Design Curves for Flexible Pavements Based on Layered System Theory

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Use of the recently developed theoretical three-layer elastic theory has aided the development of a method for design of flexible pavements. A series of design curves is presented which show the relationship between the combined thickness of granular base and asphalt surface necessary to support heavy truck loading (18,000-lb axle load). Development of the theoretical curves is based on the use of the three-layer elastic theory. The curves have been created by methods similar to those described in a paper for the International Conference on the Structural Design of Asphalt Pavements. The provisional curves of the previous paper have been modified slightly and also expanded to include a fatigue factor. Principal assumptions of the design method are outlined.

Adequate design according to the present method is based on the prevention of failure at critical locations in the pavement structure. Consideration is given to extent of displacement (strain) in the subgrade, and magnitude of tensile strain at the base of the asphalt surface. The relative severity of these conditions governs the design of the pavement. Within calculable limits, surface and base can be replaced by each other. Examples are given which demonstrate the use of these principles in the design of pavements for "weak" (CBR = 2.5) and "strong" (CBR = 20) subgrades.

•UNTIL RECENTLY, solutions to the equations for the behavior of layered systems have been limited to those for two layers. Acum and Fox (1) investigated three-layer systems within limited conditions. Jones (2) expanded the equations and tabulated stress and strain factors for three-layer structures over a wider range of values. Peattie (3) demonstrated the use of these three-layer tables in stress investigations. He also proposed a method for utilizing the data to design pavements (4). This method was recently applied in the preparation of a series of pavement design curves presented at the International Conference on the Structural Design of Asphalt Pavements (5).

The basic principle in the development of the theoretical design method is the prevention of excessive stress or strain in a pavement or in the underlying soil. This is accomplished by investigating the strain conditions at certain critical locations in the pavement and then designing to maintain strains within safe limits. The design curves presented at Ann Arbor (5) are based on limiting the vertical compressive strain in the subgrade and the tensile stress in the asphalt-bound layer. These limitations are aimed at prevention of deformation in the pavement and cracking of the asphalt surface.

Design curves prepared on the basis of these principles show many different combinations of asphalt surface and granular base which will fulfill the strain limitations. An appropriate design—depending on economic or other considerations—can be selected from several different choices.

In the previous design curves presented at Ann Arbor, no specific allowance was made for different intensities of traffic loading. Thus, there was no quantitative basis for differentiation between light and heavily traveled roads. Correlations developed

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from published results of the AASHO test, however, have aided in the development of a series of fatigue criteria. These have been added to the theoretical design method and a new series of design curves have been prepared to incorporate these principles. Thus, the method is expanded to include design for different amounts of traffic, as well as for different wheel loads.

DESIGN FACTORS

Development of the theoretical design curves has required certain assumptions to be made concerning factors influencing design. Assumptions are necessary because of uncertainties in current information relating to design. The adopted assumptions appear to be reasonable and in line with existing experience. As additional information is accumulated, changes in these criteria might be suggested which would be more realistic.

Wheel Loading

Although calculations may be made for any wheel loading, the basic load selected for these design calculations is a 9,000-lb wheel load (18,000-lb axle load). In practice this load is applied by a dual wheel. For subgrade strain calculations, however, the load is assumed to be applied by an 80-psi contact pressure acting on a single area of 6-in. radius. This is considered the most reasonable basis for design within the limitations of stress distribution data currently available.

At relatively shallow depths in the pavement, general stress analysis made by Fox (6) indicates that the maximum stress (or strain) occurs under the center of either individual wheel of the dual-wheel pair (6). Stress under the wheel is produced almost entirely by the contribution of one wheel alone. In accordance with this principle, the calculation of the tensile strain in the asphalt layer is based on the use of a single wheel

