Distributions of Strain Components and Work Within Flexible Pavement Structures

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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 to be calculated at various depths. 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 than 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, four-tired, single axle load, 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 in.; thereafter the depth of maximum shear moves toward the surface as thickness increases. An investigation of shear stress indicated that the maximum value was approximately 67 psi due to an 18-kip single axle load and tire contact pressure of 80 psi within a 4-in. full-depth asphaltic concrete pavement. Investigation of three pavements indicated shear flow could be seen as deep as 6 in. below the surface. From the stress analyses presented, the stress at the 6-in. depth would be approximately 25 psi. An established critical value for the shear stress of asphaltic concrete is not known.

The first purpose of this investigation was to determine the locations within the pavement structure showing the greatest response to wheel loads, as evidenced by stresses and strains (*1*). A second purpose was to study patterns of strain or stress under limited conditions of eight thicknesses of full-depth asphaltic concrete having an elastic modulus of 480 ksi (compatible with the modulus assigned to Kentucky thickness design curves) on a California bearing ratio (CBR) 5 subgrade (modulus of elasticity of 7,500 psi). The imposed limitations were selected to permit development of behavioral patterns suitable for comparison and understanding of the individual strain or stress components and of their interactions through strain energy density. These analyses are not intended to provide specific numerical answers covering all situations but may provide values for future analyses of a broader list of variables, such as other subgrade moduli, asphaltic concrete moduli, multilayer pavements, magnitudes of load, tire footprints subdivided into small individual areas with variable load and contact pressures, and tire and axle configurations.

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The Chevron *N*-layer computer program (Michelow, unpublished) 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 can be calculated at specified locations. Strain energy density is the internal resistance within the body at a specific location that is equal to effects of the external force on the body. Equations to calculate the strain energy density at a specified location within a three-dimensional space incorporate a combination of input parameters, strains, and 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 can be made using Simpson's rule to sum the calculated strain energy densities at specified depths for a specific set of *X-Y* coordinates. Irwin (*3*) has related strain energy with fracture energy using the same equation.

PATTERNS OF WORK

Figure 1 shows the calculated strain energy density at 1-in. increments for thicknesses of 4, 8, and 12 in. of full-depth asphaltic concrete on a CBR 5 subgrade—a resilient modulus of 7,500 psi. The three curves for each thickness represent the inside edge of the tire, the center of the tire, and the point midway between the inside edge and the center. The area under the curve indicates 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

An investigation was made to determine the internal work at specified locations. Figure 2 shows patterns of work as a function of location along the centerline of a two-tired single axle load of 18 kips on 8 in. of full-depth asphaltic concrete on a CBR 5 subgrade corresponding to a resilient modulus of 7,500 psi. The work is a summation of the strain energy density using Simpson's rule. It is summed separately for the asphaltic concrete thickness and for 8 in. 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 in.

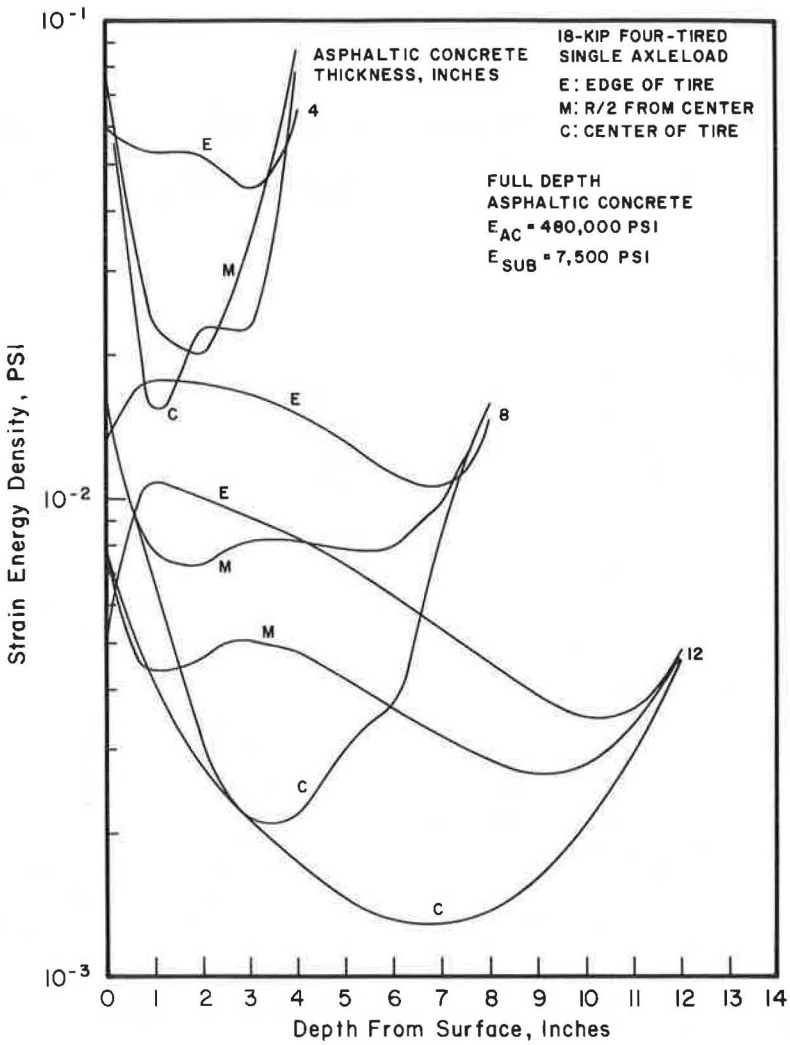

FIGURE 1 Distribution of strain energy density as a function of depth for 4, 8, and 12 in. of full-depth asphaltic concrete at center of tire, edge of tire, and midway between center and edge.

of the subgrade. Note the changes in patterns of work with increasing thickness of asphaltic concrete. The maximum work is always located under the edge of the loaded area.

Figure 3 shows patterns of work for the same structure and axle load except that four equally loaded areas replace the two areas used to obtain Figure 2. The locations of maximum accumulated work are still under the edge of the loaded areas, but the maximum has shifted to the inside edges of the dual areas.

