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DISTRIBUTIONS OF STRAIN COMPONENTS AND WORK WITHIN FLEXIBLE PAVEMENT STRUCTURES

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16. Abstract

An investigation was made to determine the location along the centerline of the axle of the maximum strain energy density, or work, in the pavement as defined by classical physics. The location is under the inside edge of either dual tire. The most influential strain was the shear component. The distribution of shear strains and stresses with depth through the full-depth asphaltic concrete and into the subgrade was investigated. Using Simpson's rule for an even number of increments, or using the trapezoidal rule, allows the summation of strain energy density calculated at various depths. This sum multiplied by a unit volume converts the strain energy density to work as defined by classical physics. The sum of work throughout the pavement structure provides a greater insight to the behavior of the pavement because all components of strain, or stress, are considered and the variation throughout the depth may be large according to the location within the tire print. The sum of strain energy density is much greater under the edge of the dual tire compared to that under the center of the dual tire, yet the magnitude of the strain energy density at the bottom of the asphaltic concrete may be nearly identical. For an 18-kip (80-kN) four-tired single axleload, the depth of maximum shear is approximately 35 to 40 percent of the thickness from the surface downward for a maximum pavement thickness of approximately 8 inches (203 mm); thereafter the depth of maximum shear moves toward the surface as the thickness increases. An investigation of shear stress indicated the maximum value was approximately 67 psi (0.46 GPa) due to an 18-kip (80-kN) single axleload and tire contact pressure of 80 psi (0.63 GPa). For an 80-kip (356-kN) tandem axleload and tire contact pressures of 100 psi (0.69 GPa), the shear stress increased to approximately 133 psi (0.92 GPa). As the tire contact pressure increases, the shear stress may approach 200 psi (1.38 GPa).

Recommendations include eliminating any construction plane between the 1- to 4-inch (25- to 102-mm) depth from the surface and determining the shear resistance of the asphaltic concrete mix to insure that the mix can withstand a higher shear stress than is currently being obtained. Target values of shear stress have not been recommended for adoption because a limiting value has not been found in the literature.

17. Key Words
Asphaltic concrete, Shear stress, Shear strain, 18-kip Axleload, Tensile strain, Tangential strain, Vertical strain, Work, Strain energy density

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INTRODUCTION

The purpose of this investigation was to determine the location(s) within the pavement structure showing the greatest response (in terms of stresses, strains, etc) to wheelloads. This analysis has been limited to produce results compatible with Kentucky thickness design curves having a modulus of elasticity of 480 ksi (3.31 GPa) for asphaltic concrete. Time and money did not permit investigating a full range of moduli, tire pressures, thicknesses, and combinations of asphaltic concrete on dense-graded aggregate bases.

The Chevron N-layer computer program (1) has been modified (2) to accept multiple tire loads located within an X-Y grid. Superposition principles have been incorporated so the effects of a single load or multiple loads may be calculated at a specified location. Strain energy density is the internal resistance within the body at a specific location that is equal to the external force applied to the body. Equations to calculate the strain energy density at a specified location within a three-dimensional space incorporates a combination of input parameters and strains and/or stresses calculated within the computer program.

Calculation of the total work caused by the external force requires a triple integration of the calculated strain energy density within the body, or the summation of the strain energy density calculated at every point within the body. Such an effort is too massive and expensive to be realistically possible. Reasonable approximations may be made using Simpson's rule to sum the calculated strain energy densities at specified depths for a specific set of X-Y coordinates.

PATTERNS OF WORK

Figure 1 presents the calculated strain energy density at 1-inch (25-mm) increments for thicknesses of 4, 8, and 12 inches (102, 203, and 305 mm) of full-depth asphaltic concrete on a CBR 5 subgrade, a resilient modulus of 7,500 psi (51.7 MPa). The three curves for each thickness are for the inside edge of the tire, at the center of the tire, and at the point mid-way between that edge and the center of the tire. The area under the curve represents the distribution of work through the pavement structure. These patterns raise the question, "Where is the location of maximum work as a function of the locations of the imposed loads?"

LOCATION OF MAXIMUM STRAIN ENERGY DENSITY

Prior to the computer age, researchers approximated multiple load configurations using a single loaded area because of the complexity of the problem. With the advent of computers, the use of only one load is no longer a restriction. Likewise, many locations may be analyzed economically. Thus, an investigation was made to determine the internal work at specified locations.

Figures 2-4 present patterns of work as a function of location along the centerline of a two-tired single axleload of 18 kips (80 kN) on 4, 8, and 16 inches (102, 203, and 406 mm) of full-depth asphaltic concrete on a CBR 5 subgrade corresponding to a resilient modulus of 7,500 psi (51.7 MPa). The "work" is a summation of the strain energy density using Simpson's rule. The "work" is summed separately for the asphaltic concrete thickness and for 8 inches (203 mm) into the subgrade; these values are then combined to obtain the total work at that location from the top of the asphaltic concrete through the top 8 inches (203 mm) of the subgrade. Note the changes in patterns of work with increasing thickness of asphaltic concrete. The maximum work always is located under the edge of the loaded area.

Figures 5-7 illustrate patterns of work for the same structures and axleload except that four equally loaded areas replace the two areas used to obtain Figures 2-4. Note that the locations of maximum accumulated work are still under the edge of the loaded areas, except that the maximum has shifted to the inside edges of the dual areas.

There appears to be a family of curves relating strain energy density at specific depths as a function of thickness of asphaltic concrete as shown in Figure 8. Figure 9 presents a sensitivity analysis (using Simpson's rule) of the accumulated strain energy density versus thickness of asphaltic concrete for locations corresponding to the edge of the tire, the center of the tire, and midway between the edge and center. The effect of adding a layer of dense-graded aggregate varying from 0 to 8 inches (0 to 203 mm) as a layer beneath the asphaltic concrete causes a relatively minor reduction of accumulated strain energy density within the asphaltic concrete layer.

INFLUENCE OF VARIOUS COMPONENTS OF STRAIN

Figures 1-7, particularly Figure 1, prompt the question, "Which one component or components of strain cause the wide variation in strain energy density under the same loaded area?" Figures 10-12 illustrate the distributions of strains through 4, 8, and 12 inches (102, 203, and 305 mm) of asphaltic concrete, respectively, caused by an 18-kip (80-kN) four-tired single axleload. The distributions are shown for each component of strain for locations at the edge, center, and midway between the edge and center of the tire. The XX component is in the plane of the pavement surface and perpendicular to the centerline of the axle. Component YY also is in the plane of the pavement surface and is parallel to the centerline of the axle. Component ZZ is perpendicular to the centerline of the axle and increases with increasing pavement depth. Note that there are relatively minor differences for each component except for shear (XY). The shear (XY) component for each loaded area is zero at the center of that area and appears to be a maximum at the edge of the area. There is a residual effect of shear at the center of the area due to other loaded areas. However, the magnitude of shear varies greatly with depth within the asphaltic concrete and location within the loaded area. Therefore, the shear component is the major factor influencing variations in distributions of strain energy density within the asphaltic concrete.

Figures 13-15 illustrate the variations in each strain component for thicknesses of 4, 8, and 12 inches (102, 203, and 305 mm) of full-depth asphaltic concrete at locations corresponding to the inside edge of a dual tire. Figures 16-18 present the family of strain distributions with depth for various thicknesses of full-depth asphaltic concrete. A study of Figure 19 reveals that the depth at which the maximum shear strain occurs varies with the thickness of the asphaltic concrete. The variation of depth at maximum shear versus pavement thickness is illustrated in Figure 20. For an 18-kip (80-kN) single axleload, the maximum shear for pavements up to 8.5 inches (216 mm) of full-depth asphaltic concrete occurs at a depth below the surface corresponding to approximately 35 to 40 percent of the layer thickness. For example, the maximum shear for a 6-inch (152-mm) pavement occurs 2.5 inches (64 mm) below the surface. For 8.5 inches (216 mm), the depth is 3 inches (76 mm) below the surface. Figure 20 also indicates that, for an 18-kip (80-kN) single axleload, the maximum shear will occur no deeper than 3 inches below the surface even when the pavement thickness exceeds 8.5 inches.

STRESS ANALYSIS

To determine what shear strength is required of the asphaltic concrete mix to resist shear flow, Figures 21-24 display the results of analyses using stress components instead of strain components. Figures 21-24 are similar to Figures 19 and 20. Figure 21 illustrates the distribution of shear stress with depth of full-depth asphaltic concrete due to a four-tired, 18-kip (80-kN) single axleload; the stress pattern is similar to the strain pattern shown in Figure 19. Figure 22 shows the maximum stress as a function of thickness of asphaltic concrete.

An 80-kip (356-kN) tandem axleload having a contact pressure of 80 psi (0.55 MPa) was applied to the same pavement structures on a subgrade having a resilient modulus of 7,500 psi (51.8 MPa). Figure 23 shows, that while the same general pattern exists as in Figure 19, the depth of maximum shear decreases from 50 percent of the thickness for a 4-inch (102-mm) thickness to 35 percent of the thickness for 9 inches (228 mm) of asphaltic concrete. For thicknesses exceeding 9 inches (228 mm), the depth corresponding to maximum shear decreases in a manner similar to that shown in Figure 20.

Figures 21 and 22 indicate that a maximum shear stress of 67 psi (0.46 MPa) results from an 18-kip (80-kN) single axleload on a 4-inch (102-mm) thickness of asphaltic concrete. However, Figures 23 and 24 indicate the shear stress will increase to 133 psi (0.91 MPa) under an 80-kip (356-kN) tandem axleload. As the tire contact pressure increases, the shear stress will increase.

IMPLICATIONS FOR COMPOSITE PAVEMENTS

Analyses presented in this report illustrate some significant impacts for asphaltic concrete overlays. Because shear stresses/strains reach a maximum within the top 40 percent of the asphaltic concrete layer, rehabilitation of older pavements having two or more overlays may require a different strategy. Kentucky's surface mix has the lowest modulus compared to binder and/or base mixes. When a new overlay is constructed, the older courses of surface mix become the zones of increased shear stress/strain. Aggregate particles may have been reoriented by traffic until they are nearly parallel to the pavement surface. Tack coats are necessary to assure bonding of the new overlay to the existing pavement. However, the combination of an initially weaker modulus and parallel aggregate orientation coupled with a tack coat leads to potential weak zones with regard to shear resistance. Therefore, milling the old surface mixes and replacing that thickness with new material and/or reclaimed asphaltic concrete should be considered. For older pavements, initial milling and overlay costs may be considerably higher. However, benefits would include the removal of material already susceptible to lateral displacement (contributing to rutting) and placement of a thick lift having better aggregate interlocking and increased resistance to rutting.