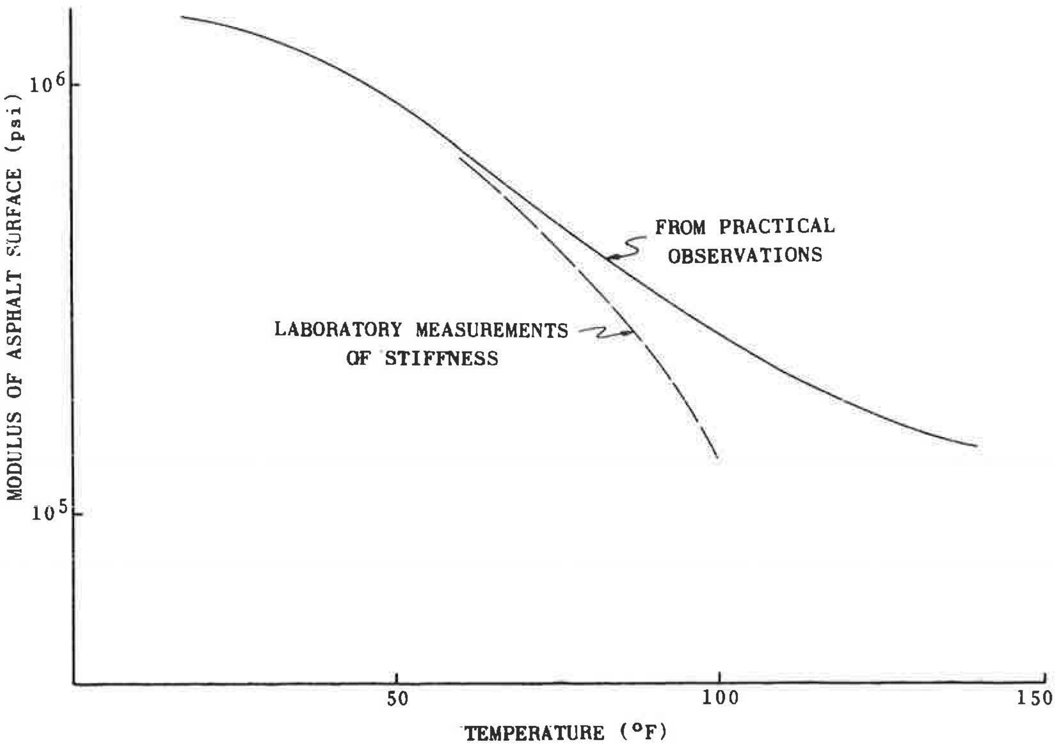

Figure 1. Relation of modulus of asphalt layer to temperature.

in a dual pair. This is represented by the 80-psi contact pressure acting on an area of 4.2-in. radius.

In all calculations for strain in the subgrade or in the asphalt surface, impact effects are considered to be negligible, especially in view of the conservative nature of the basic wheel loading assumption.

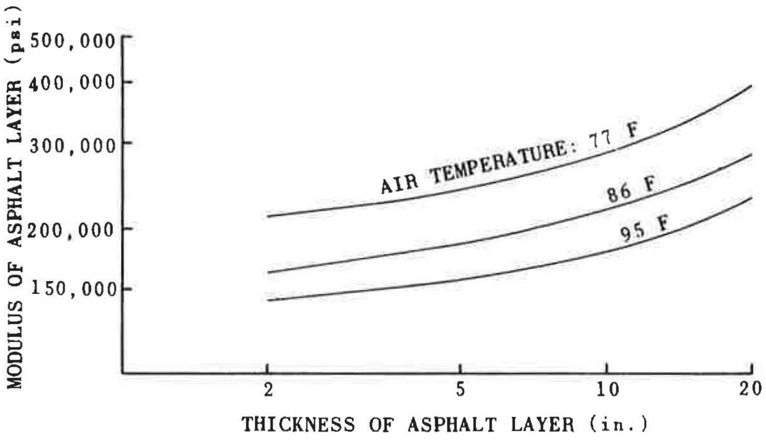

Figure 2. Relation of asphalt modulus to thickness of layer.

