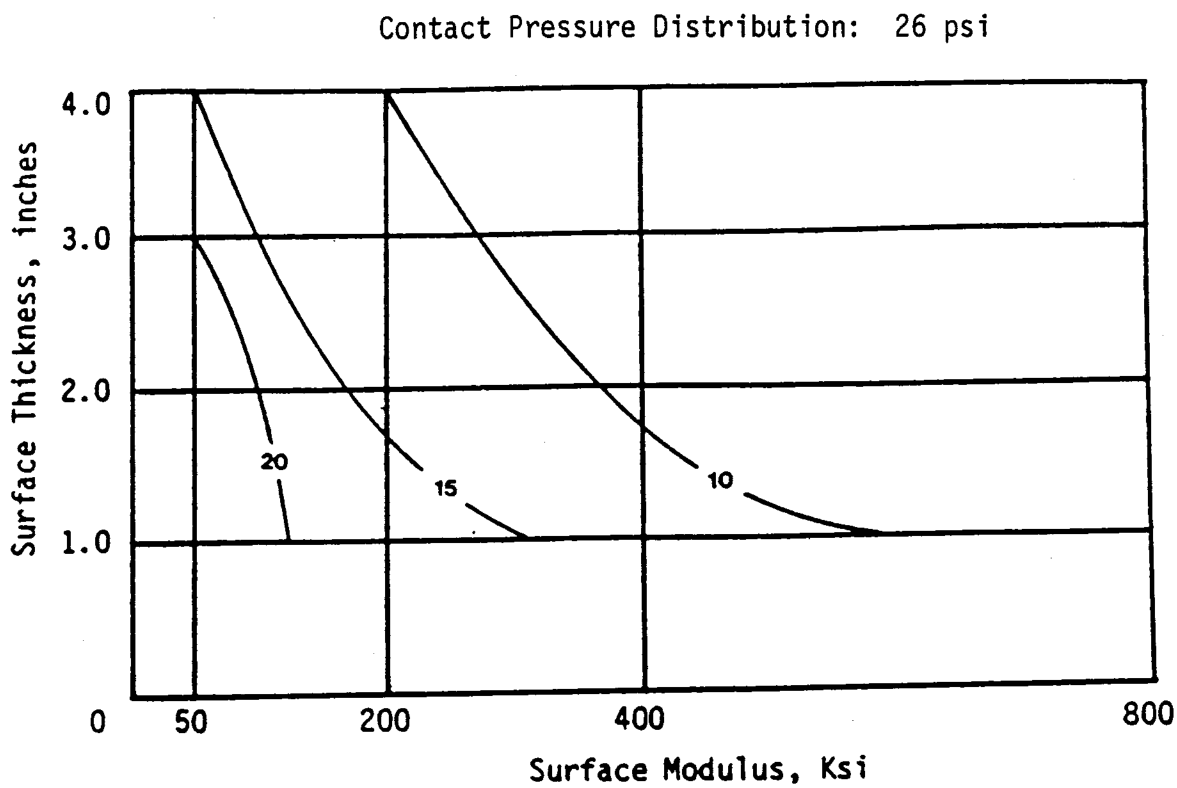


Figure 21. Tensile micro-strain contours at the top of the surface for a 30 Ksi base modulus and a tire load of 1320 lbs.



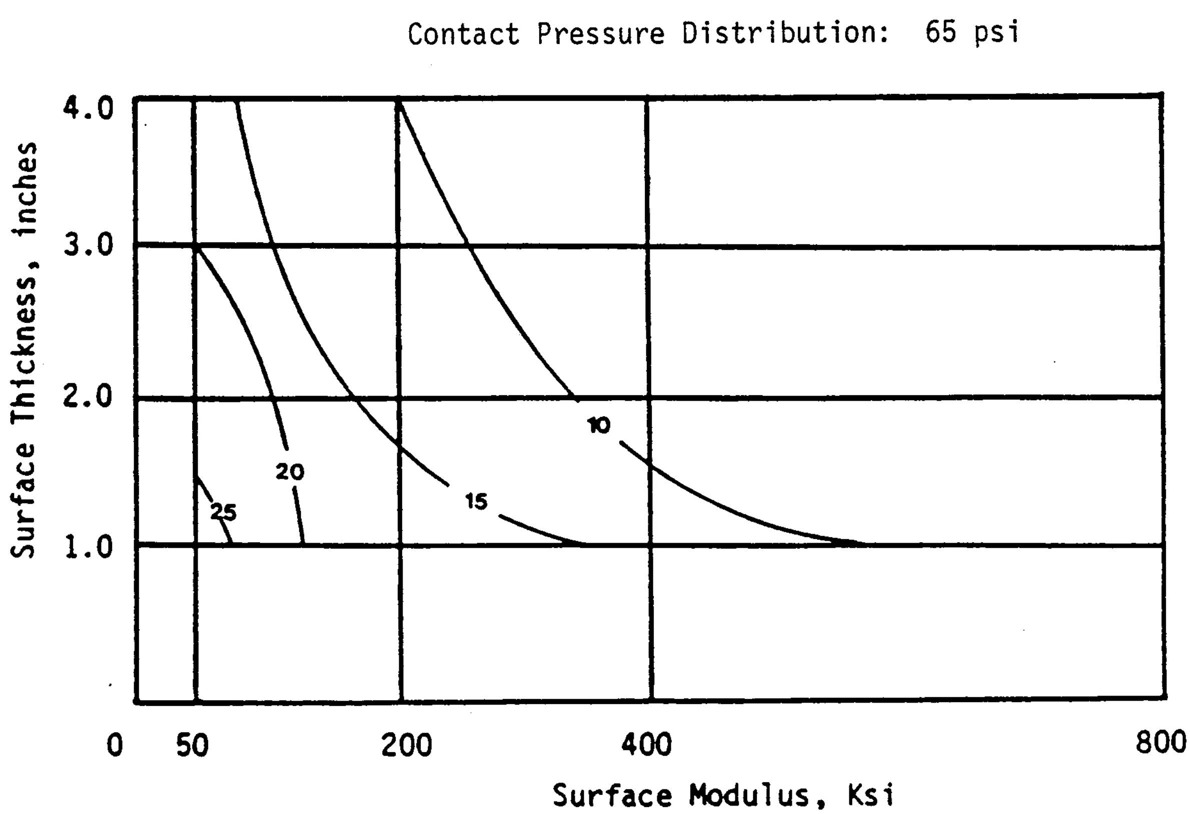
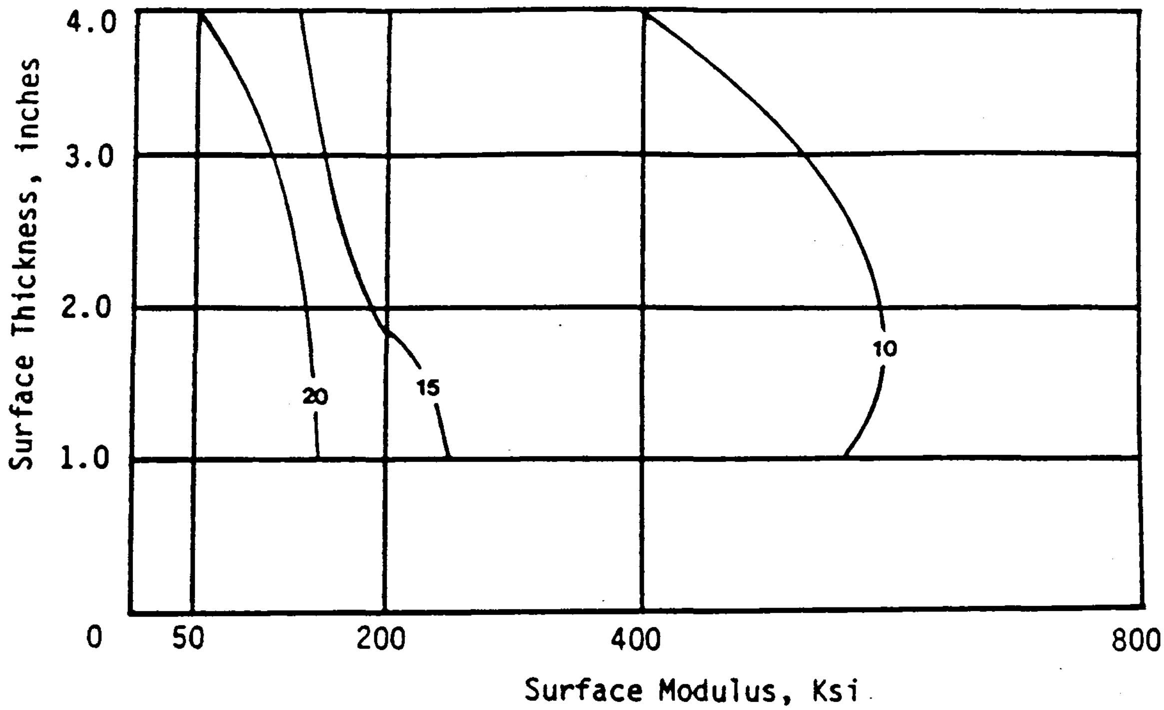