A composite pavement cross section consisting of 4 inches of asphaltic concrete on 10 inches of portland cement concrete was analyzed. Distribution of stresses and strains differed considerably from the normal pattern for flexible pavements where stresses and strains dissipate with increasing depth. Analyses indicated higher shear stresses and strains may occur at the flexible-rigid interface than near the surface and becomes more pronounced with increasing tire contact pressure. The rigid layer beneath the flexible layer is contributing reactionary stresses/strains within the flexible layer. It is very possible that increased tire contact pressure and axleload may cause lateral displacement of the asphaltic concrete, resulting in surface rutting. Such phenomenon may suggest that some pavement failures may be based on other than fatigue criteria.

RESULTS

1. Strain energy density incorporates the effects of all components of strain or stress into one representative value.
2. Strain energy density decreases with depth into the full-depth asphaltic concrete pavement to a depth approximately 45 to 60 percent of the total thickness and then increases in magnitude until the bottom of the layer is reached.
3. Calculated strain energy densities at the top and bottom of the asphaltic concrete layer are approximately identical whether the X-Y coordinate corresponds to the center of the tire, the edge of the tire, or midway between the center and tire edge. However, the magnitude of the strain energy density varies significantly as a function of the depth within the asphaltic

concrete layer and the X-Y location. The magnitude is a maximum at the edge of the tire and a minimum under the center of the tire.

4. Simpson's rule, or a modification of Simpson's rule, may be used to obtain an approximate sum of the strain energy distribution through the thickness of the pavement for a specific X-Y coordinate at the pavement surface. Simpson's rule should be used when there are an even number of increments to be summed. For an odd number of increments, Simpson's rule is modified to include a trapezoidal function for the bottom increment.

5. The summation of strain energy density in the pavement along the length of an axle varies as a function of the number and locations of loads applied to the pavement.

6. The location of maximum summation of strain energy density occurs at the edges of the tires and not at the center.

7. Use of one 9-kip (40-kN) load to represent two 4.5-kip (20-kN) loads does not produce an accurate description of the location of maximum summation of strain energy density within the pavement.

8. The location of maximum strain energy density is under the edge of either dual tire nearest the other dual tire. The magnitude of the strain energy density at the edge of the tire nearest the other tire is approximately twice that at the center of the tire.

9. Comparing distributions of strains corresponding to locations at the edge of the tire, center of the tire, and midway between show that there is relatively little difference in magnitudes for the tangential, radial, and vertical components, but varies greatly for the shear component. For one given load, the shear must be zero at the center of the load. When two or more loads are analyzed using superposition principles, there will be a small amount of shear at the center of a load due to the effects of the other loads.

10. The magnitude of the shear component reaches its maximum at a depth approximately 35 to 40 percent of the total thickness of asphaltic concrete up to a thickness of 8.5 inches (216 mm) due to the application of an 18-kip (80-kN) single axleload. For thicknesses greater than 8.5 inches (216 mm), the depth of maximum shear decreases to approximately the 1-inch (25-mm) depth when the thickness is approximately 16 inches (406 mm) and remains at the 1-inch (25-mm) depth for greater thicknesses of asphaltic concrete. For an 80-kip (356-kN) tandem axleload with a tire contact pressure of 80 psi (0.55 MPa), the maximum shear occurs at 35 to 40 percent of the total asphaltic thickness up to 9 inches (229 mm); then the depth of maximum shear decreases from 3.1 inches (79 mm) to approximately 2.3 inches (58 mm) at a thickness of 18 inches (457 mm) and appears to remain constant thereafter.

11. A 17-inch (432-mm) full-depth asphaltic concrete pavement was trenched in 1980 or 1981. A visual inspection showed shear flow from the surface to approximately the 6-inch (152-mm) depth; no shear flow was evident below that depth. The same observation was noted when an 18-inch (457-mm) full-depth asphaltic concrete pavement on another route was trenched. Those observations confirm the theoretical analyses in that the maximum

shear will occur at a depth of approximately 35 to 40 percent of the total thickness of asphaltic concrete. In Kentucky, a typical 8-inch thickness of asphaltic concrete is constructed of two 2.5-inch courses of bituminous base mix, one 2-inch course of bituminous binder mix, and one 1-inch course of bituminous surface mix. The interface between the base and binder courses therefore is located 3 inches below the surface -- right where the maximum shear is being generated. A better selection of pavement thicknesses might be two 3.5-inch courses of bituminous base mix followed by the 1-inch course of bituminous surface mix. This combination would place the second interface at 4.5 inches below the surface. Another alternative combination might be a 4-inch bituminous base mix followed by a 3-inch bituminous base mix and then the 1-inch bituminous surface mix.

12. For a 4-inch (102-mm) thickness of asphaltic concrete, an 18-kip (80-kN) single axleload causes a maximum shear stress of 67 psi (0.46 GPa). For an 80-kip (356-kN) tandem axleload and a tire contact pressure of 80 psi (0.55 GPa), the maximum shear stress increases to 133 psi (0.91 GPa) and easily could reach 175 psi (1.21 GPa) as the contact pressure rises above 100 psi (0.69 GPa).

13. The traditional axleloads and lower tire pressures prior to the use of radial tires did not cause shear stresses that exceeded the tolerable shear stresses/strains of the current asphaltic concrete mixes. Current axleloads and increased contact pressures have exceeded the tolerable shear stress/strain limits of current mix design.

14. For traditional thicknesses of 6 to 8 inches (152 to 203 mm) of asphaltic concrete, the usual course thicknesses specified in Kentucky have been a 1-inch (25-mm) surface course on a 1.5- to 2-inch (38- to 51-mm) layer of binder mix and the remaining thickness composed of a base mix. Thus, for a 6-inch (152-mm) or 8-inch (203-mm) asphaltic concrete layer, maximum shear will occur at the 2.5-inch (64-mm) or 3-inch (76-mm) depth respectively -- right where a construction plane produces the least aggregate interlock. Thus, shear flow should be expected.

15. For composite pavements, analyses indicate shear stresses/strains may be higher at the flexible-rigid interface than near the surface which is contrary to the distribution within full-depth asphaltic concrete construction. Increasing tire contact pressures increases the stresses/strains at the interface.

RECOMMENDATIONS

1. Traditional asphaltic concrete mix designs should be analyzed for shear resistance. Mix designs should be developed to withstand shear stresses of at least 200 psi (1.38 GPa).

2. Consideration should be given to either
   a. increase the shear resistance of the binder mix or
   b. eliminate the binder-mix layer and replace it with a base-mix layer. Further research is needed to determine which alternate is the best.

3. The 1-inch (25-mm) surface-mix layer should be placed on

a minimum of a 3-inch (76-mm) layer of a high shear-resistant mix to eliminate a construction interface in the zone of maximum shear.

4. Pavements having two or more overlays of surface mix that are candidates for another overlay should be considered for milling all surface mixes and placing one layer of base mix followed by a surface mix to eliminate material already weakened by shear flow.

5. In-place pavements exhibit distresses indicating shear failures within the asphaltic concrete layers. Research is under way to determine shear parameters of hollow cylindrical specimens of asphaltic concrete, but it is not clear how those values would compare to results obtained using solid specimens. Critical values for shear stresses or strains are not known at this time. Torsional testing of solid specimens may provide insight, but development of higher-capacity equipment than is currently available is necessary. Future research may provide critical values of stresses and guidance for use in design.

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1. J. Michelow, "Analysis of Stresses and Displacements in an N-Layered Elastic System under a Load Uniformly Distributed on a Circular Area", Unpublished, Richmond, CA, September 24, 1963.

2. H. F. Southgate, R. C. Deen, and J. G. Mayes, "Strain Energy Analysis of Pavement Designs for Heavy Trucks," Transportation Research Board, Record 949, Washington, D.C., 1981.