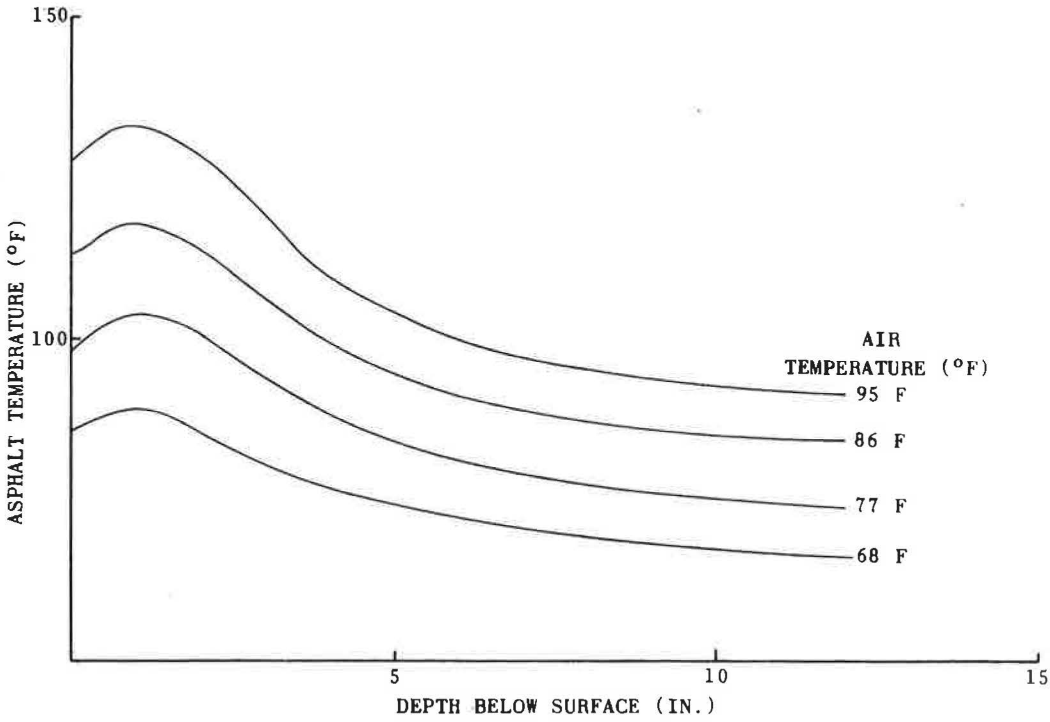

Figure 3. Relation of temperature of asphalt surface to depth below surface.

Properties of Pavement Components

Modulus of Asphalt-Bound Layer. —A curve illustrating the influence of temperature on the elastic modulus of the asphalt layer is shown in Figure 1. The graph depicts information obtained from two separate sources. The dashed line traces the relation between modulus and temperature for a series of laboratory stiffness measurements at a loading time of 0.02 sec. The solid line was prepared by use of the results of subgrade stress measurements at different pavement temperatures reported by Whiffin and Lister (7) of the Road Research Laboratory.

Critical strain in the subgrade occurs when the effective modulus of the asphalt-bound layer is at a minimum. This takes place as the asphalt becomes warm and the asphalt layer affords less protection to the subgrade. Figure 2 shows a plot of the asphalt layer moduli corresponding to selected air temperatures. Moduli used in strain calculations are those pertaining to a maximum air temperature of 95 F. It is evident in this figure that an allowance is also made for a reduction in the effective temperature of thicker asphalt layers. This is reflected by an increase in the effective modulus of the layer. Typical maximum temperature/depth relationships deduced for asphalt-bound materials are shown in Figure 3. These provide the basis for the preparation of the curves in Figure 2. The effective modulus of the asphalt-bound layer is associated with the temperature at a depth equal to one-third of the layer.

Modular Ratio of Base Subgrade. —Investigations by Heukelom and Klomp (8) have indicated that the effective modulus developed by a granular base tends to be related to the modulus of the subgrade. Theoretical design curves in the Ann Arbor paper (5) assumed the effective modulus of a combined thickness of base and subbase course to be in a range of 2 to 4 times greater than the subgrade modulus.

To make allowance for the surcharge effect on modular ratio, the ratio $E_2/E_3(K_2)$ is varied according to the thickness of the granular layer as shown in Figure 4. This relation is arbitrarily chosen to give designs which correlate reasonably well with empirically developed CBR curves.

PERMISSIBLE STRAIN VALUES

Development of the design curves is based on the principle of limiting the magnitude of strains produced at certain critical locations in the pavement structure. The pres-