Figure 22. Tensile micro-strain contours at the top of the surface for a 60 Ksi base modulus and a tire load of 800 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

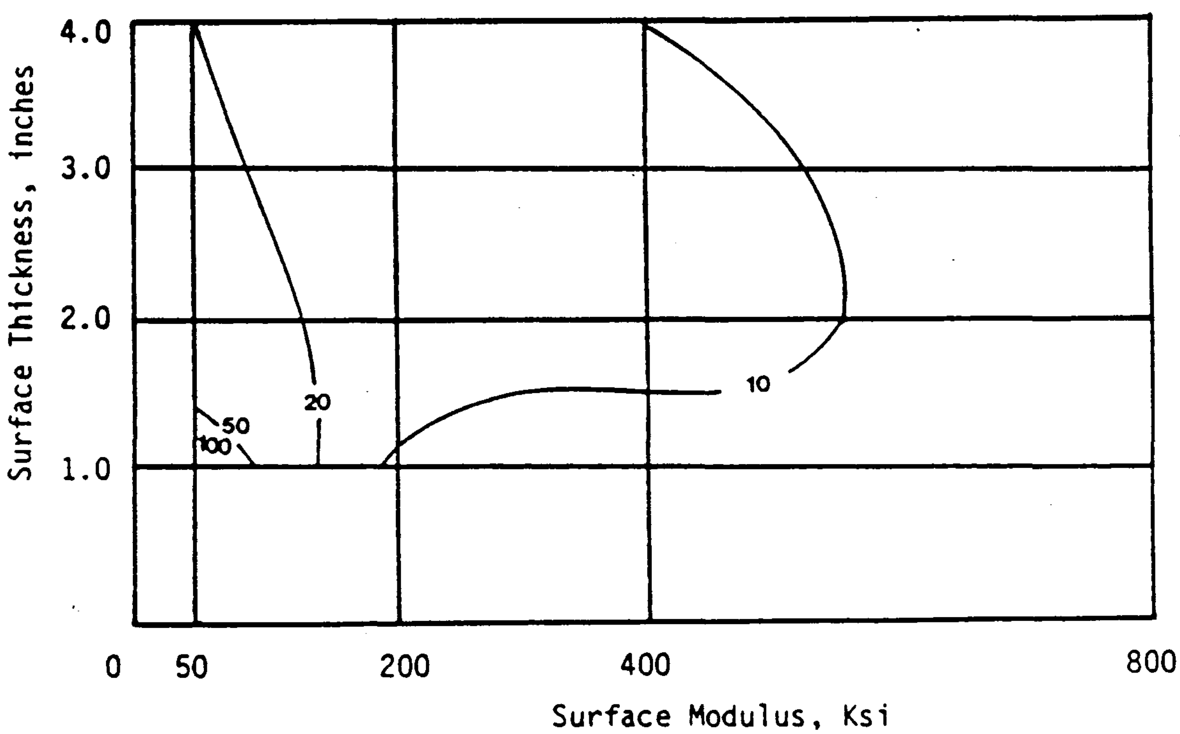


Figure 23. Tensile micro-strain contours at the top of the surface for a 30 Ksi base modulus and a tire load of 800 lbs.

observations and theoretical studies to develop a fatigue relationship for the AASHO Road Test asphalt concrete pavements (5,6).