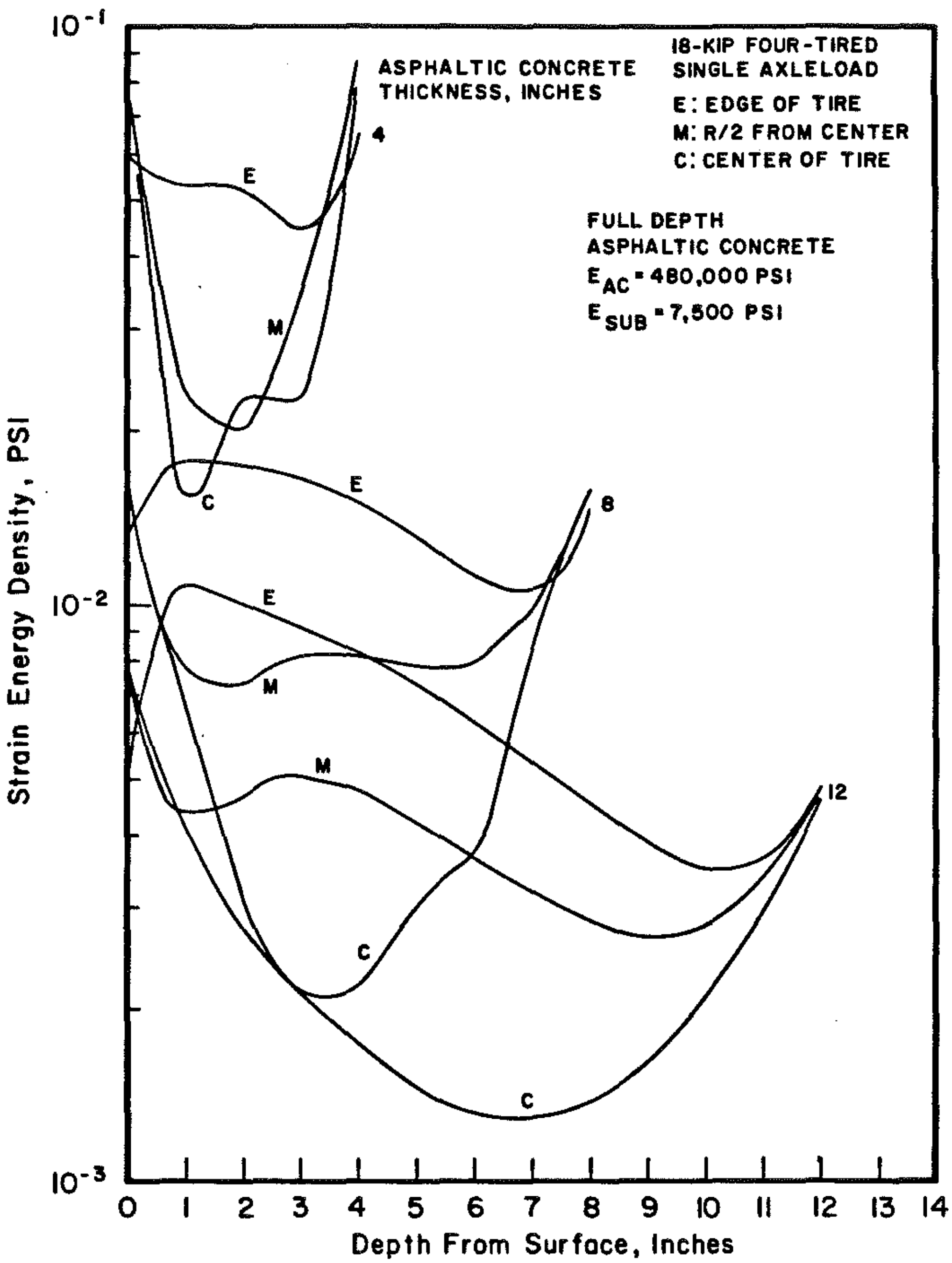


Figure 1. Distribution of Strain Energy Density as a Function of Depth for 4, 8, and 12 inches (102, 203, and 306 mm) of Full-Depth Asphaltic Concrete at the Center of the Tire, at the Edge of the Tire, and Midway between the Center and Edge of the Tire.

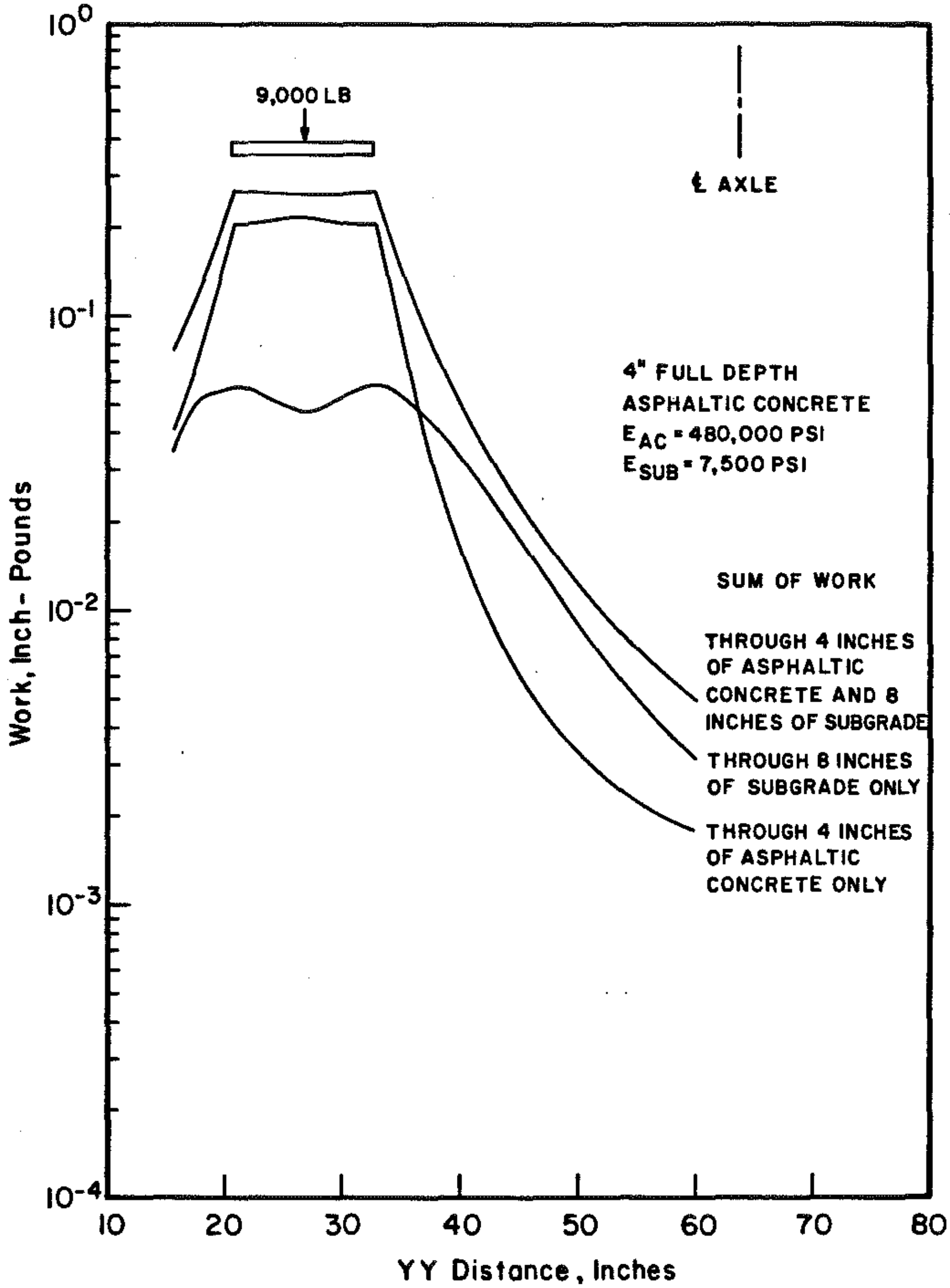


Figure 2. Distribution of Work for a 4-inch (102-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Two-Tired 18-kip (80-kN) Axleload.

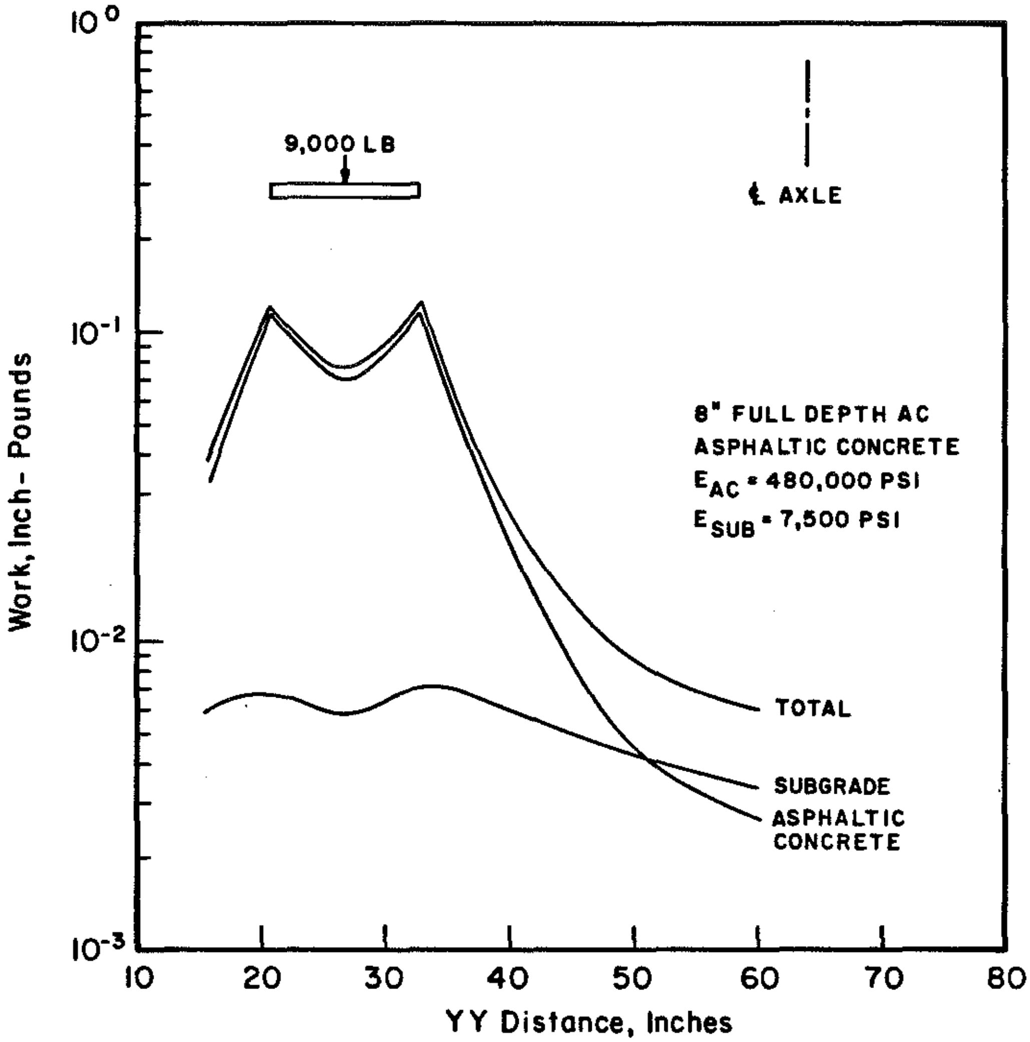


Figure 3. Distribution of Work for a 8-inch (203-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Two-Tired 18-kip (80-kN) Axleload.