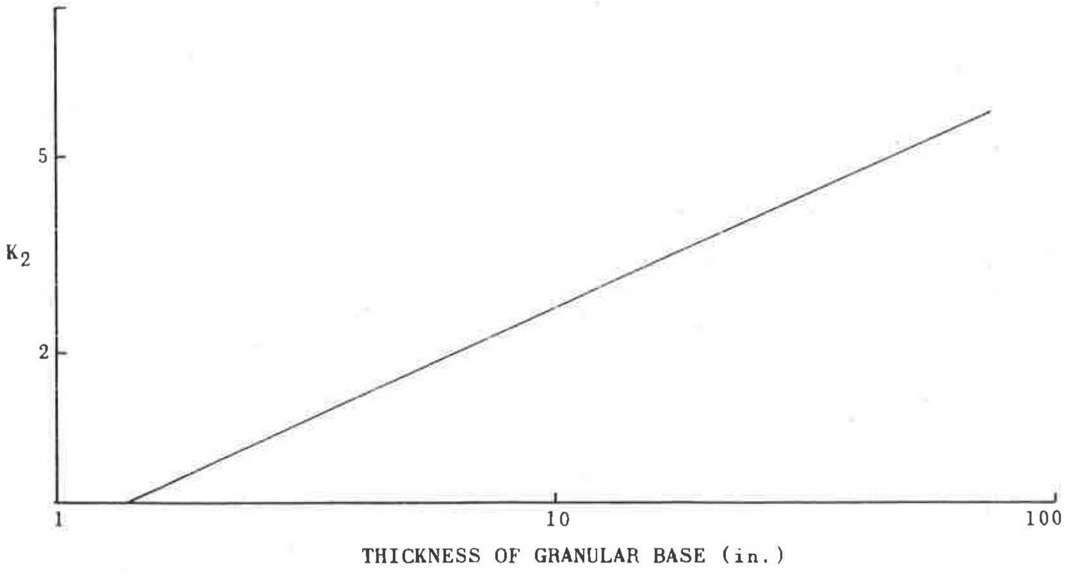

Figure 4. Relation of modular ratio, K_2, to thickness of granular base.

ent method places emphasis on consideration of the vertical compressive strain on the subgrade and the tensile strain at the base of the asphalt-bound layer. Control of the strain at these places contributes to the control of important elements in pavement performance. Compressive strain on the subgrade has an influence on pavement deformation. Tensile strain in the asphalt layer influences the tendency for cracks to develop.

Compressive Strain on Subgrade

Design curves previously presented (5) were based on the use of a single critical strain value representing one condition of heavy traffic loading. By empirical correlation with AASHO results, the relation between compressive strain and number of load applications shown in Figure 5 was established. Use of this relationship permits the introduction of fatigue criteria into the theoretical method.

Several different procedures were coordinated to produce the load application curve in Figure 5. First, calculation of vertical compressive strain in the subgrade for several different sections in the AASHO test indicated that a compressive strain of 6.5×10^{-4} was associated with 10^6 applications (5).

The AASHO results (9) also provided information by which the effects of different wheel loads of mixed traffic could be weighted. This relationship, shown in Figure 6 led to the development of the wheel load weighting curve in Figure 7. Subsequently, the compressive strain values previously assigned to different wheel loads (5) were plotted according to their equivalent numbers as shown in Figure 5. Table 1 lists the permissible strains obtained for use in design calculations.

Tensile Strain in Asphalt-Bound Layer

The provisional laboratory fatigue data for asphalt-bound materials (Fig. 8) employed by Heukelom and Klomp (8) were used to provide information on strain/load-repetition