Roberts and Rosson (1) recalculated the tensile strains at all AASHO test sections using ILLIPAVE and an estimate of the contact pressure distribution for a truck tire inflated to 75 psi. The revised fatigue equation is:

$$W = 5.0957E\text{-}13 \ (1/e_t)^{4.65644}$$

where W = number of axle loads prior to class 2 cracking and

e_t = transverse tensile strain.

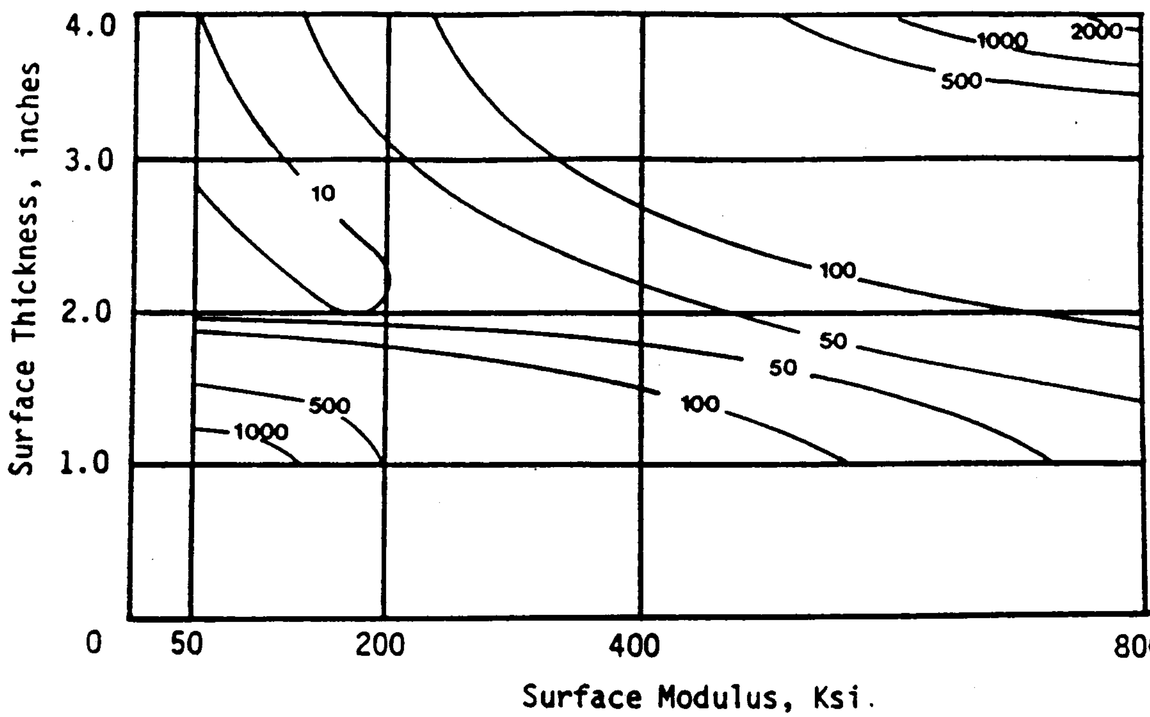
The value of K1, 5.0957E-13g in the fatigue equation is an average value that reflects the temperature condition during the AASHO Road Test since the applications to failure data were secured from those experiments. However, seasonal effects for different environments can be evaluated by varying K1 with temperature as shown by Roberts, von Quintus, Finn, and Hudson (5).

Since the objective of this portion of the analysis is to demonstrate the magnitude of the effect of tire pressure, the authors decided that using a constant value of K1 was sufficient. It should be noted, however, that K1 varies over several orders of magnitude for temperature ranges experienced in most locations.

Figures 24 through 27 show the number of loads to failure, N_f, calculated by converting the strains from Figures 12-15 to N_f for the various combinations of surface thicknesses and moduli. These data also show that the highest number of applications to failure occur in the upper right and lower left corners where the lowest strains occurred.

Surface modulus and thickness have a very significant effect on the number of applications to failure. To keep the fatigue life of the pavement high, the surfaces should be either weak and thin or strong and thick. To translate these data into years of life, consider that a low volume road experiences approximately 500 average daily traffic. For this type of road, the normal traffic in 5 years would apply 1,905,000 axle loads. Figure 28 shows the cummulative number of vehicle load applications for such a road in a period of up to 20 years. Figure 24 indicates that thick, low moduli surfaces will not provide adequate life