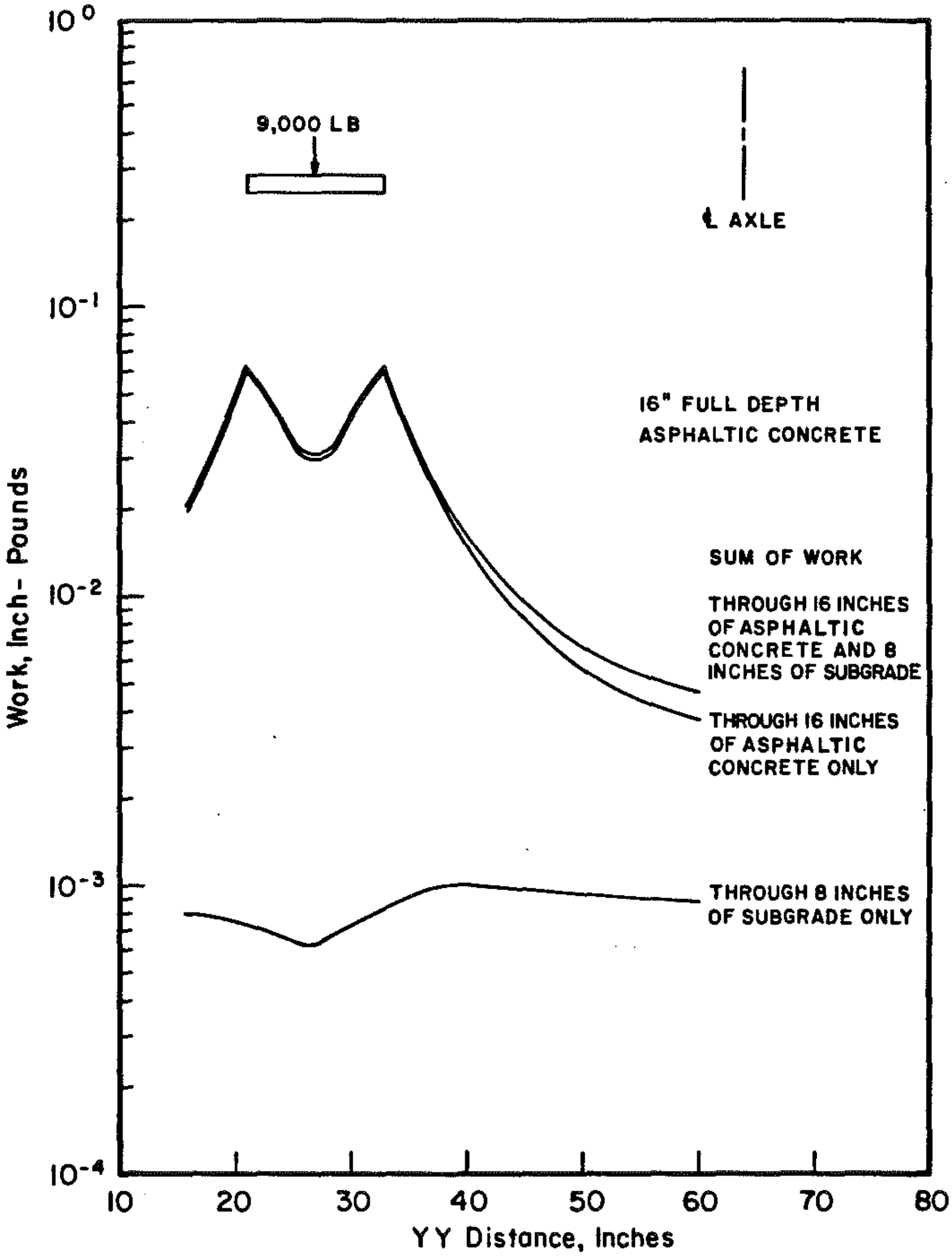


Figure 4. Distribution of Work for a 16-inch (406-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Two-Tired 18-kip (80-kN) Axleload.

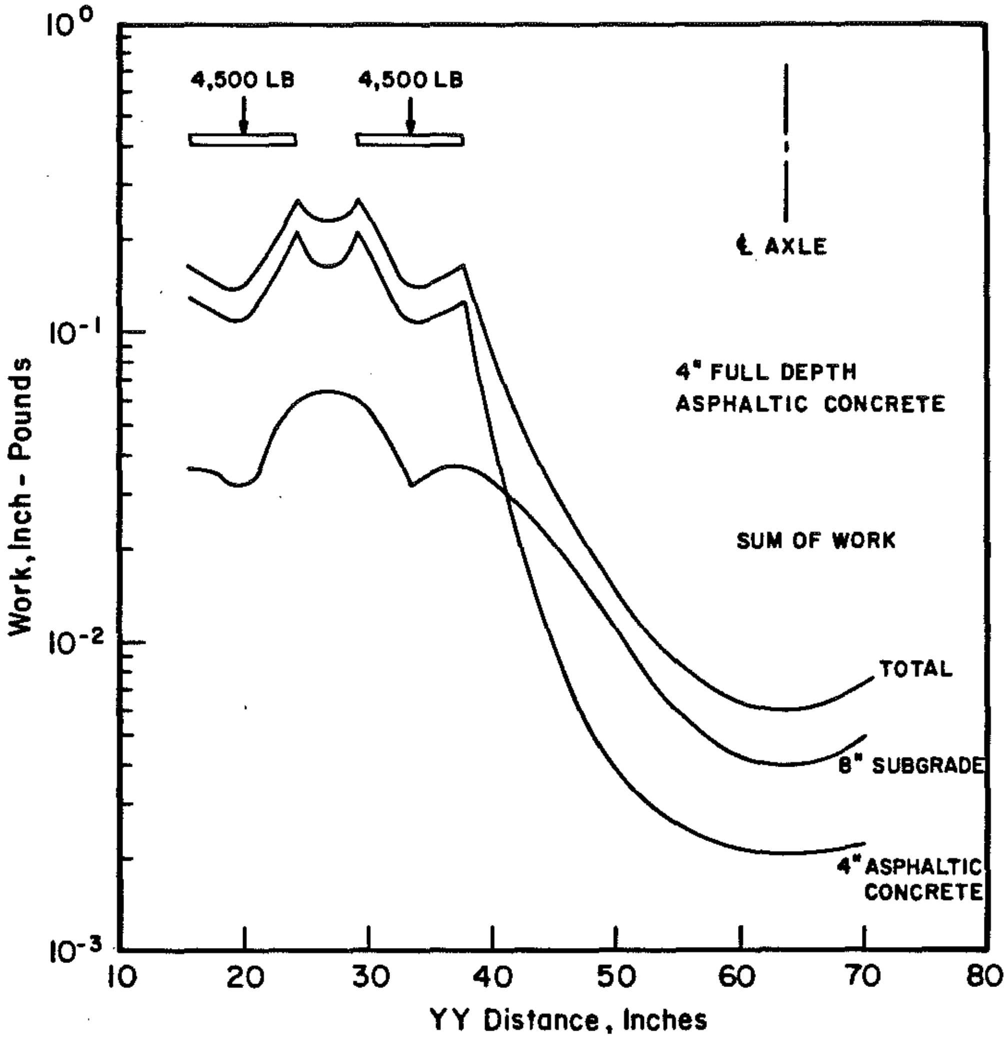


Figure 5. Distribution of Work for a 4-inch (102-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Four-Tired 18-kip (80-kN) Axleload.

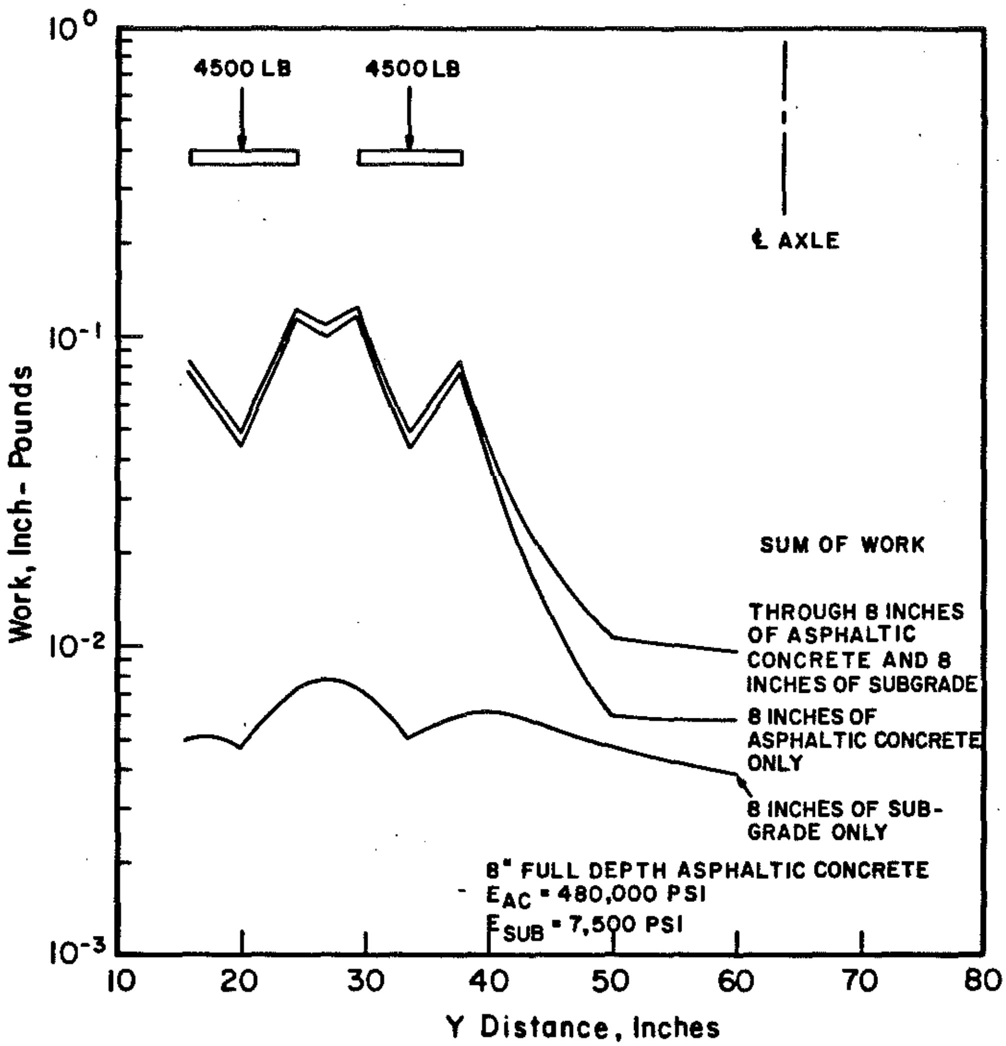


Figure 6. Distribution of Work for a 8-inch (203-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Four-Tired 18-kip (80-kN) Axleload.