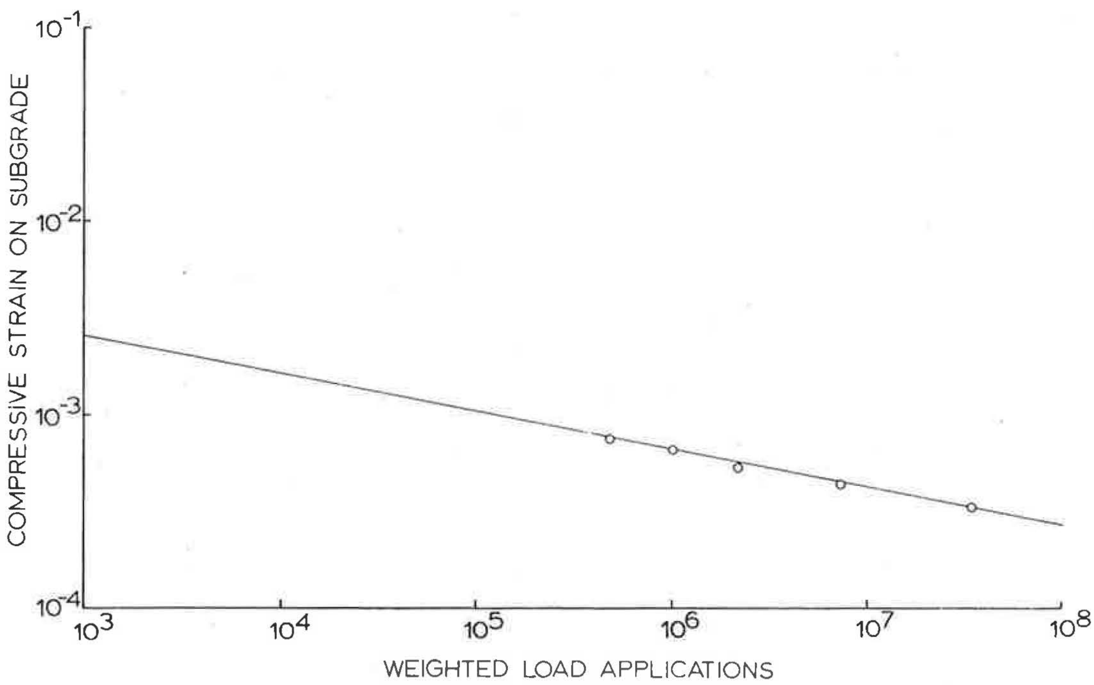

Figure 5. Relation of compressive strain to number of load applications, 18,000-lb axle load.

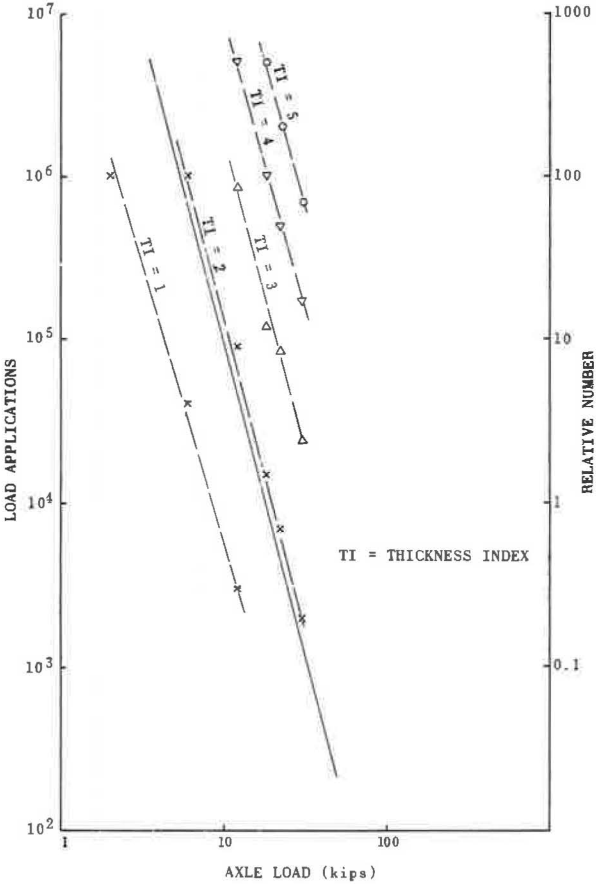

Figure 6.

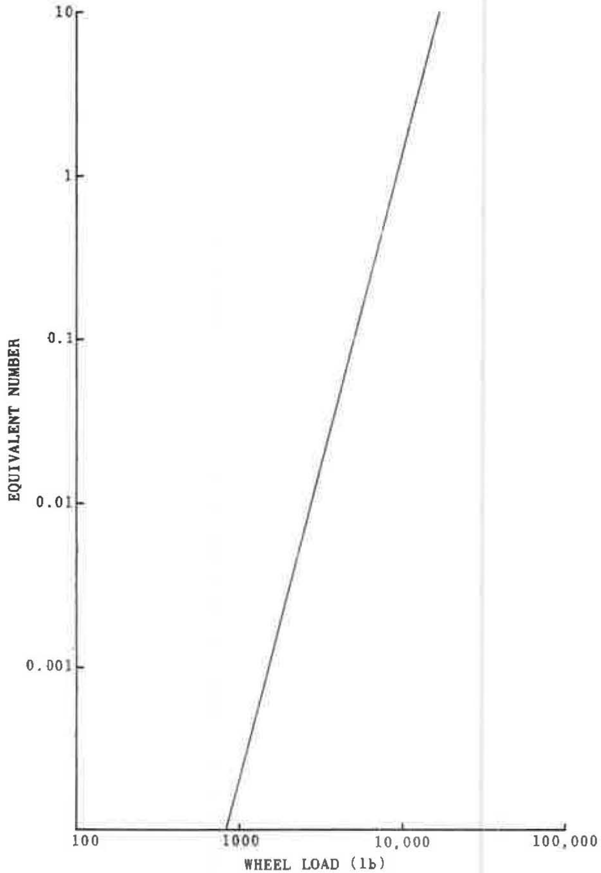

Figure 7. Wheel load weighting.