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

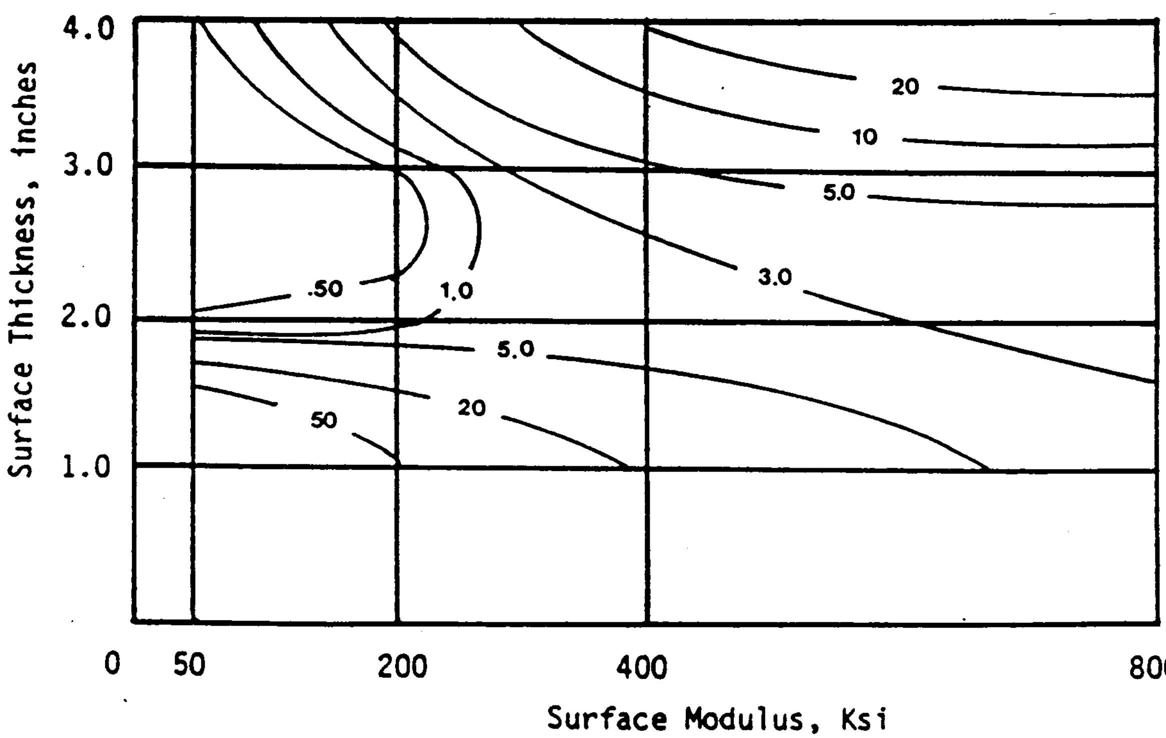
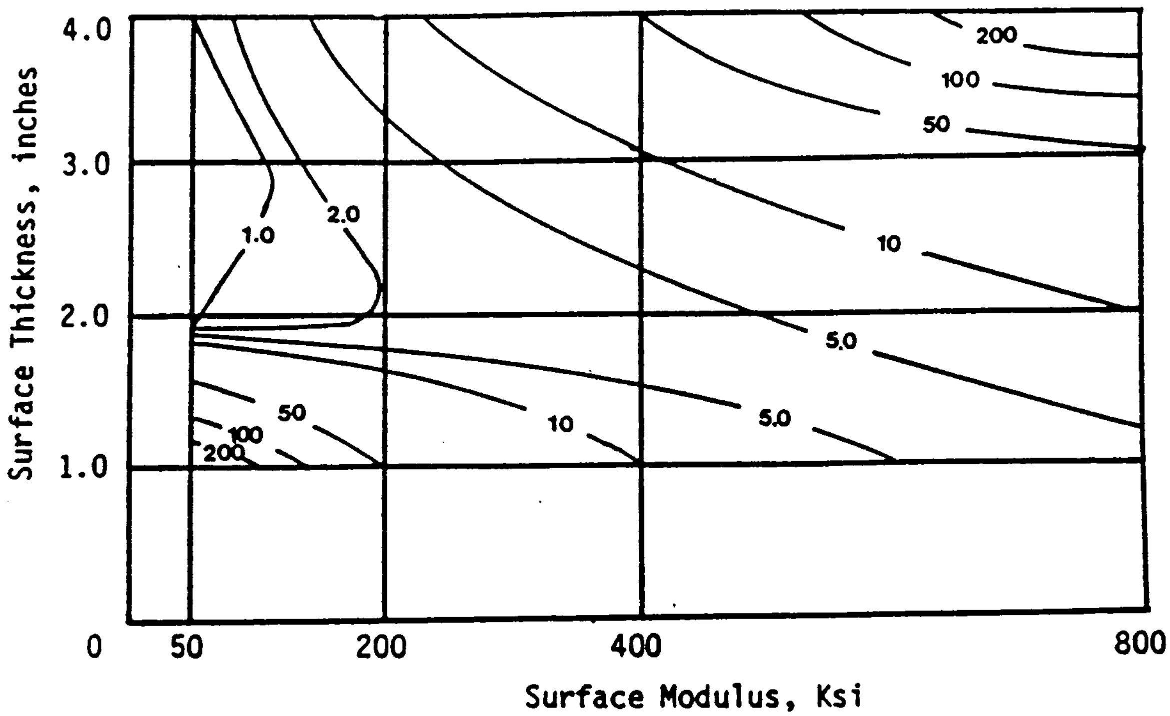


Figure 24. N_f contours in millions as a function of the tensile strain at the bottom of the surface for a 60 Ksi base modulus and a tire loads of 1320 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