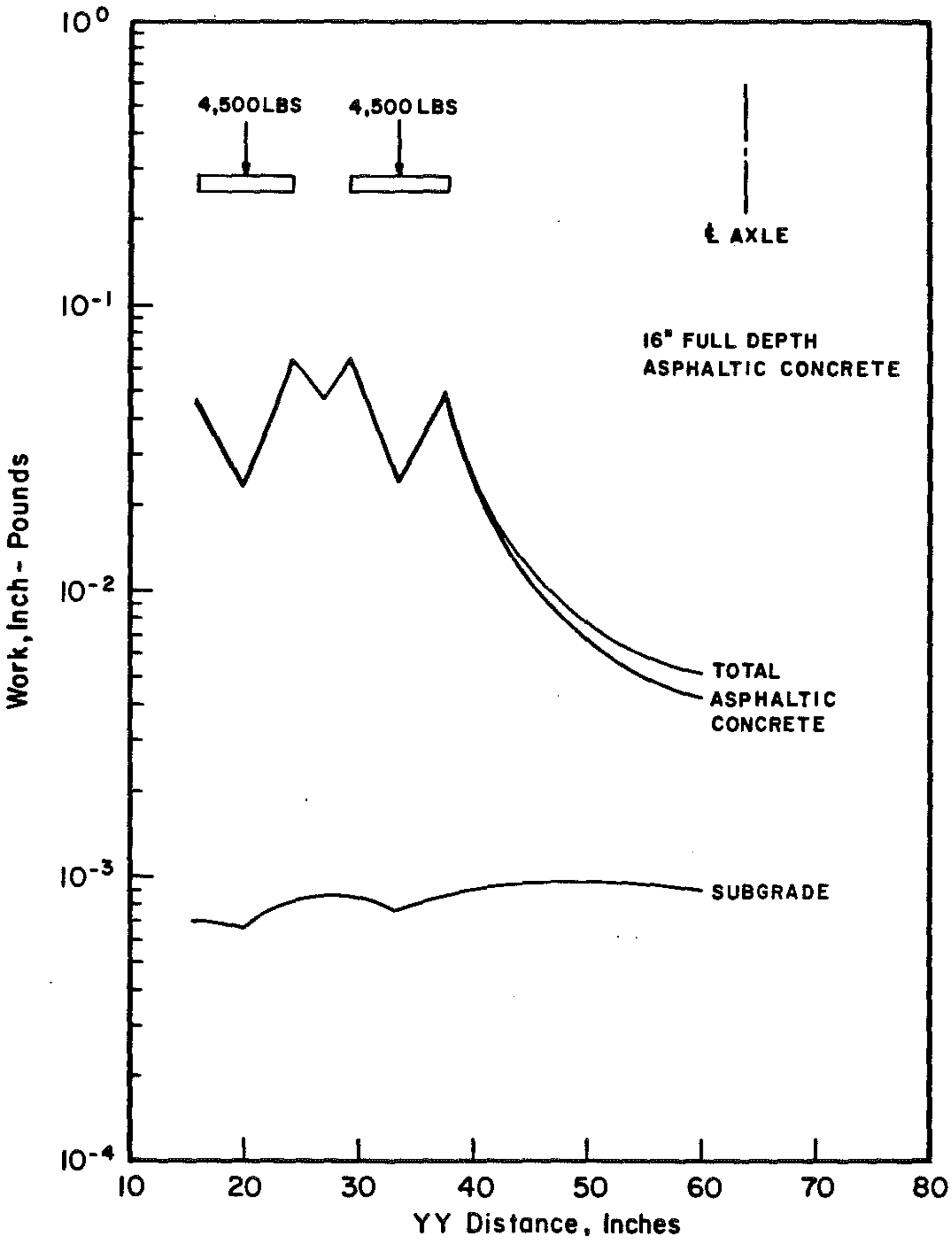


Figure 7. Distribution of Work for a 16-inch (406-mm) Full-Depth Asphaltic Concrete Pavement versus Location along the Centerline of the Axle for a Four-Tired 18-kip (80-kN) Axleload.

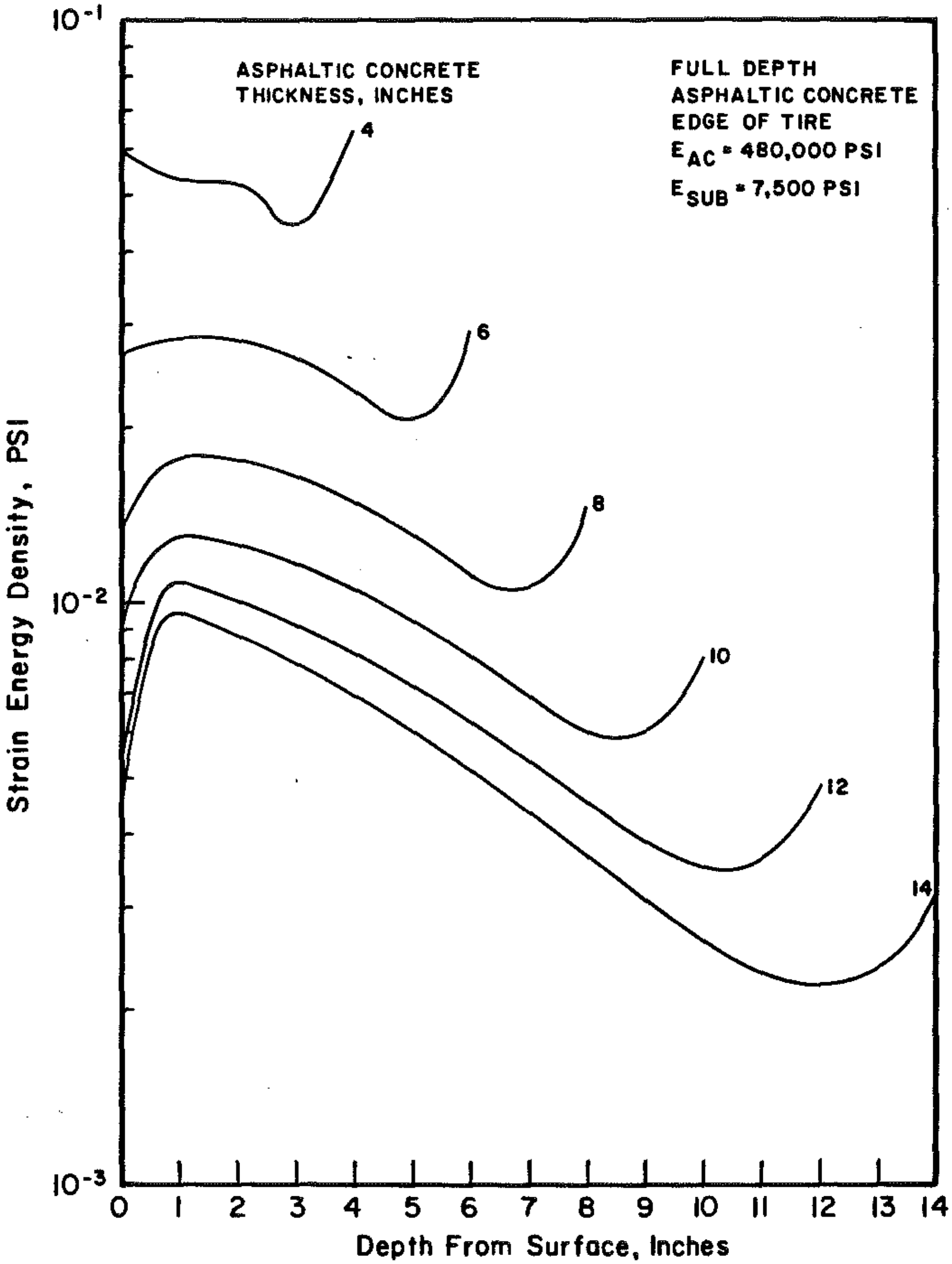


Figure 8. Distribution of Strain Energy Density under the Inside Edge of Dual Tires of a Four-Tired 18-kip (80-kN) Single Axleload for Various Thicknesses of full-Depth Asphaltic-Concrete.

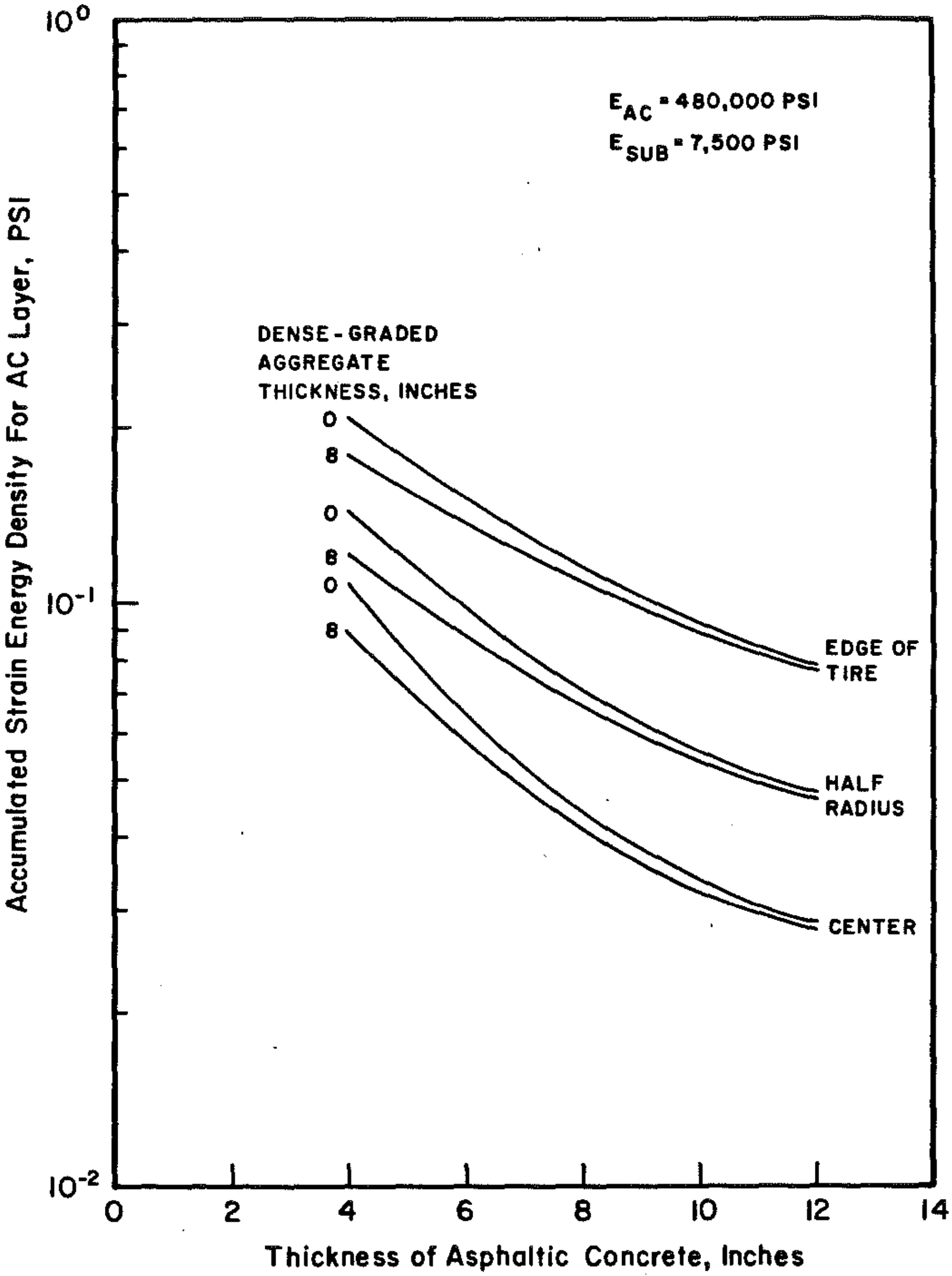


Figure 9. Accumulated Strain Energy Density as a Function of Thickness of Dense-Graded Aggregate Base for Various Asphaltic Concrete Layer Thicknesses.