TABLE 1

SUBGRADE COMPRESSIVE STRAIN VALUES CORRESPONDING TO DIFFERENT LOAD APPLICATIONS

Load	Strain
10^5	1.05×10^{-3}
10^6	6.5×10^{-4}
10^7	4.2×10^{-4}
10^8	2.6×10^{-4}

TABLE 2

TENSILE STRAIN IN ASPHALT-BOUND LAYER CORRESPONDING TO DIFFERENT LOAD APPLICATIONS

Load	Strain
10^5	2.3×10^{-4}
10^6	1.45×10^{-4}
10^7	9.2×10^{-5}
10^8	5.8×10^{-5}

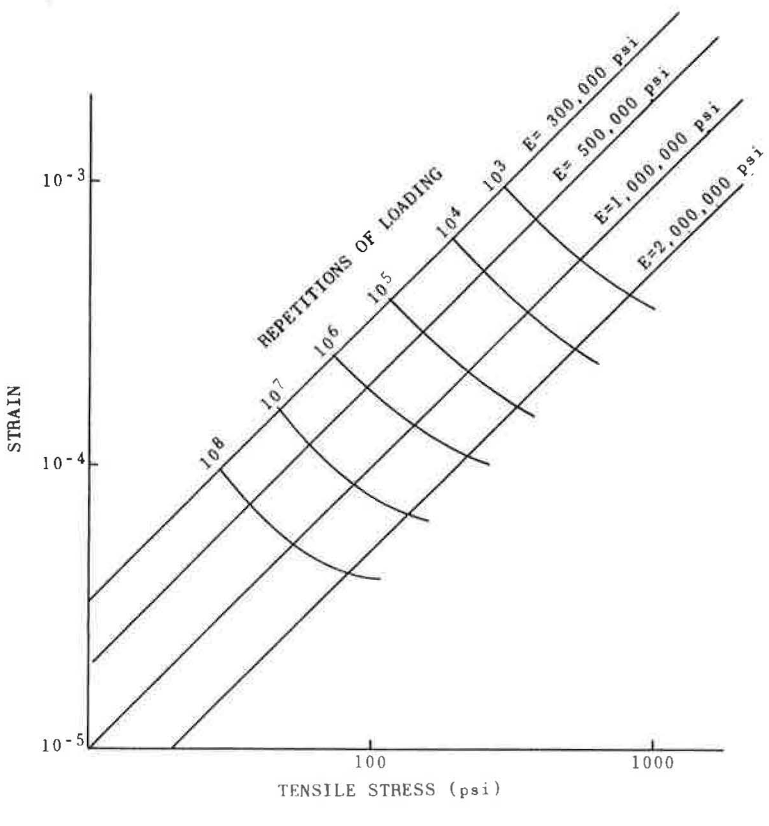

Figure 8. Provisional fatigue data for asphalt base course materials.

relationships at different temperatures. Meiner's law was then applied to integrate the effect on fatigue life of yearly temperature variations. A number of hypothetical constructions were investigated to determine an equivalent temperature for design purposes. It was found that a temperature between 50 and 60 F was suitable, and 50 F was selected for calculations. Figure 1 indicates that the effective modulus of a typical asphalt layer at this temperature is 900,000 psi. Fatigue data for tensile strain relationships for an elastic modulus of 900,000 psi are contained in Figure 9. Table 2 lists the critical strain values obtained by the method for use in design calculations.