As shown in Figure 4, there appears to be a family of curves relating strain energy density at specific depths as a function of thickness of asphaltic concrete. Figure 5 shows 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 in. 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 1–3, 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 6–8 show the distributions of strains through 4, 8, and 12 in. of asphaltic concrete, respectively, caused by an 18-kip, four-tired, single axle load. The distributions are shown for each component of strain for locations at the edge, at the center, and midway between the edge and center of the tire. The XX component is in the plane of the pavement surface, 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. In Figure 6, the XX strain at the bottom of the asphaltic concrete is relatively high. Also, there is almost no difference in pattern or magnitude for the three different answer locations within the tire contact area. The same can

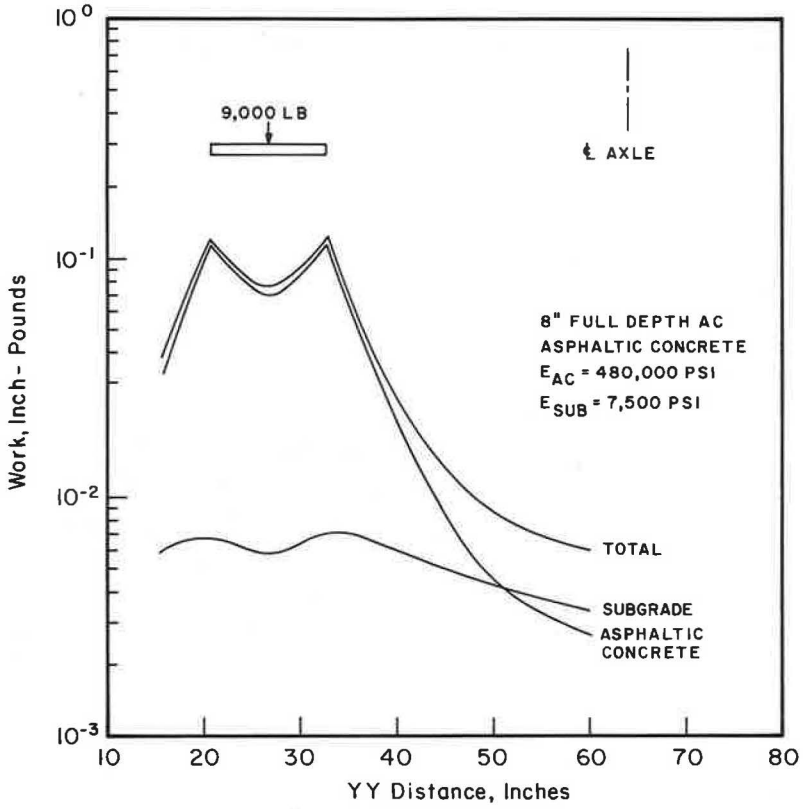

FIGURE 2 Distribution of work for an 8-in. full-depth asphaltic concrete pavement versus location along centerline of the axle for a two-tired 18-kip axle load.

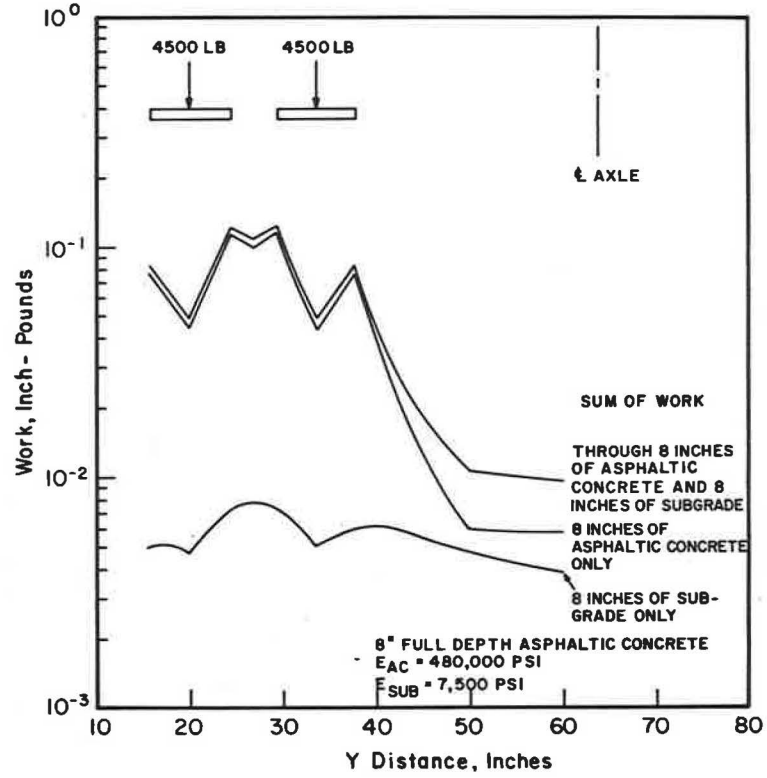

FIGURE 3 Distribution of work for an 8-in. full-depth asphaltic concrete pavement versus location along the centerline of the axle for a four-tired 18-kip axle load.

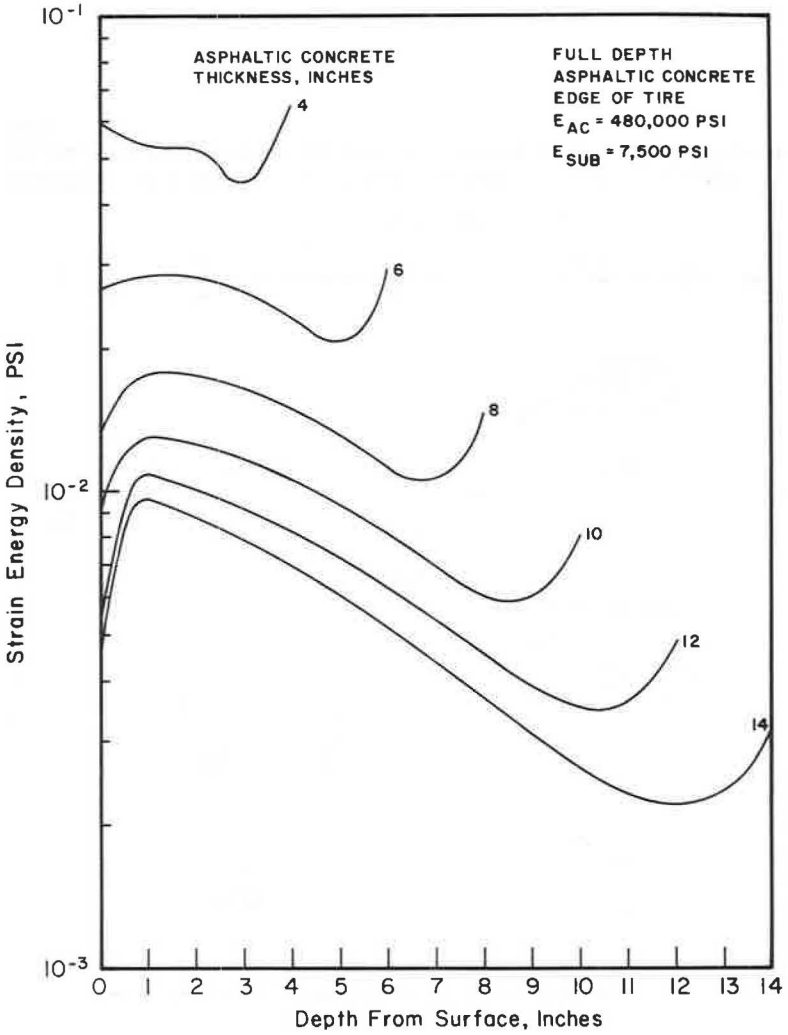

FIGURE 4 Distribution of strain energy density under the inside edge of dual tires of a four-tired, 18-kip, single axle load for various thicknesses of full-depth asphaltic concrete.