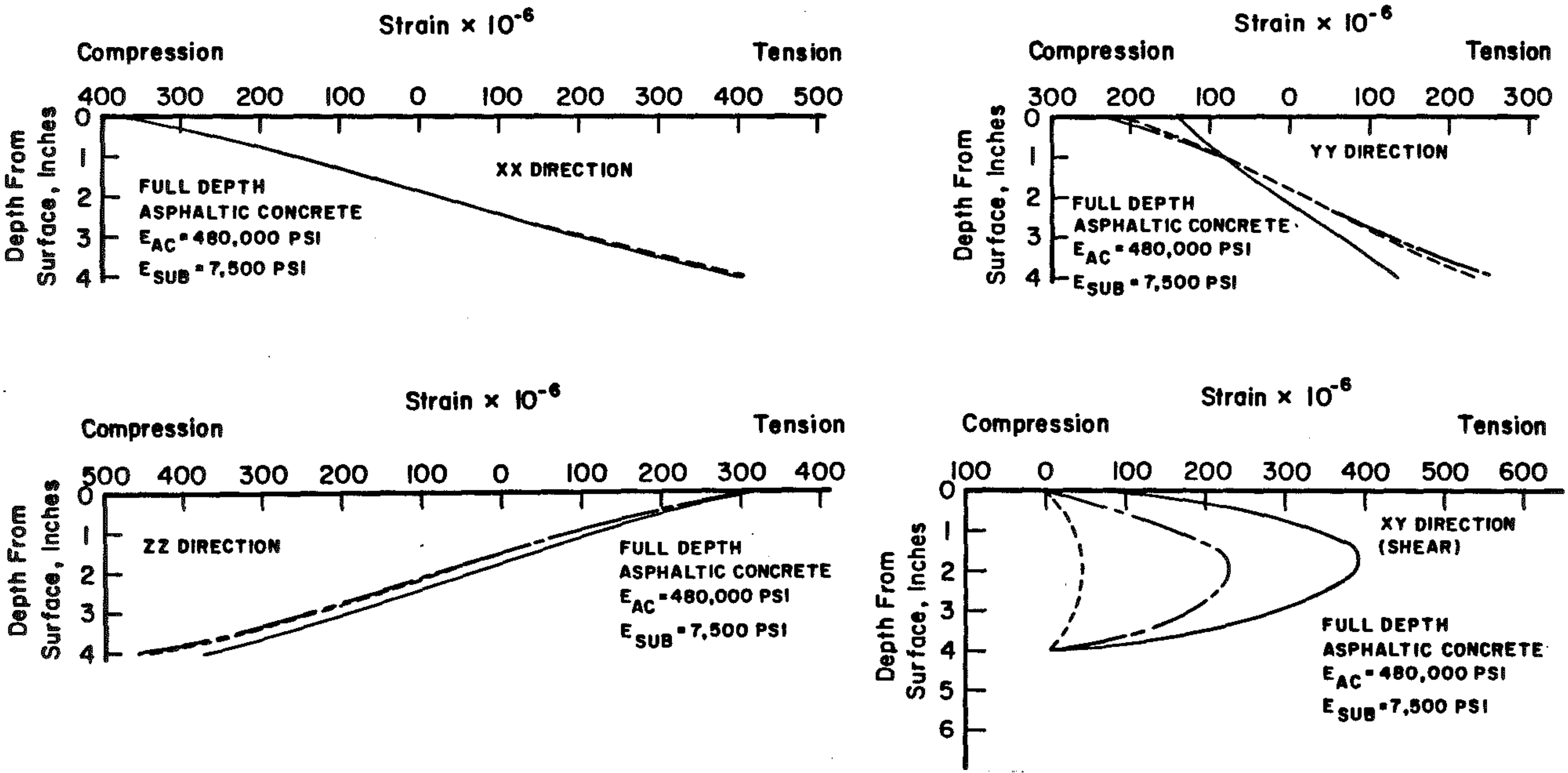


Figure 10. Distribution of Strains from Surface through 4 inches (102 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.
Line Code: Solid Line is at Edge of Tire.
Short Dashed Line is at Center of Tire.
Short and Long Dash is at 1/2 Radius.

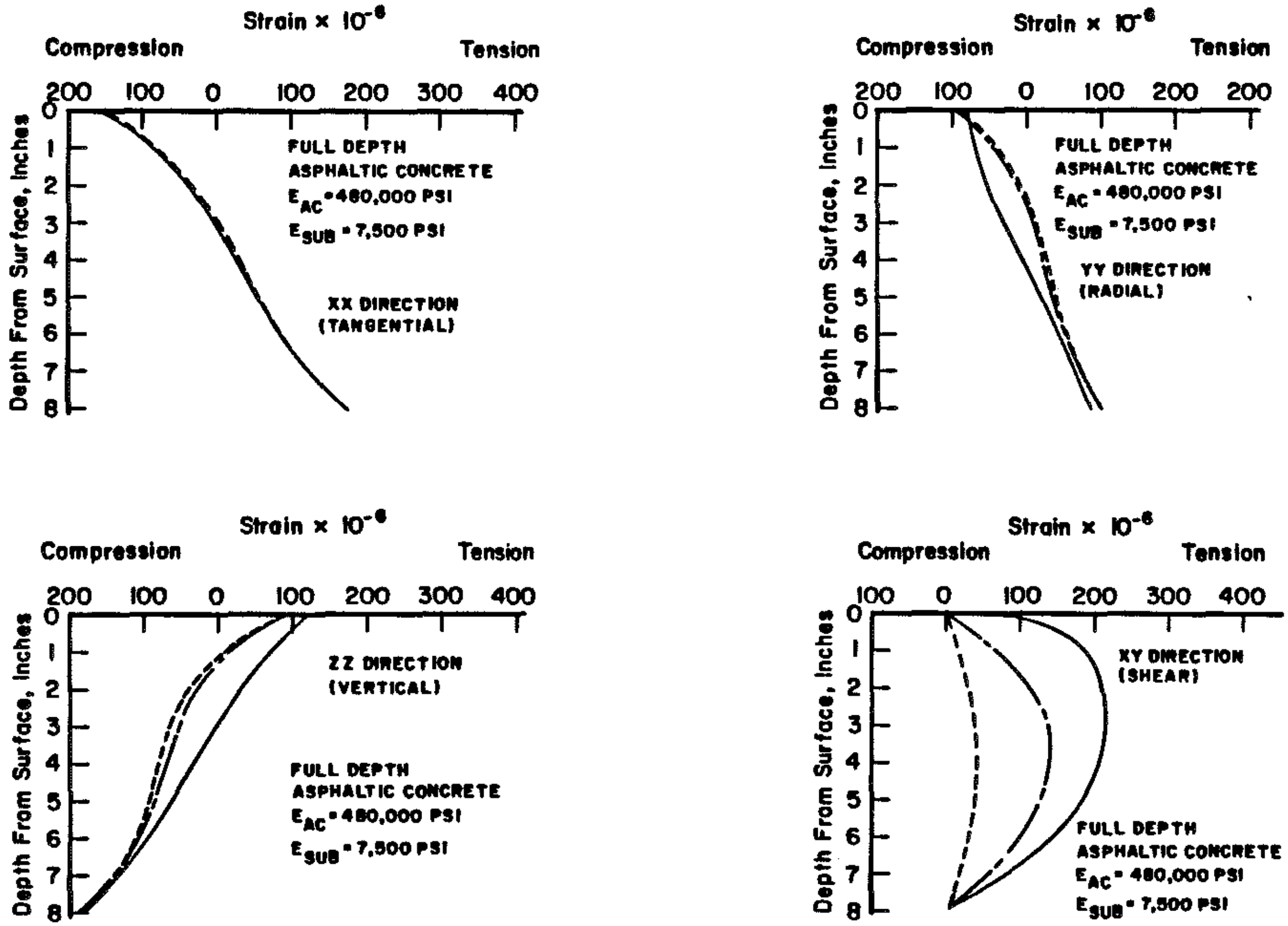


Figure 11. Distribution of Strains from Surface through 8 inches (203 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.
Line Code: Solid Line is at Edge of Tire.
Short Dashed Line is at Center of Tire.
Short and Long Dash is at 1/2 Radius.