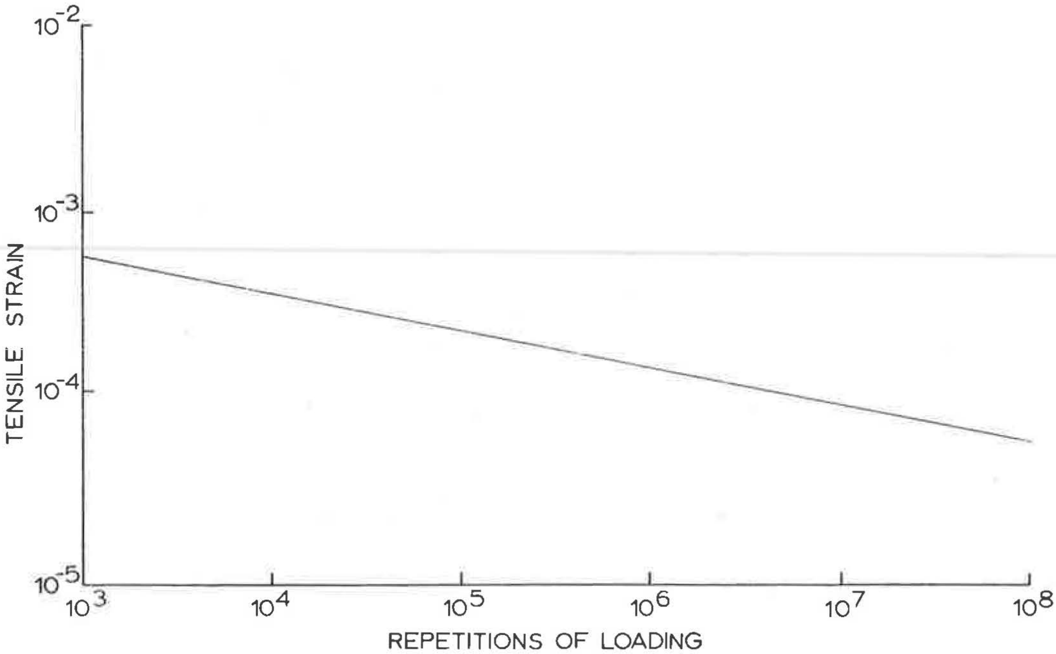

Figure 9. Fatigue curve tensile strain of asphalt base material.

The influence of different wheel loads on the tensile strain in the asphalt can be calculated directly for any particular construction. The wheel load weighting obtained depends on the construction. Because it is similar to that derived on the basis of the compressive strain in the subgrade (Fig. 7), the latter has been adopted for general use.

PAVEMENT DESIGN CURVES

Interpretation and Significance

On the basis of the foregoing criteria, pavement design curves have been prepared to show the relationship between thickness of asphalt surface and thickness of granular base for the representative 18,000-lb axle loading. Typical design curves in Figure 10 represent conditions of equal strain produced by the design load in the subgrade and in the asphalt surface. The subgrade compressive strain curve shows the combinations of asphalt surface and granular base at which the subgrade strain is 6.5×10^{-4} (10^{6} load applications). The tensile strain curve shows the combination of surface and base at which the strain in the asphalt layer is limited to 14.5×10^{-5}. Each curve represents equivalent designs for the respective critical strains. Sample calculations for the construction of these curves are shown in the Appendix.

In this example, for thicknesses of granular base less than 21 in., compressive strain in the subgrade controls the design. This means that a greater thickness of asphalt-bound material is required to prevent damage to the subgrade than is required to prevent cracking in the asphalt layer. For granular bases thicker than 21 in., the situation is reversed. A thicker surface is required to prevent cracking than to prevent excessive subgrade strain. This demonstrates that a specific minimum thickness of asphalt surface is required for protection against cracking, even though a thinner surface combined with a thick base might otherwise offer ample protection to the subgrade. Thus, the design takes into consideration two separate limitations.

Comparison of the separate design requirements reveals that tensile strain is not influenced greatly by the thickness of the base. The tensile strain curve is nearly horizontal and, thus, the susceptibility to cracking does not change to any large degree on