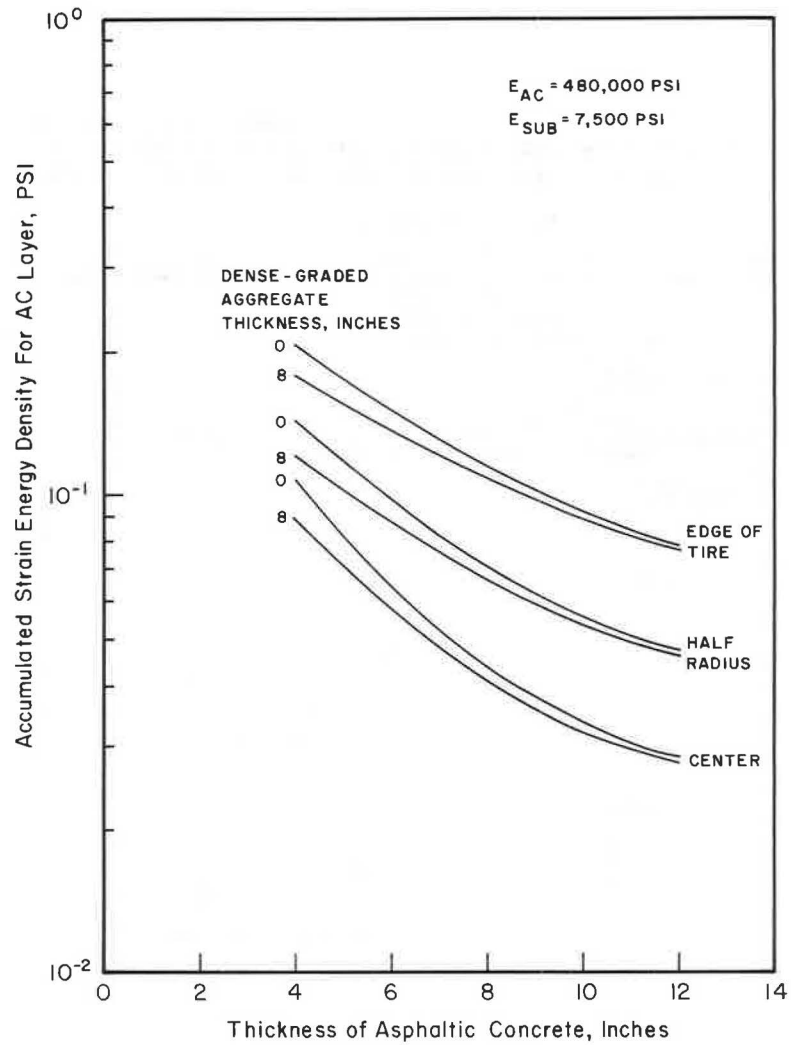

FIGURE 5 Accumulated strain energy density as a function of thickness of dense-graded aggregate base for various asphaltic concrete layer thicknesses.

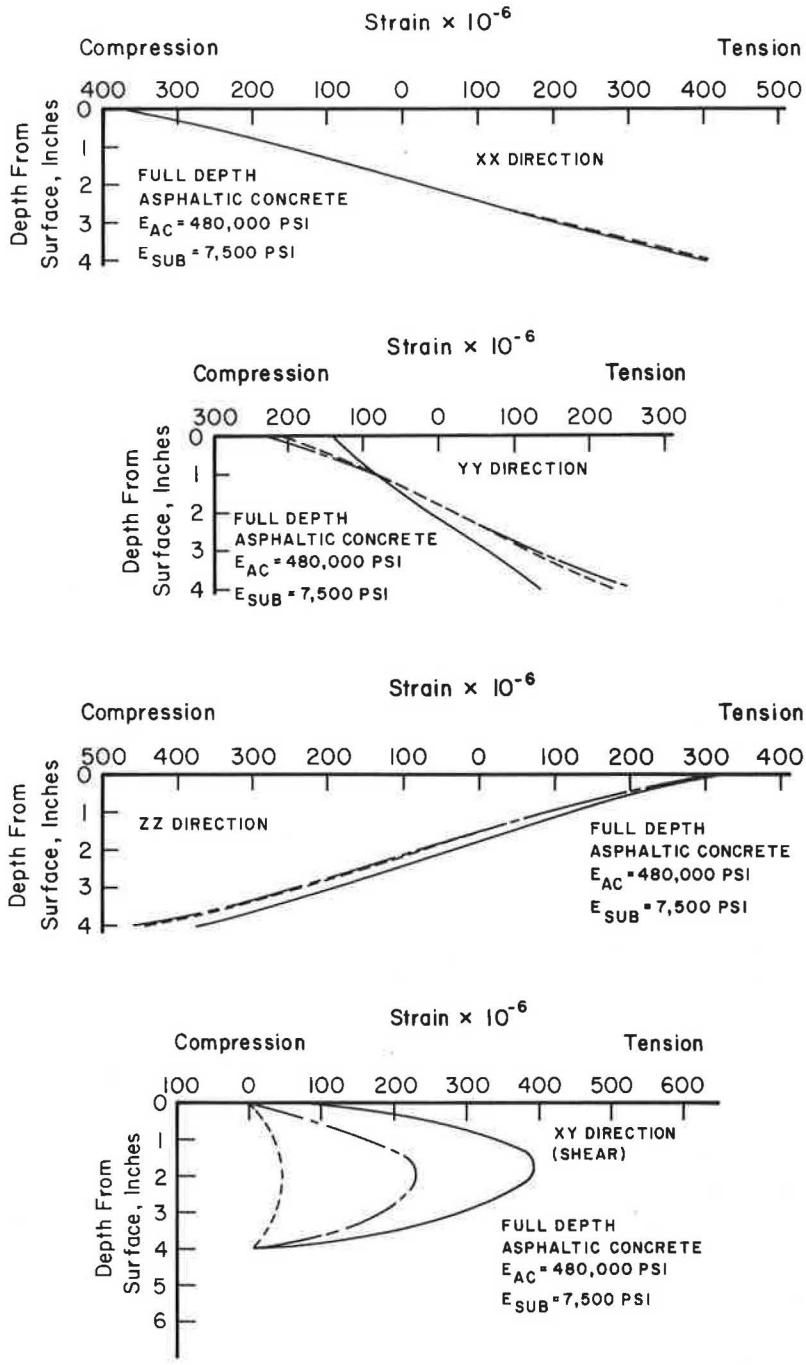

FIGURE 6 Distribution of strains from surface through 4 in. of full-depth asphaltic concrete under an 18-kip four-tired, single-axle load (solid line is at edge of tire; short dashed line is at center of tire; line with short and long dashes is at 1/2 radius).