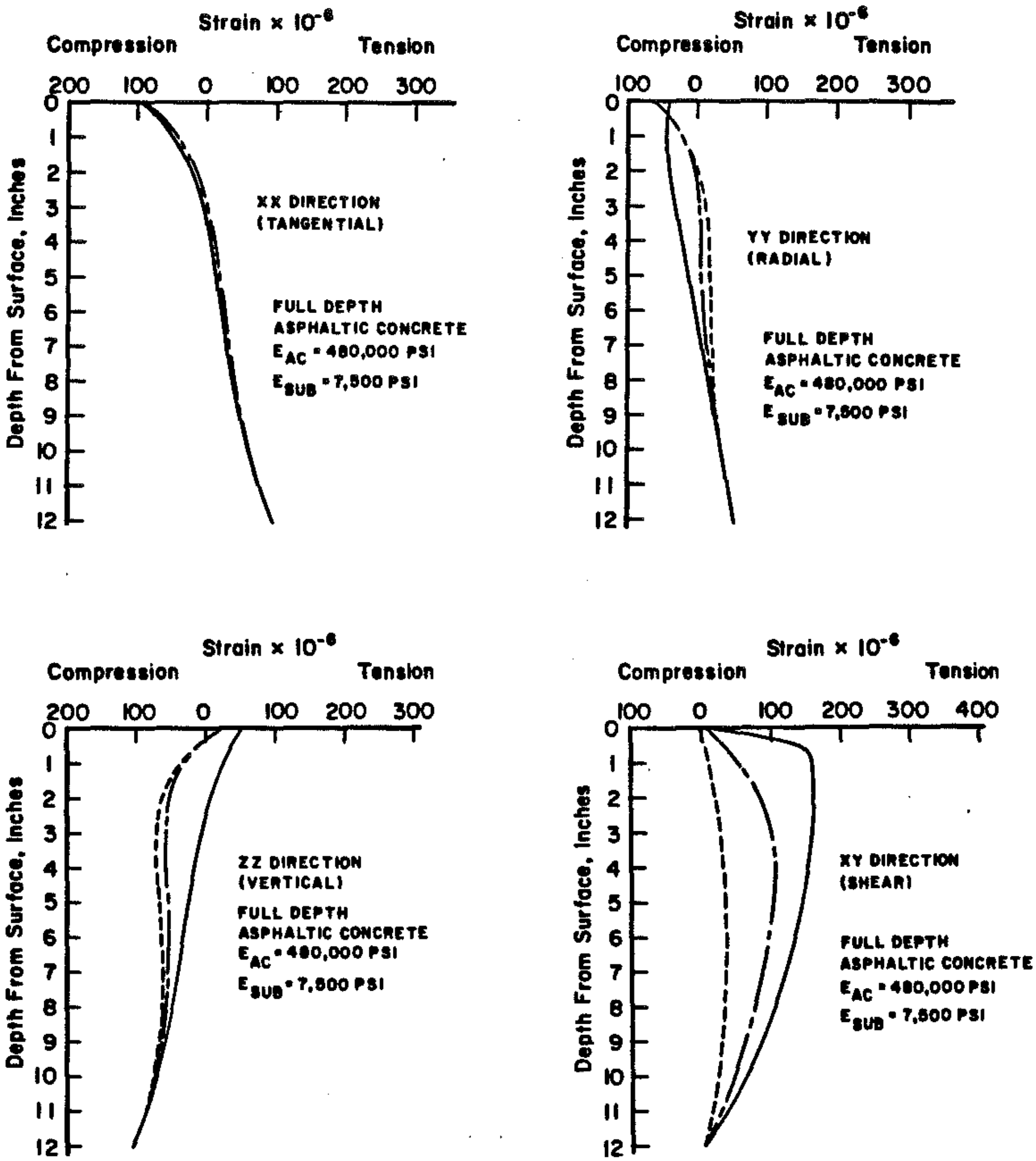


Figure 12. Distribution of Strains from Surface through 12 inches (305 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.
Line Code: Solid Line is at Edge of Tire.
Short Dashed Line is at Center of Tire.
Short and Long Dash is at 1/2 Radius.

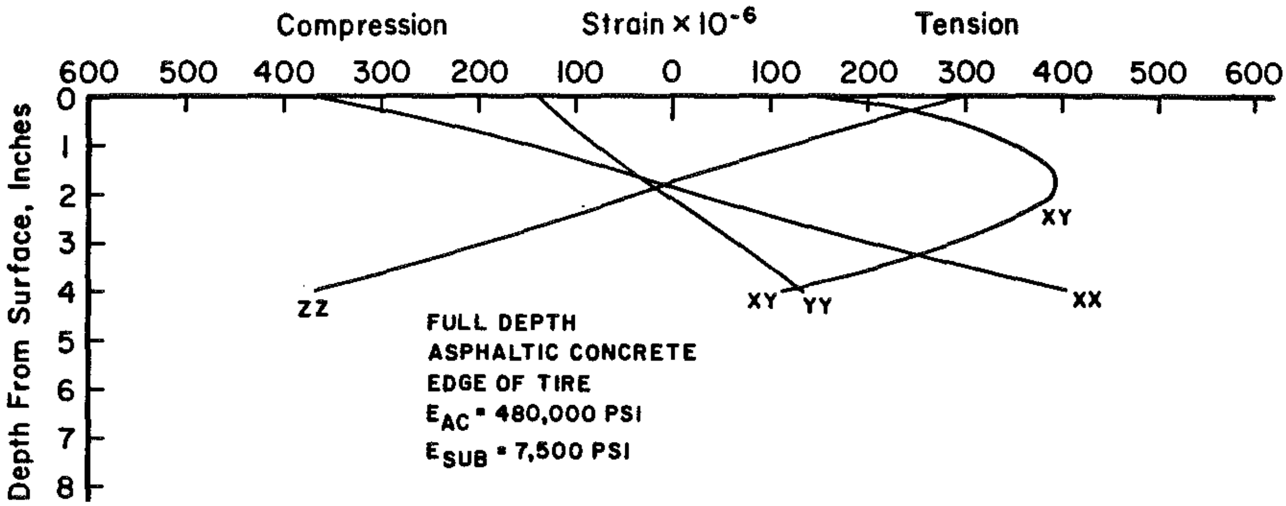


Figure 13. Distribution of All Strain Components from Surface through 4 inches (102 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

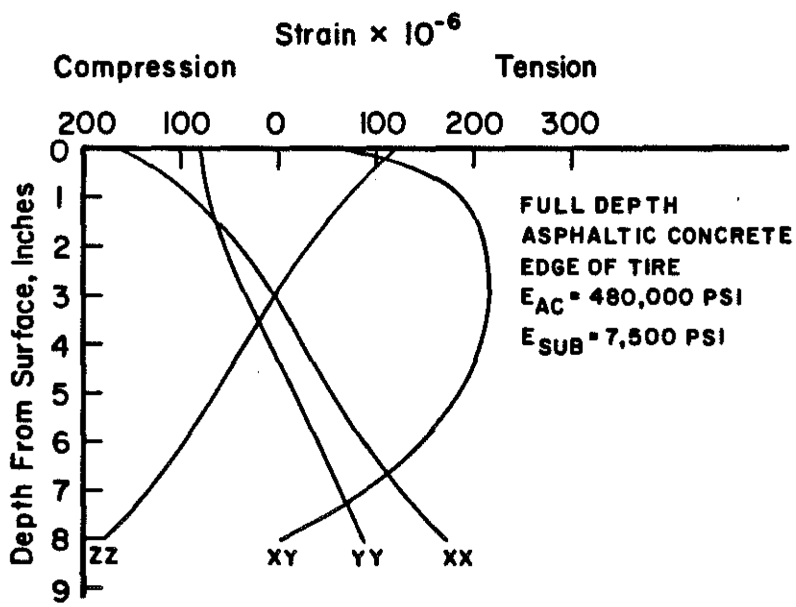


Figure 14. Distribution of All Strain Components from Surface through 8 inches (203 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

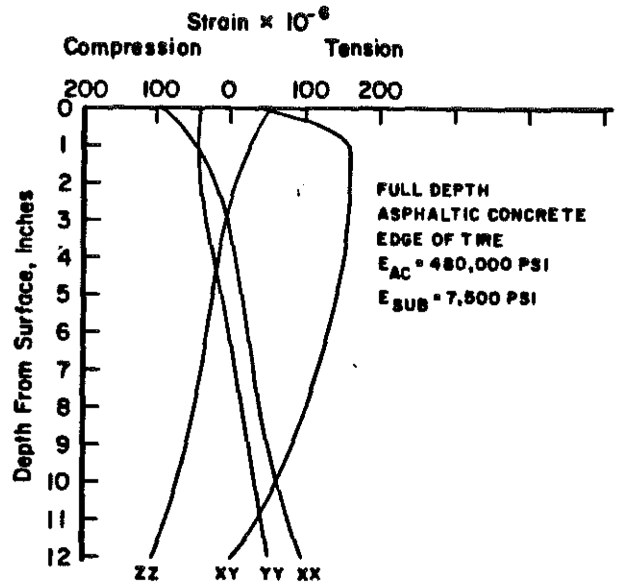


Figure 15. Distribution of All Strain Components from Surface through 12 inches (102 mm) of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

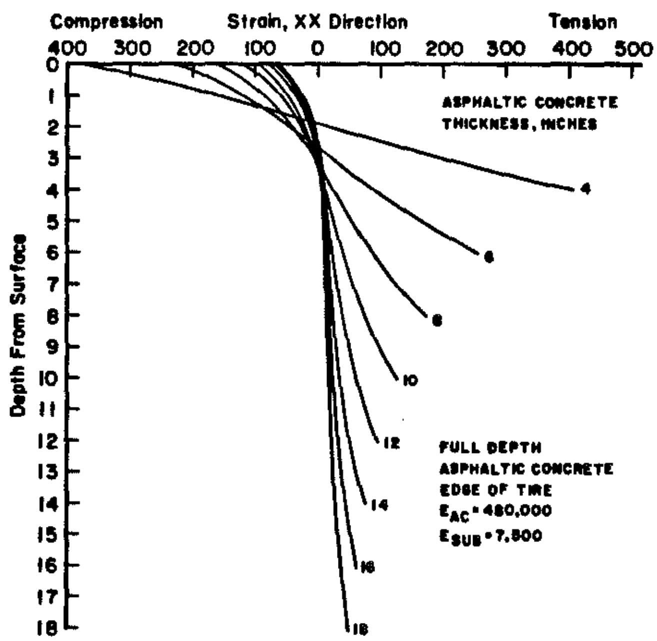


Figure 16. Distribution of Strain in XX (Tangential) Direction from Surface through Various Tincknesses of Full-Depth Asphaltic Concrete uner an 18-kip (80-kN) Four-Tired Single Axleload.