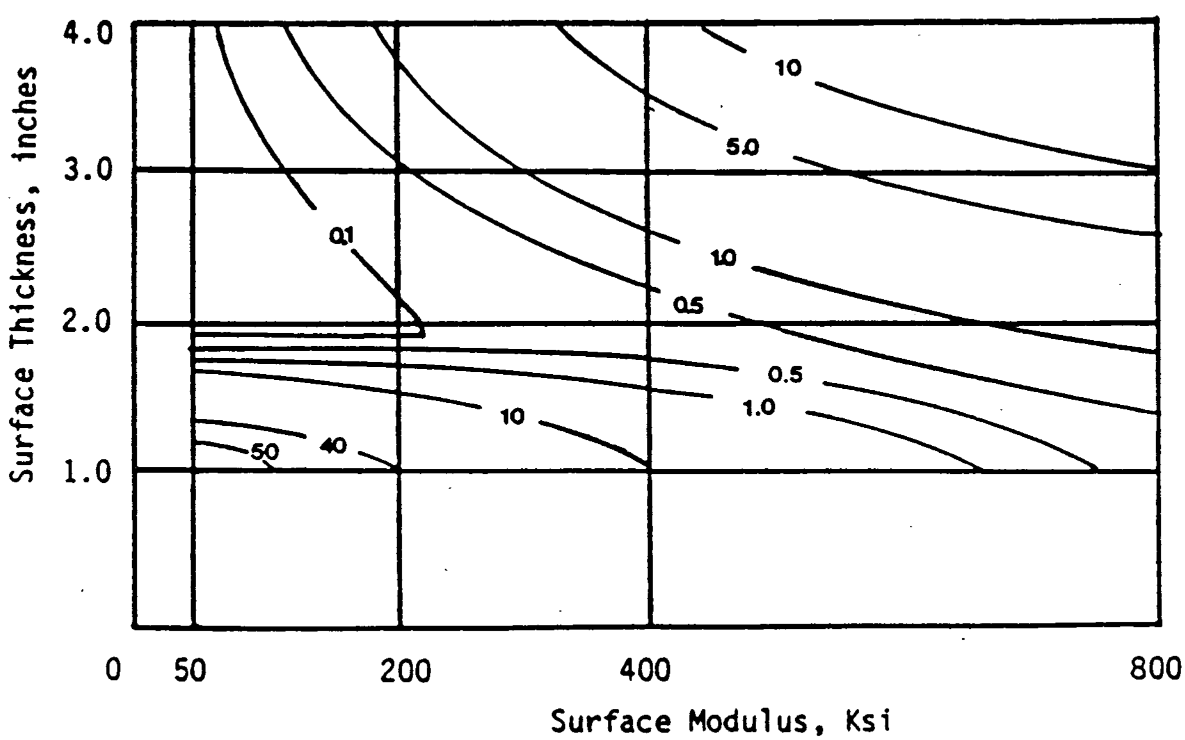
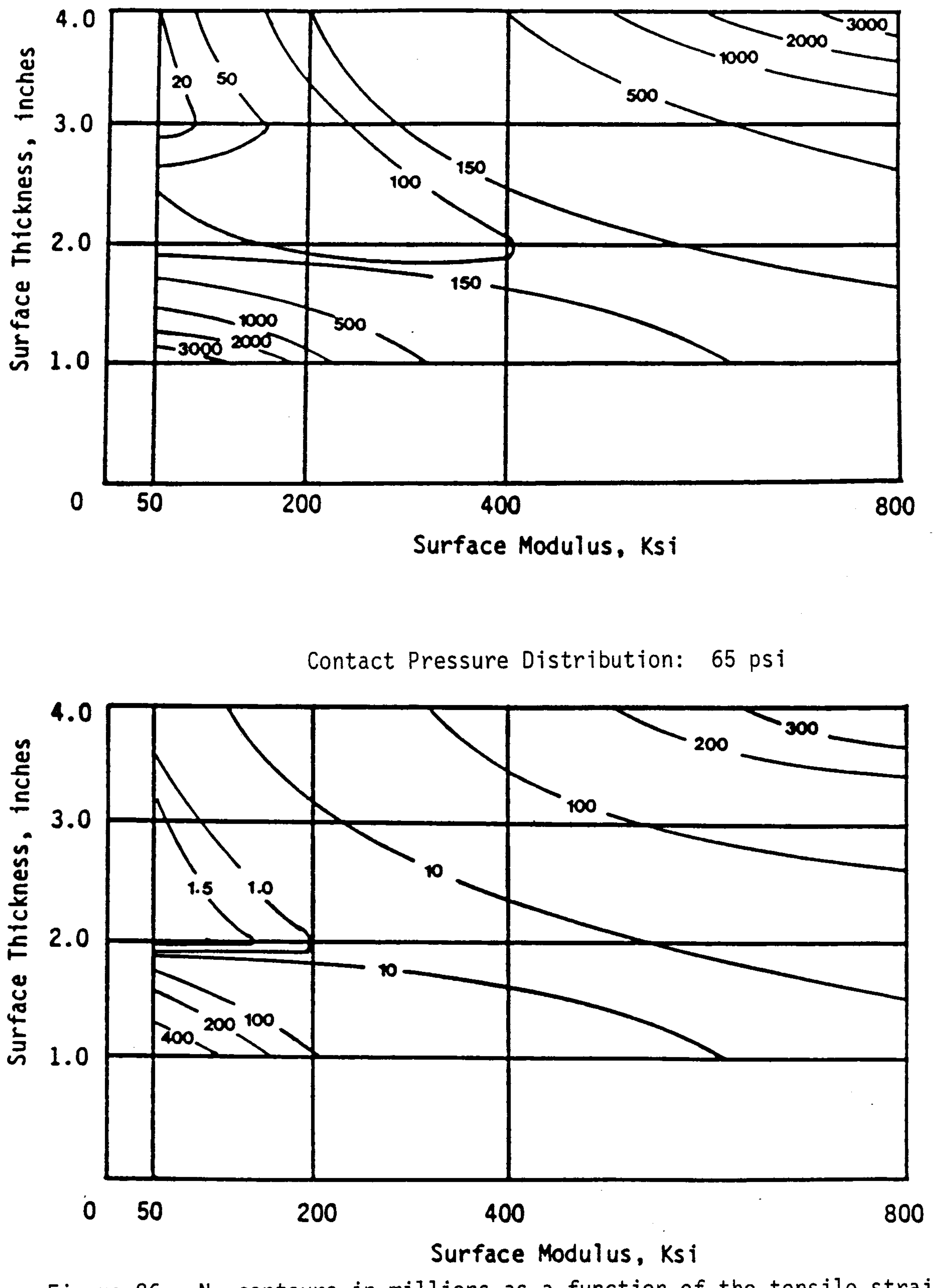


Figure 25. N_f contours in millions as a function of the tensile strain at the bottom of the surface for a 30 Ksi base modulus and a tire load of 1320 lbs.

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

Figure 26. N_f contours in millions as a function of the tensile strain at the bottom of the surface for a 60 Ksi base modulus and a tire load of 800 lbs.