be said for the YY and ZZ components. The magnitude of the shear (XY) component is highly dependent on the answer location within the tire contact area. 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 with location within the loaded area. Therefore, the shear component is the major factor influencing the variations in distributions of strain energy density for the asphaltic concrete illustrated in Figure 1. The same comments are true for Figures 7 and 8 except that the magnitudes of the strains are decreasing and the angularity of strain versus depth increases with increasing thickness of asphaltic concrete.

Figures 9–11 show the variations in each strain component for thicknesses of 4, 8, and 12 in. of full-depth asphaltic concrete at locations corresponding to the inside edge of a dual

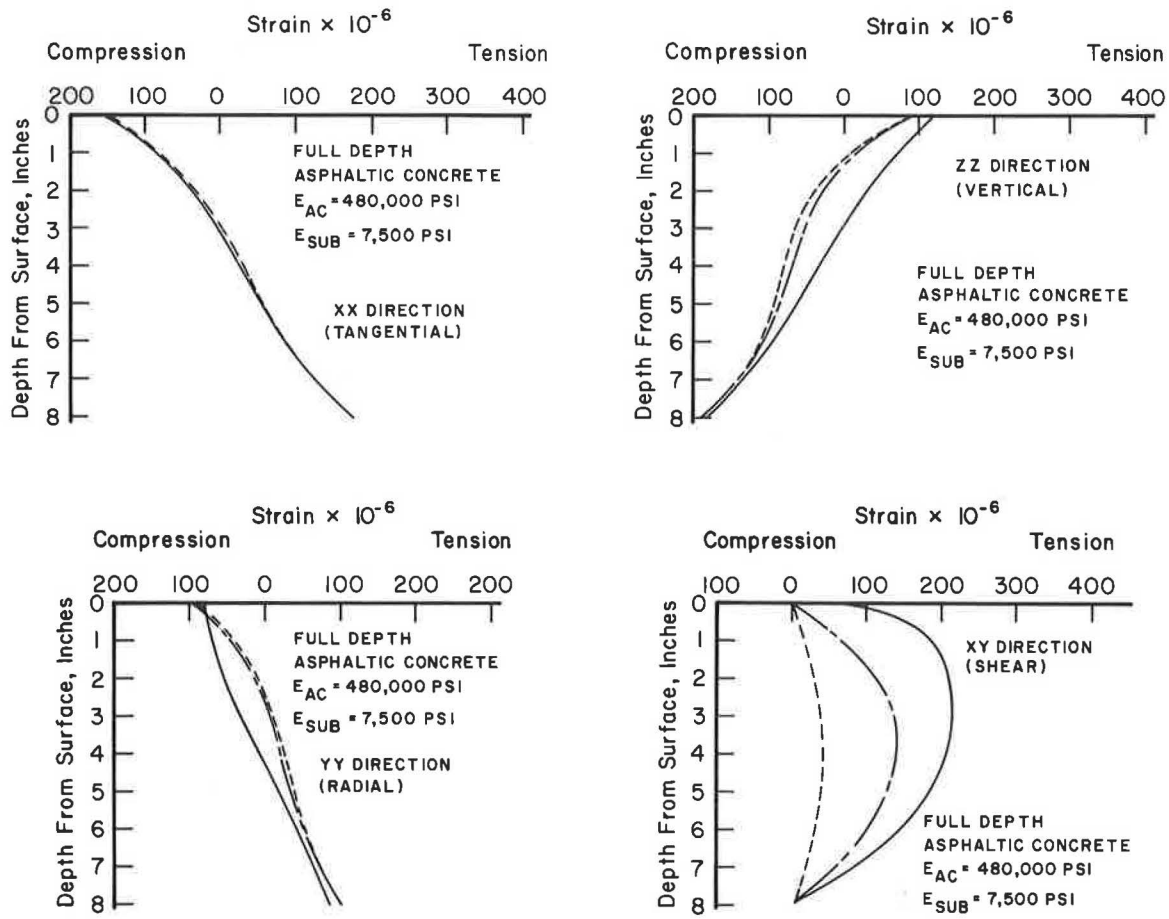

FIGURE 7 Distribution of strains from surface through 8 in. of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load (solid line is at edge of tire; short dashed line is at center of tire; line with short and long dashes is at 1/2 radius).

tire. Each figure also illustrates the complexity of the XX component's being in compression then progressively changing to tension while the YY component is exactly the opposite, the ZZ component is always in compression, and the XY component is always in tension but varies from nearly zero at the interfaces to a much higher value near the center of the asphalt layer. Figures 12–15 show the family of strain distributions with depth for various thicknesses of full-depth asphaltic concrete (XX, YY, ZZ, and XY, respectively). Figure 15 indicates 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 shown in Figure 16. For an 18-kip single-axle load, the maximum shear for pavements up to 8.5 in. 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-in. pavement occurs 2.5 in. below the surface. For 8.5 in. (216 mm), the depth is 3 in. below the surface. Figure 16 also indicates that, for an 18-kip (80-kN) single axle load, the maximum shear will occur no deeper than 3 in. below the surface even when the pavement thickness exceeds 8.5 in. Just because the maximum shear force will occur no deeper than 3 in. does not mean that the asphalt will not experience shear flow below 3 in. If the maximum tolerable shear strain corresponds to a shear force less than the maximum shear force, shear flow will occur below the surface until the depth corresponding to the tolerable shear strain is reached. The maximum lateral displacement of aggregate particles probably should coincide with the depth at which the maximum shear strain (or force) occurs. Lesser movement of particles should take place at deeper depths until the material can withstand the shear force. This phenomenon has been observed and is discussed in a later section.