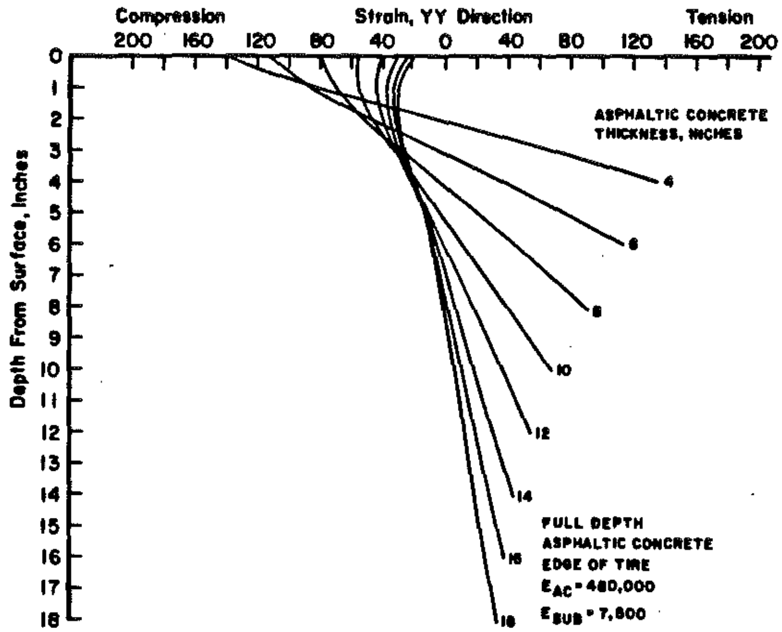


Figure 17. Distribution of Strain in YY (Radial) Direction from Surface through Various Thicknesses of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

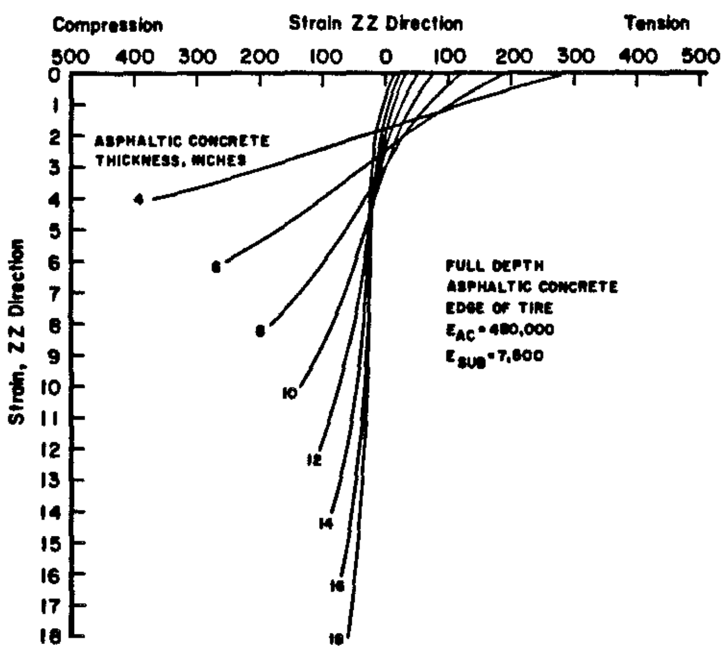


Figure 18. Distribution of Strain in ZZ (Vertical) Direction from Surface through Various Thickness of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

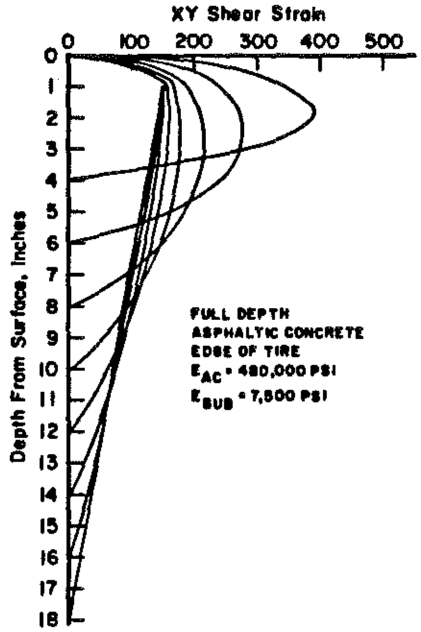


Figure 19. Distribution of Strain in XY (Shear) Direction from Surface through Various Thicknesses of Full-Depth Asphaltic Concrete under an 18-kip (80-kN) Four-Tired Single Axleload.

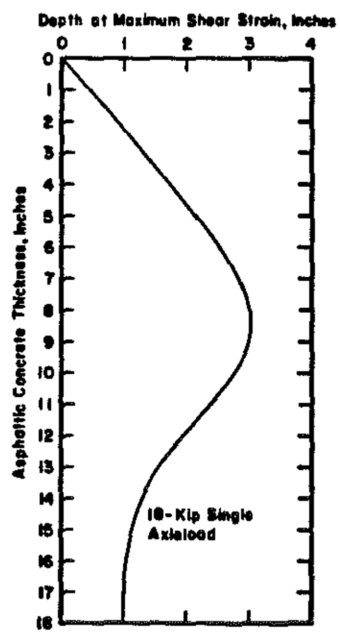
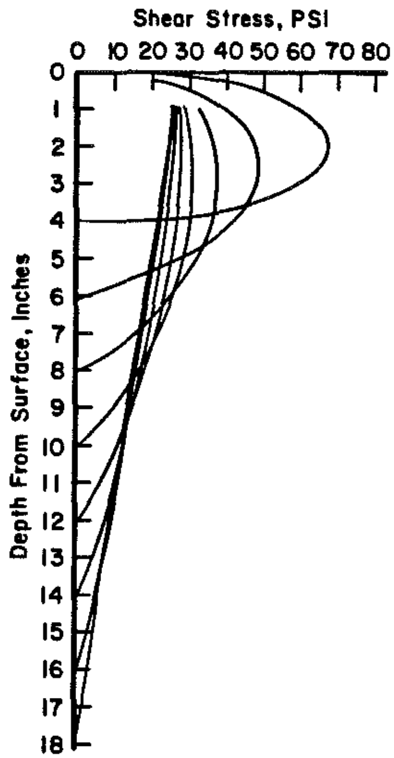


Figure 20. Depth of Maximum Strain under an 18-kip (80-kN) Four-Tired Single Axleload Versus Thickness of Full-Depth Asphaltic Concrete.

Figure 21. Distribution of Shear Stresses under an 18-kip (80-kN) Four-Tired Single Axleload from Surface to Bottom of Various Thicknesses of Full-Depth Asphaltic Concrete.



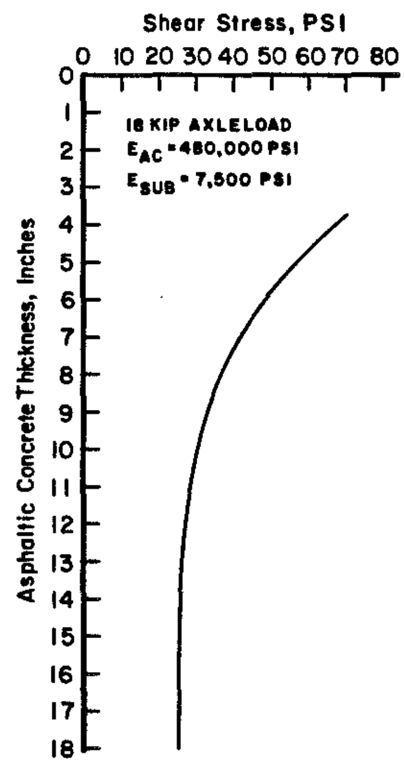
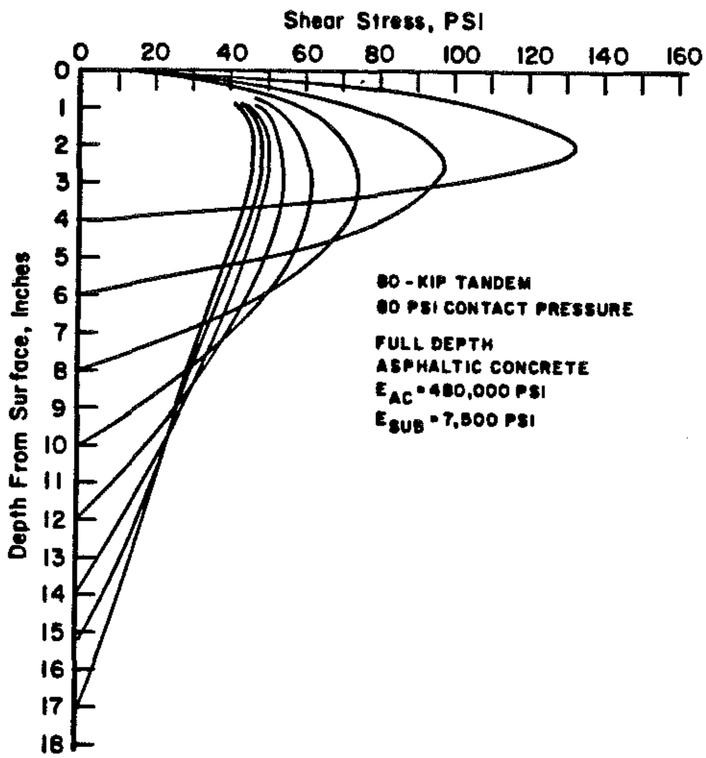


Figure 22. Distribution of Maximum Shear Stress under an 18-kip (80-kN) Four-Tired Single Axleload Versus Thickness of Full-Depth Asphaltic Concrete.

Figure 23. Distribution of Strain in XY (Shear) Direction under an 80-kip (356-kN) Eight-Tired Tandem Axleload from Surface through Various Thicknesses of Full-Depth Asphaltic Concrete.



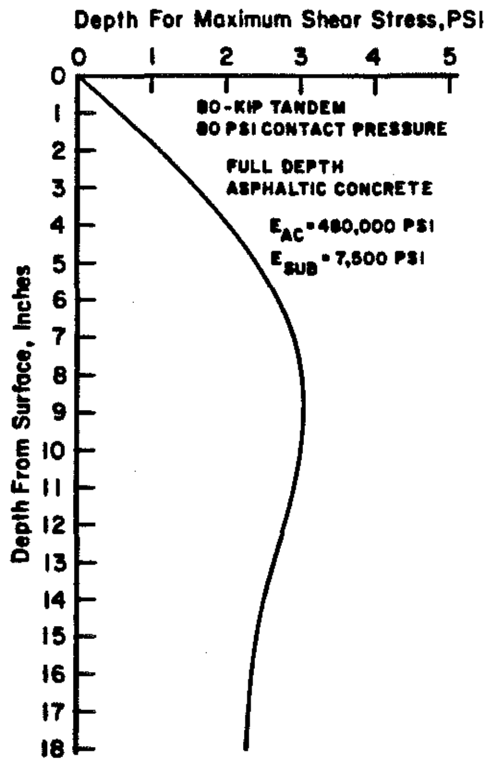


Figure 24. Depth of Maximum Strain under an 80-kip (356-kN) Eight-Tired Tandem Axleload versus Thickness of Full-Depth Asphaltic Concrete.