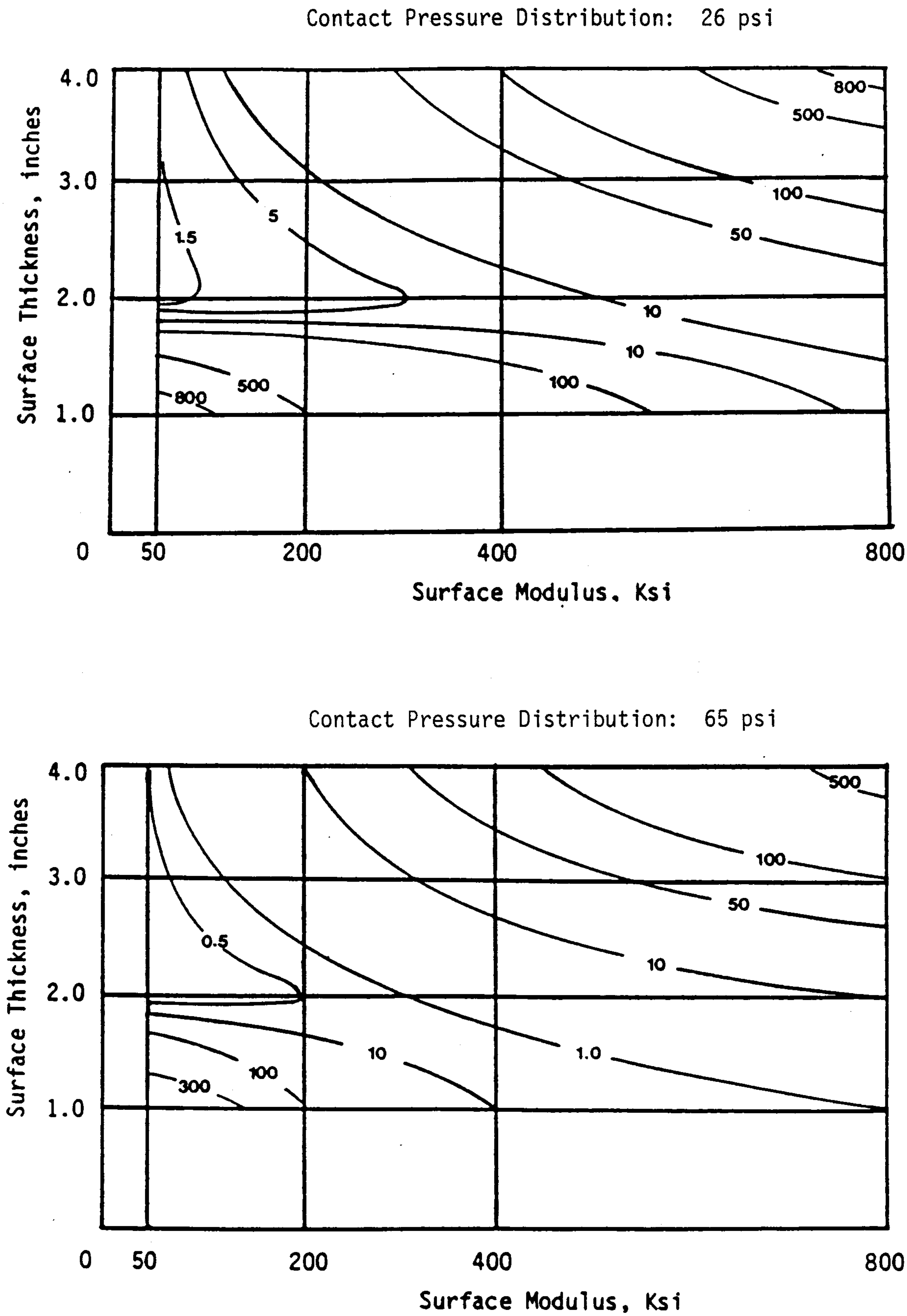


Figure 27. N_f contours in millions as a function of the tensile strain at the bottom of the surface for a 30 Ksi base modulus and a tire load of 800 lbs.

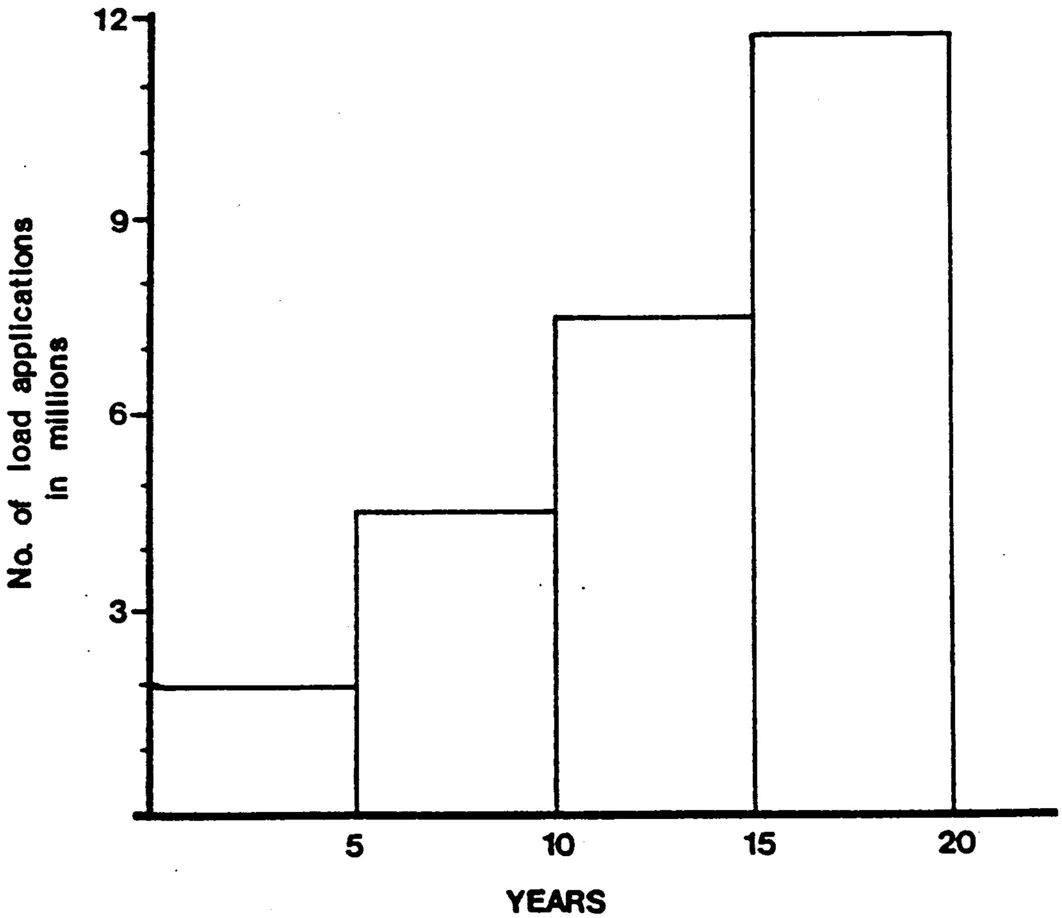


Figure 28. Cumulative number of vehicle load applications.

for this road. Observe that these thick, low moduli surfaces provide less than 1,000,000 axle load applications.

The number of axle load applications is considerably reduced as the base modulus decreases as shown in Figure 25. Notice again that thick, high modulus surfaces or thin, low modulus surfaces can provide adequate service.

Rutting Effects

The calculation of cumulative permanent deformations in pavement structures is a complex problem and research is still being conducted. Rutting can be the result of permanent strains that occur in any or all of the layers of a pavement structure.

Previous studies (5) have shown that protection of the subgrade from rutting can occur if the vertical compressive strains are kept below a critical level. The compressive strains at the top of the subgrade have been calculated using ILLIPAVE and these strains were used to estimate the number of axle load applications until excessive wheel path rutting develops. The model used for these estimates was developed by Shell Development Corporation. Shell engineers (7) used results from the AASHO Road Test to develop a compressive strain criteria equation:

$$W = 6.15E17\ (1/e_c)^{4.0}$$

where W = No. of loads required to produce a rutting failure.

e_c = vertical subgrade compressive strain.