STRESS ANALYSIS

To determine the shear strength required of the asphaltic concrete mix to resist shear flow, Figures 17 and 18 show the results of analyses using stress components instead of strain components. These two figures are similar to Figures 15 and 16. Figure 17 shows the distribution of shear stress with depth of full-depth asphaltic concrete caused by a four-tired, 18-kip, single-axle load; the stress pattern is similar to the strain pattern shown in Figure 15. Close inspection of Figure 17 shows that the depth of maximum shear stress is the same as that for shear strain for the same pavement thickness. Thus,

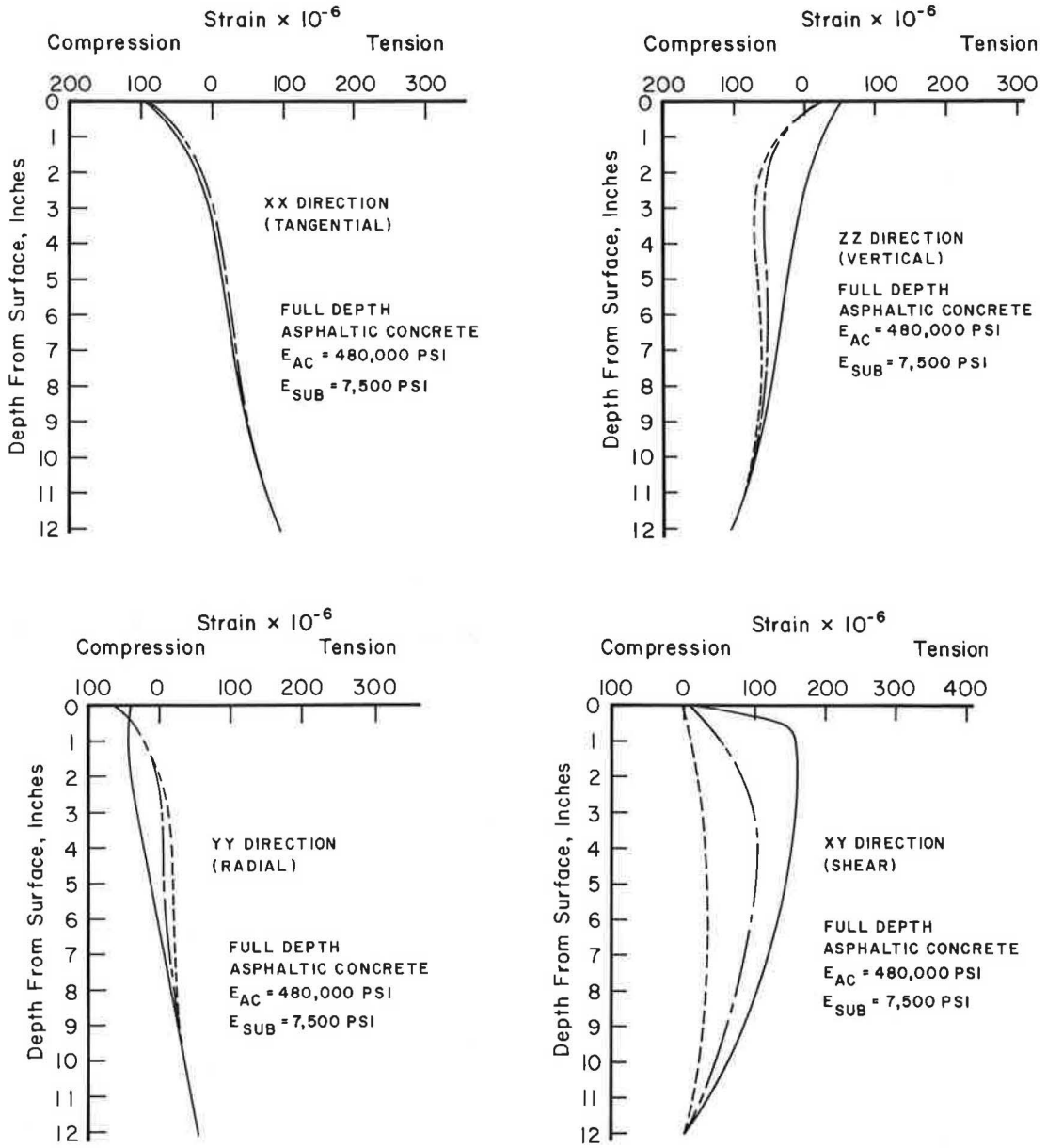

FIGURE 8 Distribution of strains from surface through 12 in. of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load (solid line is at edge of tire; short dashed line is at center of tire; line with short and long dashes is at 1/2 radius).

Figure 16 is applicable either for shear strain or for shear stress. Figure 18 shows the maximum stress as a function of thickness of asphaltic concrete.

IMPLICATIONS FOR COMPOSITE PAVEMENTS

These analyses illustrate some significant impacts for asphaltic concrete overlays. Because shear stresses and 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 with that of binder and base mixes. When a new overlay is constructed, the older courses of surface mix become the zones of increased shear stress and strain. Aggregate particles may be reoriented by traffic until they are parallel to the pavement surface. Tack coats are necessary to ensure 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 potentially weak zones with regard to shear resistance. Therefore, milling the old surface mixes and replacing that thickness with new material or reclaimed asphaltic concrete, or both, 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 one lift having

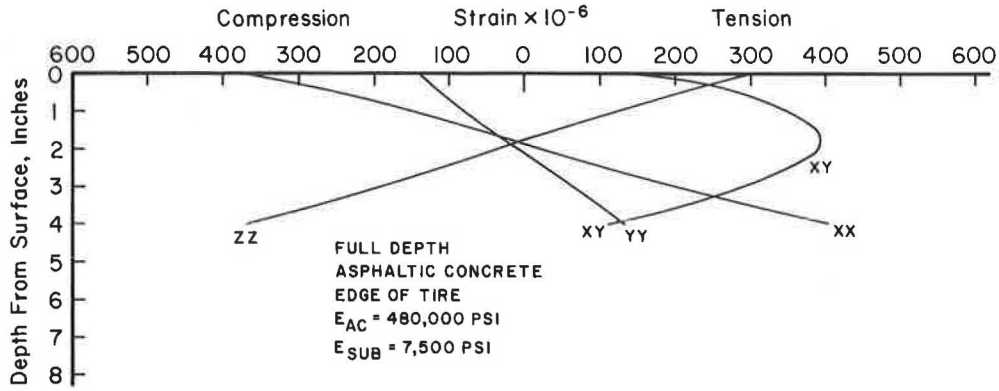

FIGURE 9 Distribution of all strain components from surface through 4 in. of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