Since the tensile strain criterion was developed using data from the AASHO Road Test, the Shell compressive strain equation was selected for use in this analysis for compatibility with the fatigue model included in the previous section.

Table 1 shows the vertical subgrade compressive strain for different combinations of surface moduli and thicknesses for the weak base layer, 65 psi contact pressure, and the 1320 pounds tire load. For the highest compressive strain, 1226 micro-inches for the 1 inch, 50 Ksi surface, the Shell equation produces an N_f of 240,000 load applications. In a similar study conducted on truck tires (1), the ESAL for a 1 inch, 50 Ksi surface on a weak base layer was only 13,900 wheel load applications. However,

Table 1. Vertical Subgrade Compression Strain for a Base Modulus of 30 Ksi, a Contact Pressure of 65 psi, and a Tire Load of 1320 lbs.

Tire Load: 1320 lbs.

Base Moduli: 30 Ksi

Asphalt Thickness (inch)	Surface Modulus (Ksi)	Vertical Compressive Strain ($x\ 10^{-6}$ in/in)	Single Axle Load Applications in Millions
4.0	800	156.64	1021
4.0	400	197.65	403
4.0	200	238.95	188
4.0	50	319.20	60
3.0	800	205.00	348
3.0	400	250.00	157
3.0	200	290.60	86
3.0	50	370.30	33
2.0	800	285.08	93
2.0	400	327.50	53
2.0	200	420.00	20
2.0	50	501.40	8
1.0	800	410.55	22
1.0	400	600.00	5
1.0	200	850.00	1.2
1.0	50	1266.30	.24

in either case these high strains indicate that the pavement structure does not provide adequate protection of the subgrade. For a low volume road with a 500 ADT and 10 percent trucks, 10 years of service life require that the pavement sustain about 4.5 million load applications, as shown in Table 2.

Comparison of the Response of Stress Sensitive and Linear Elastic Granular Materials

In the past several years, the use of elastic layered theory in flexible pavement design has significantly increased. The use of this theory requires that the layer modulus, Poisson's ratio, and thickness be known for each layer in order to compute the stress, strain and displacements in a pavement. While material moduli can be obtained from laboratory tests, unbound granular materials have been found to exhibit moduli that are nonlinear or stress dependent. As mentioned earlier, one of the important features of the ILLIPAVE finite element model is the ability to incorporate both linear and non-linear stress-strain behavior of component materials.

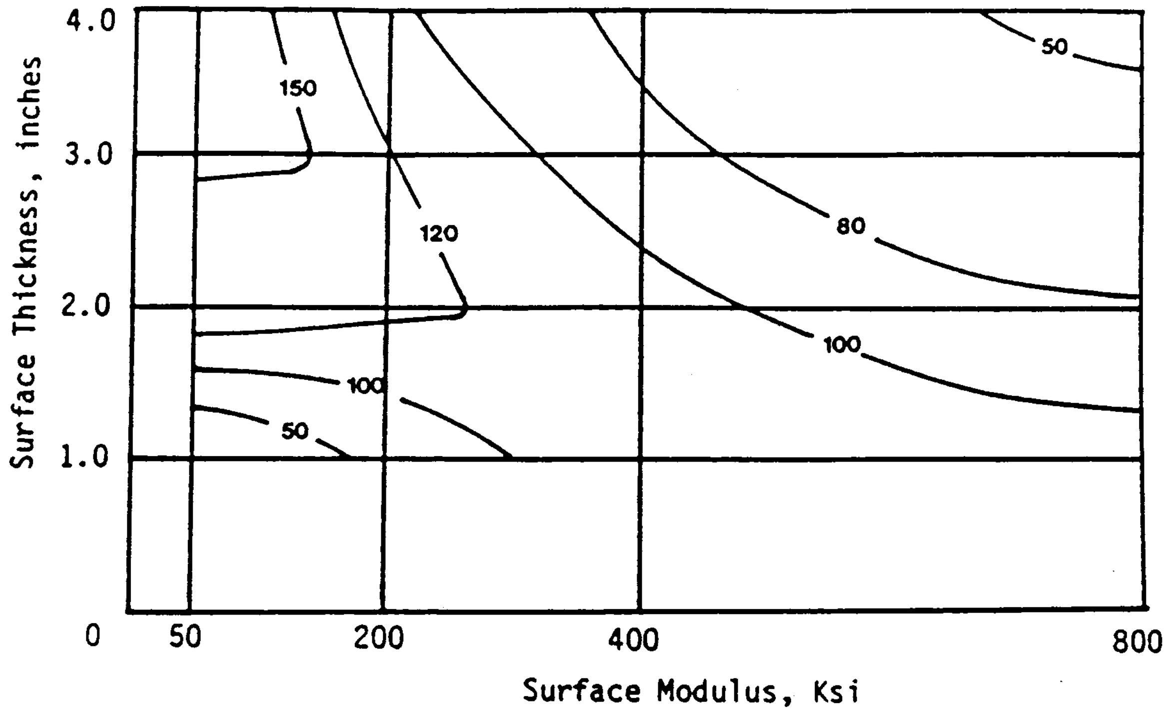
To compare the predicted response of ILLIPAVE using the non-linear and the linear material models a series of computer runs were made in which the non-linear behavior of the unbound granular base layer was incorporated.

Figure 29 shows the horizontal tensile strains at the bottom of the surface for different surface moduli and thicknesses corresponding to the non-linear model. Observe the difference in the tensile strains. The strains from the non-linear base model (Figure 29) show an increase of approximately 100% on the horizontal tensile strains as compared to data from runs using the linear elastic base modulus from Figure 12. The difference is more significant for low moduli surfaces 2 inches or thinner. For surfaces greater than 2 inches the effects begin to decrease but not to the point where the strains are comparable. These large discrepancies in strain may help to explain why thin pavement surfaces begin to crack before predictions indicated by analytical studies assuming linear elastic response of granular base materials.

Table 2. Cumulative Number of Vehicle Load Applications for 500 ADT and 10 Percent Trucks.