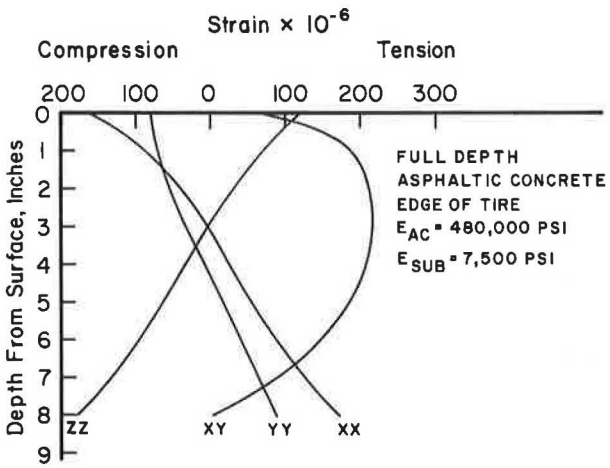

FIGURE 10 Distribution of all strain components from surface through 8 in. of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

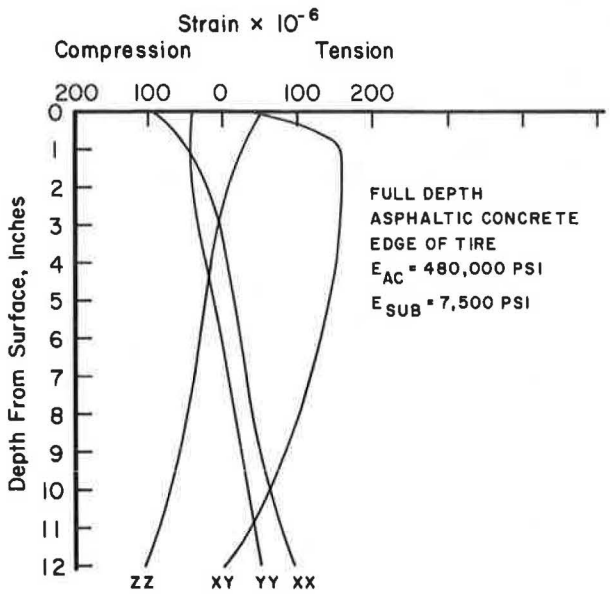

FIGURE 11 Distribution of all strain components from surface through 12 in. of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

better aggregate interlocking and increased resistance to rutting. These benefits should result for lifts up to 3.5 or 4 in. If the milled thickness exceeds 4 in., consideration should be given to constructing a minimum thickness as a leveling course on top of the remaining original pavement and then constructing a 3-in. lift followed by the final surfacing course.

An alternative might be to consider the development of an asphalt mix having a coarser gradation with a top size of 1.5 or 2 in. The larger aggregate gradation may provide more stability and resistance to shear flow. Kentucky has developed a so-called "big-stone mix" that has a top size of 2.5 in. for use in pavements subjected to very heavy loads. For the same period of time, preliminary results indicate that rutting (shear flow) in the big-stone mix is less than half that for conventional mixes (1-in. top size) subjected to relatively the same volume of heavy loadings. Considering the general rule that the minimum lift thickness corresponds to approximately twice the size of the largest aggregate in the gradation, lift thicknesses greater than 3 in. might become feasible.

A composite pavement cross section consisting of 4 in. of asphaltic concrete on 10 in. of portland cement concrete was analyzed. Distribution of stresses and strains differed considerably from the normal pattern for flexible pavements in which stresses and strains dissipate with increasing depth. Analyses indicated that higher shear stresses and strains may occur at the flexible-rigid interface than near the surface and become more pronounced with increasing tire contact pressure. The rigid layer beneath the flexible layer contributes reactionary stresses and strains within the flexible layer. Increased tire contact pressure and axle loads may cause lateral displacement of the asphaltic concrete, resulting in surface rutting. Such phenomena suggest that some pavement failures may be based on shear and other factors rather than on fatigue criteria alone.

OBSERVATIONS

A 17-in. full-depth asphaltic concrete pavement was trenched in 1980 or 1981. A visual inspection showed shear flow from the surface to approximately the 6-in. depth. Within approximately the top 3 in. (the zone of maximum shear), nearly all aggregates were parallel to the pavement surface and appeared to be separated by a thin layer of asphalt cement—

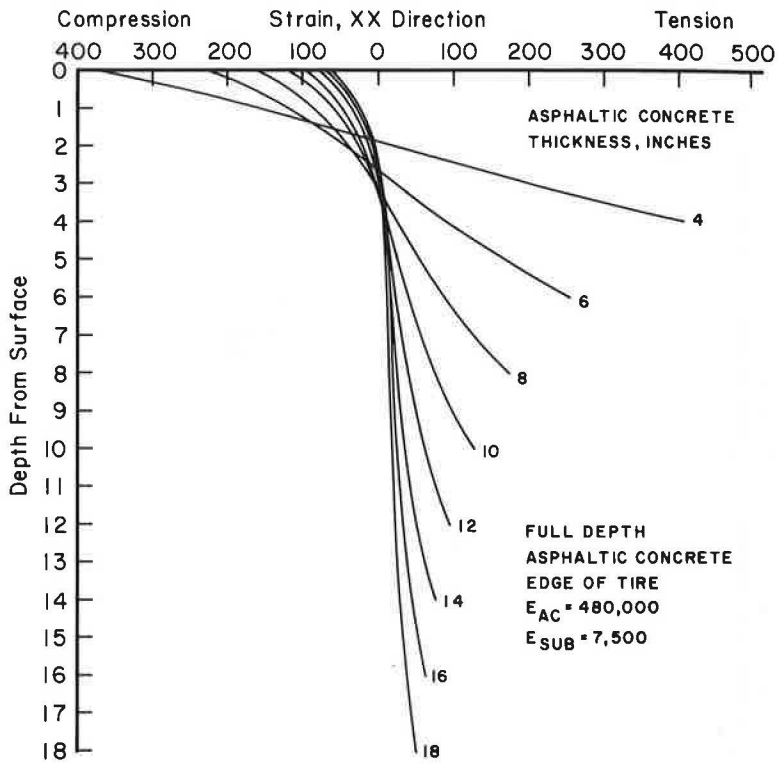

FIGURE 12 Distribution of strain in XX (tangential) direction from surface through various thicknesses of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