No. of Years	Cumulative Number of Vehicle Load Applications
5	1,904,107
10	4,414,765
15	7.676,884
20	11,866,150

Contact Pressure Distribution: 26 psi



Contact Pressure Distribution: 65 psi

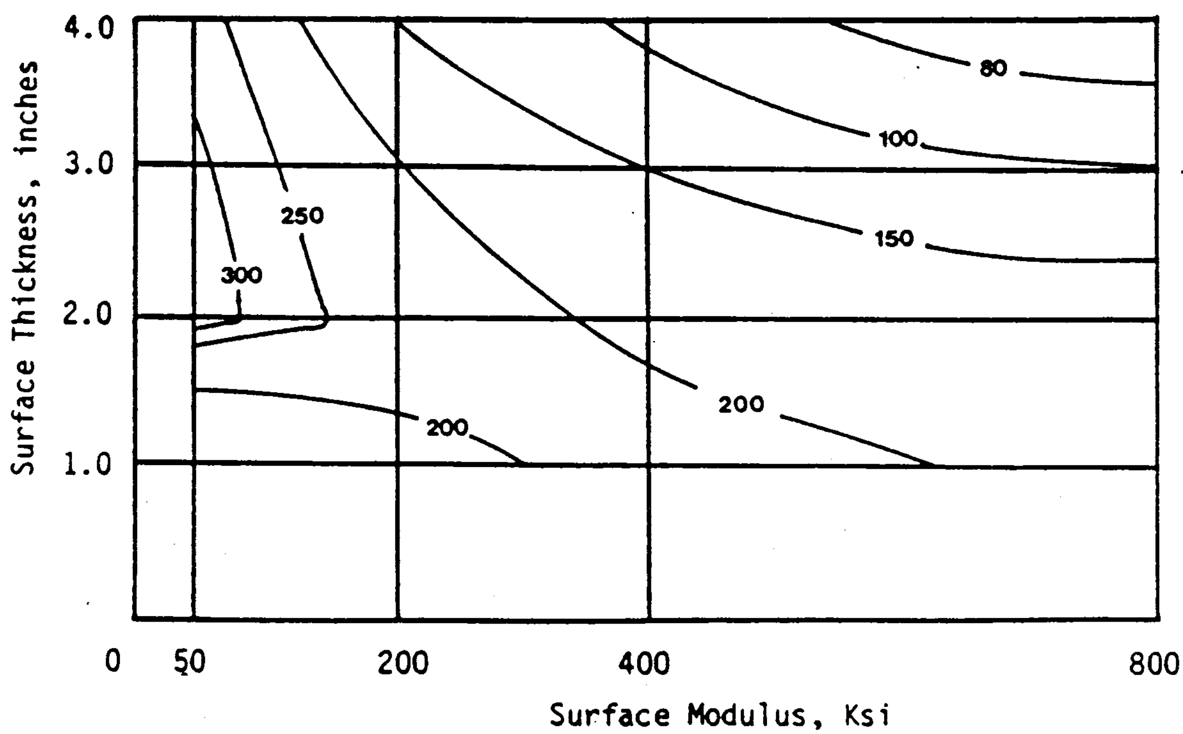


Figure 29. Tensile micro-strain contours at the bottom of the surface for a $8787\Theta^{0.325}$ base modulus and a tire load of 1320 lbs.

field project construction performance needs to be established. As a minimum a peel strength of 0.01 lbs. per inch (0.00178 N/mm) of fabric width is recommended. The peel strength should be determined at the expected "old surface" pavement temperature, at optimum tack coat and preferable on a surface that duplicates as nearly as possible that pavement surface upon which the fabric is to be placed. It should be noted that the above criteria are meaningful only when tests are performed using the same testing techniques upon which the criteria is based.

Interface Shear Strength

Individual and mean values of interface shear strength for Fabrics A, D, E, F and G are presented in Appendix C. Figures 20 through 24 illustrate the influence of test temperature on shear strength. Figure 25 illustrates the effect of tack coat quantity on shear strength for the fabrics tested. Optimum tack coat was established by use of Equation 1. Low tack coat is one-half the optimum value while high tack coat is twice the optimum value.

Curves associated with Control-1 samples indicate strengths for typical old pavement-new overlay interfaces. Five hundredths of a gallon per square yard of AC-10 asphalt cement was used as the interface tack coat. Curves associated with Control-2 indicate mixture shear strength (i.e. no construction interface in the plane of shear). As expected the shear strength of the mixture is in excess of the interface shear strength. At the calculated optimum tack coat and low temperatures the shear strength of those samples without a fabric at the interface (Control-1) is usually in excess of those samples with fabric at this interface. At

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Evaluations of the results from this study show that for flexible pavements over unbound, granular bases, the surface thickness and stiffness combinations affect the tensile strains significantly. In general, asphalt concrete surfaces of 1 inch or less should be very flexible and placed on very stiff bases, 4 inch surfaces should be stiff and placed on stiff bases, and 2 to 3 inches surfaces should probably not be used since the strains are quite high, even for automobile loadings, and early cracking may occur.

Special consideration should be given to adequate material characterization for pavement design. There is a significant difference in terms of fatigue and rutting life in assuming a linear elastic behavior of pavement materials from non-linear behavior.

Conclusions

1) The difference in stress and strains calculated using the Tielking tire model and the uniform pressure model are very significant. For the Tielking tire model the tensile strains at the bottom of the surface are more than 100 percent higher than those for the uniform pressure model for surfaces less than 2 inches.
2) The large increases in strains produced using the Tielking tire model may help to explain why thin pavements crack in service before strains calculated from the uniform pressure models indicate that fatigue cracking should begin.
3) The effects of increased tire contact pressures on tensile strains at the bottom of the surface are greatest for low modulus surfaces over low modulus bases.

4) The effect of changing the base modulus on tensile strain is comparable to the change in strain that occurs with the increase in contact pressure between the two models. These results indicate the importance of both modeling the tire contact pressure correctly and having a strong base.
5) Increasing the tire load from 800 to 1320 pounds has little effect on the subgrade strain for the thick, stiff surface but has a substantial effect for the thin, flexible surfaces.

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3. Duncan, J.M., Monismith, C.L., and Wilson, E.L., "Finite Element Analysis of Pavements", Highway Research Record 228, Highway Research Board Washington D.C., 1968.

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6. "Asphalt Concrete Overlays of Flexible Pavements, Vol.1, Development of New Design Criteria", Final Report, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June, 1975.

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