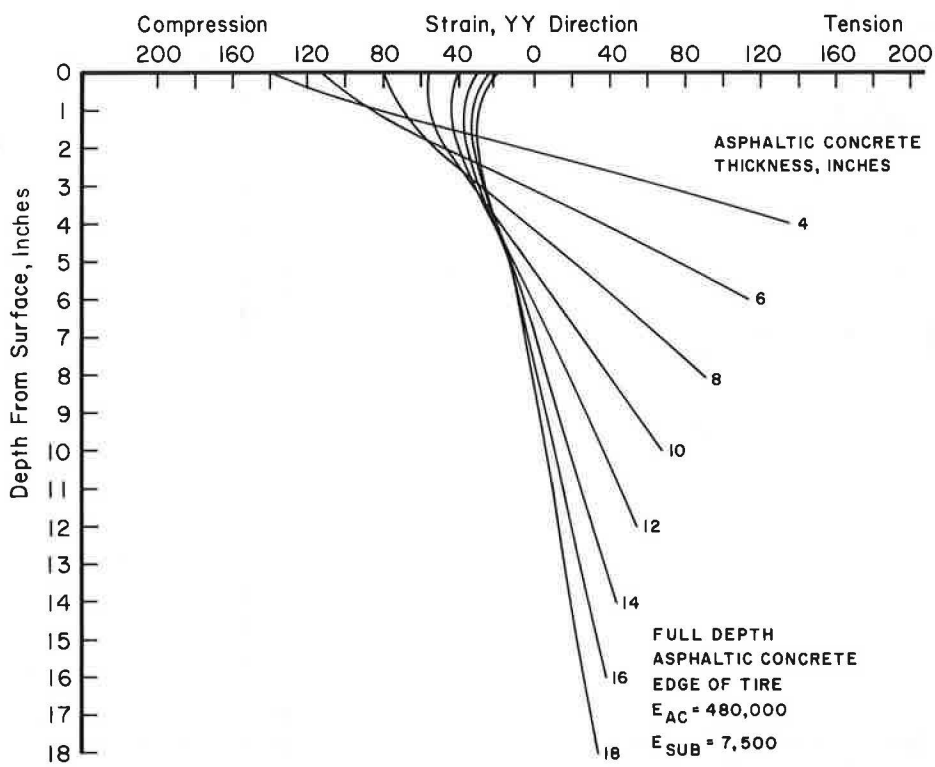

FIGURE 13 Distribution of strain in YY (radial) direction from surface through various thicknesses of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

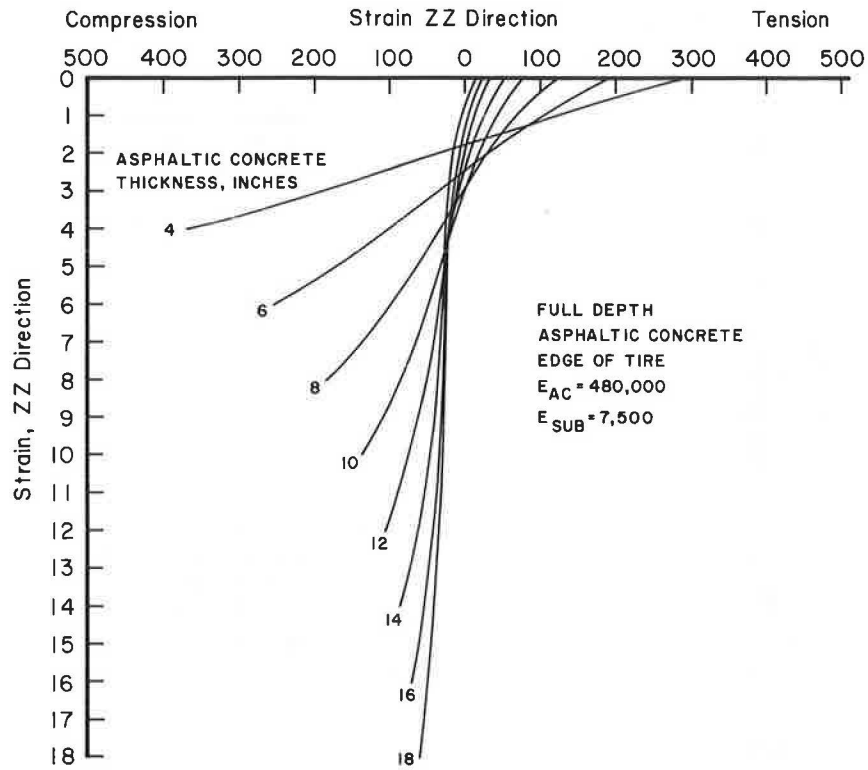

FIGURE 14 Distribution of strain in ZZ (vertical) direction from surface through various thicknesses of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

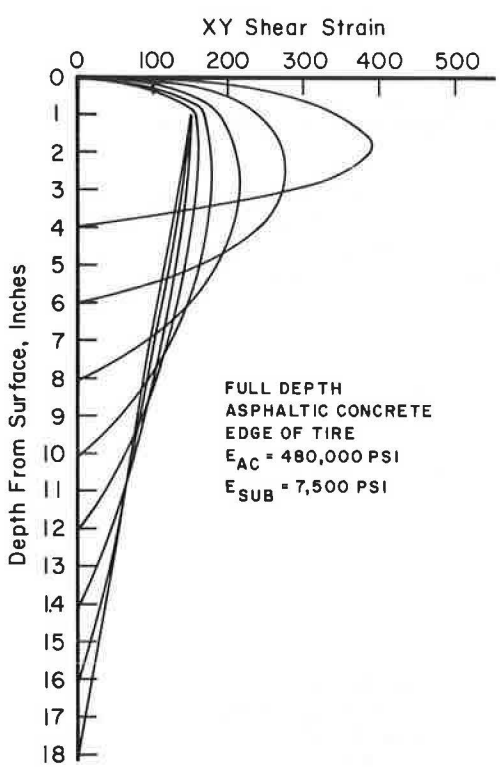

FIGURE 15 Distribution of strain in XY (shear) direction from surface through various thicknesses of full-depth asphaltic concrete under an 18-kip, four-tired, single-axle load.

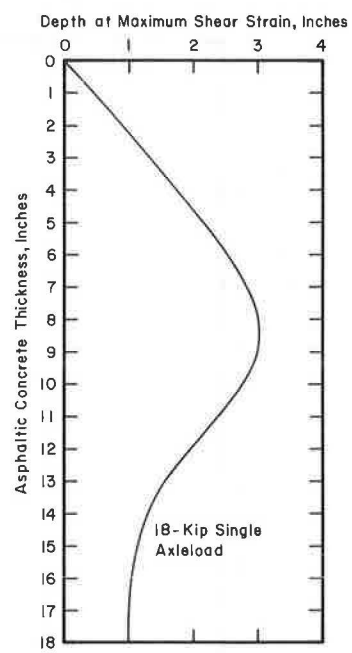

FIGURE 16 Depth of maximum shear strain under an 18-kip, four-tired, single axle load versus thickness of full-depth asphaltic concrete.

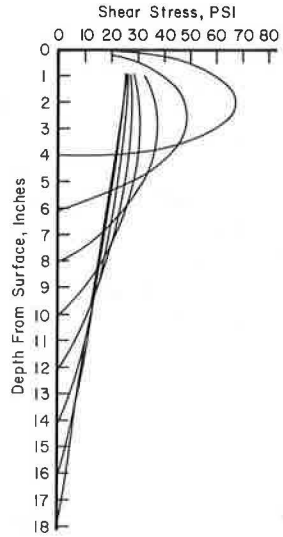

FIGURE 17 Distribution of shear stresses under an 18-kip, four-tired, single axle load from surface to bottom of various thicknesses of full-depth asphaltic concrete.

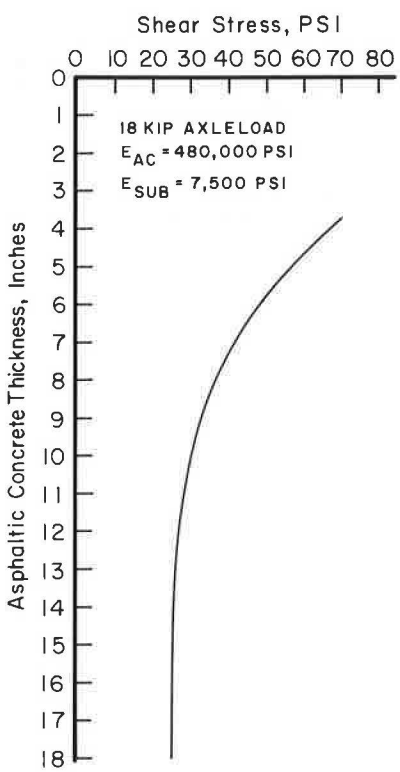

FIGURE 18 Distribution of maximum shear stress under an 18-kip, four-tired, single-axle load versus thickness of full-depth asphaltic concrete.

similar to a sandwich. The 1.25-in. surface mix had been reduced to approximately 0.5 in. in the wheel track and was nearly 2.5 in. thick between wheel tracks. Thus, material had been moved laterally by shear-flow action. At each of two construction interfaces, the long axes were parallel to the construction surface for the layer below. Between the 3- and 6-in. depths, the orientation of the aggregates became more random with increasing depth from the surface. Below the 6-in. depth, the aggregates were randomly oriented to each other except at layer interfaces, as should be expected, and no shear flow was evident below that depth. Compaction equipment had turned the long axis of the aggregate particles parallel to the surface.

The same observation was noted when two 18-in. full-depth asphaltic concrete pavements were trenched on another route. On another pavement consisting of 7.5 in. of asphaltic concrete on 12 in. of crushed stone aggregate, there was a slight indentation at the top of the aggregate base. However, the indentation was so slight that it may have been caused by construction equipment during paving of the bottom layer of asphaltic concrete. The same shear-flow action was observed in the asphaltic concrete at this site as seen at the full-depth asphaltic concrete pavement sites. Orientation of the aggregates was nearly random at the bottom of the 7.5 in. of asphaltic concrete.

CORRELATION OF THEORY AND OBSERVATION

Shear is most likely to occur wherever the shear resistance is the least. One inherent zone of potential weakness to shear forces is at interfaces of construction lifts. At such interfaces, the roller may turn the top layer of aggregates in the lower lift parallel to the surface. Therefore, the aggregates at the bottom of the upper layer have the least opportunity of interlocking with the top aggregates of the layer below. Lift thicknesses can be determined easily by examining cores in which the long axis of too many of the aggregate particles are parallel to the interface. Typical lift thicknesses constructed in Kentucky consist of 0.75 to 1 in. of surface mix, 1.5 to 2 in. of binder mix, and 2 to 2.5 in. of base mix. Thus, for a 6- or 8-in. asphaltic concrete pavement, maximum shear will occur at the 2.5- or 3-in. depth, respectively—right where a construction plane produces the least aggregate interlock. Thus, shear flow should be expected where aggregate interlock is the least.

For the pavements that were trenched, shear flow was observed down to the 6-in. depth. Figure 17 shows that the shear stress at the 6-in. depth for these pavements would be approximately 25 psi. A shear stress of 25 psi might be a safe level or might be excessively high for asphaltic concrete pavements. The tolerable shear stress level for asphaltic concrete is not known at this time. a value of 25 psi might be safe for asphaltic concrete modulus of 480 ksi but might change as the modulus changes.

SUMMARY

Following are the most important findings of these sensitivity analyses:

1. Sensitivity analyses indicate that the maximum-strain energy density occurs under the edge of the tire closest to the other tire in a dual tire arrangement.

2. For a given thickness of asphaltic concrete, the distribution of any one of the three principal strains or stresses varies slightly with location within the tire contact area.

3. Shear is the strain or stress component that exhibits the most variation throughout the thickness of the asphaltic concrete and is primarily a function of the location within the tire contact area. The maximum variation occurs under the edge of the tire closest to the adjacent dual tire.

4. The depth of maximum shear is a function of the thickness of the asphaltic concrete layer. For thicknesses up to approximately 8.5 in., that depth is approximately equal to 35 to 40 percent of the thickness of asphaltic concrete. For greater thicknesses, the depth of maximum shear appears to move up toward the surface and might become asymptotic at approximately the 1-in. depth. These values are appropriate for a four-tired, 18-kip, single axle load and would vary for other magnitudes of load and configurations of tires and axles.

RECOMMENDATIONS

1. Consideration should be given to any or all of the following:

- Increasing the shear resistance of the binder mix,
- Eliminating the binder-mix layer and replacing it with a base-mix layer, and
- Developing a coarser mix for use immediately below the wearing course.

2. Consideration might be given to the placement of a 1-in. surface-mix layer on a minimum of a 3-in. layer of a high shear–resistant mix to eliminate a construction interface in the zone of maximum shear.

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

4. In-place pavements exhibit distresses that indicate shear failures within the asphaltic concrete layers. Research is under way to determine shear parameters of hollow cylindrical specimens of asphaltic concrete (*4*). 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 as well as guidance for use in design of new pavements and rehabilitation strategies.

ACKNOWLEDGMENTS

The financial support provided by the Kentucky Transportation Cabinet and FHWA is gratefully acknowledged.

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