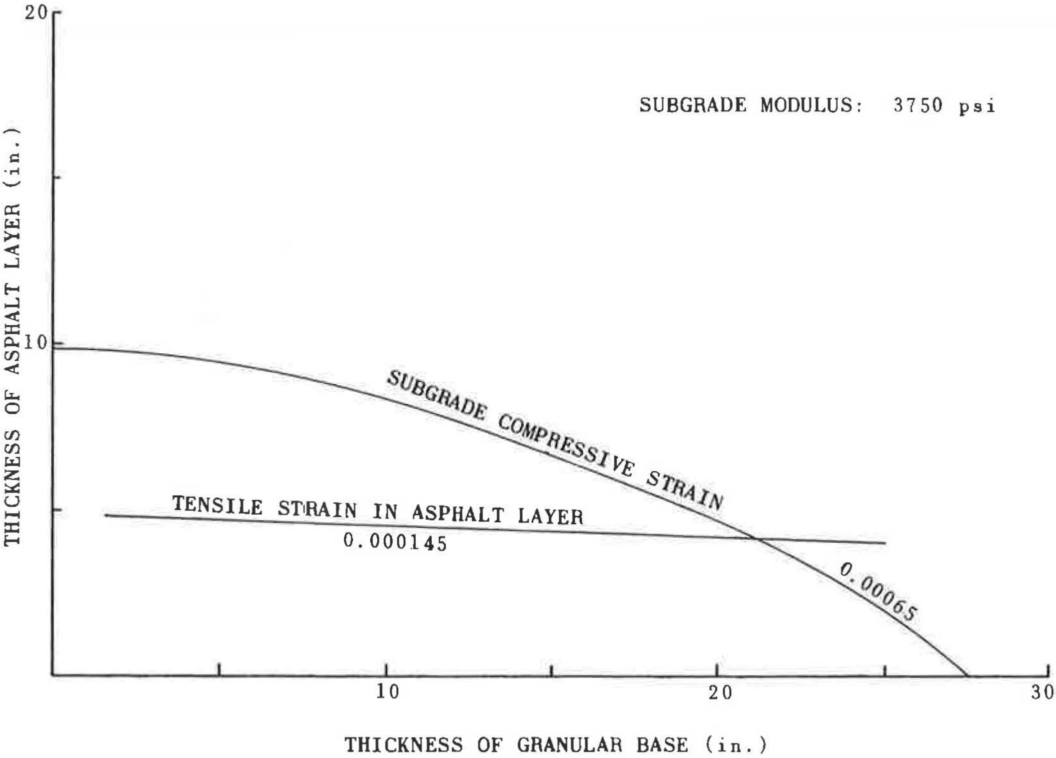

Figure 10. Typical design curves, 18,000-lb axle load (10^6 repetitions).

either thin or thick bases. The subgrade strain curve, however, is more strongly influenced by surface and base thicknesses.

It should be noted that the reciprocal of the slope at any point on the design curve is equal to the equivalency ratio between granular base and asphalt surface. The design curve is essentially dominated by the subgrade strain line which is curvilinear. Thus, the equivalency ratio does not have a constant value in this region. As the thickness of the base approaches zero, the equivalency ratio becomes very large (reflecting the flat slope of the curve). As base thickness increases, the ratio gradually decreases. A pavement with a 21-in. base has an equivalency ratio approximately equal to 2.1 (i.e., 1 in. of asphalt surface equals 2.1 in. of granular base). An average equivalency ratio representing a wider range of designs yields a higher value. If a pavement with no base (9.9-in. surface) is compared to the pavement with a 21-in. base (4.1-in. surface), the equivalency ratio is 3.6, i.e., 21/(9.9 - 4.1). Similar comparisons can be made for other combinations of surface and base.

Points on the design curves define strain contours and, therefore, they represent equivalent designs. This offers an opportunity to interchange thicknesses of asphalt surface and granular base to meet economic necessities. The data in Table 3 describe several equivalent designs taken from the curve in Figure 10.

TABLE 3

EQUIVALENT PAVEMENT DESIGNS[a]

Design	Thickness (in.)		
	Surface	Base	Total
1	9.9	0.0	9.9
2	8.4	10.0	18.4
3	6.7	15.0	21.7
4	4.1	21.0	25.1

[a]Subgrade modulus; 3,750 psi; 18,000-lb axle load, 10^6 applications.

Application of Fatigue Criteria to Design Curves

Individual design curves in Figures 11 through 14 have been prepared for subgrade moduli of 3,750, 7,500, 15,000 and 30,000 psi, respectively. These moduli correspond to CBR values of 2.5, 5, 10 and 20 according to an approximate relationship between modulus and CBR (Dynamic Modulus = 1,500 CBR) (10). In each figure separate curves are plotted for different numbers of load applications from 10^5 to 10^8. These are based on the application of the fatigue criteria outlined previously. The same calculation method is employed in the construction of each curve, but separate values of the limiting strain are used for each magnitude of loading.

Similar trends can be found in all curves. It is important to note, however, that design for larger volumes of traffic involves consideration of more than an increase in the thickness of granular base. The minimum thickness of asphalt-bound layer needed to prevent cracking also increases as traffic becomes greater.

CORRELATION WITH PRACTICE

A description has been given here of the way in which the results of the AASHO Road Test were used to establish subgrade strain criteria. In addition, it is shown in the Ann Arbor paper (5) that reasonable agreement exists between the behavior of the AASHO test sections and the theoretical trends of the design curves. It might be expected that some agreement also exists between the theoretical design curves and the empirical design criteria developed by the AASHO tests.

In Figure 15, the AASHO design criteria as proposed by Liddle (11) are superimposed on the theoretical design curves for the designated number of load applications. The AASHO lines correspond to the equation:

$$D = 0.44\ D_1 + 0.14\ D_2 \qquad (1)$$

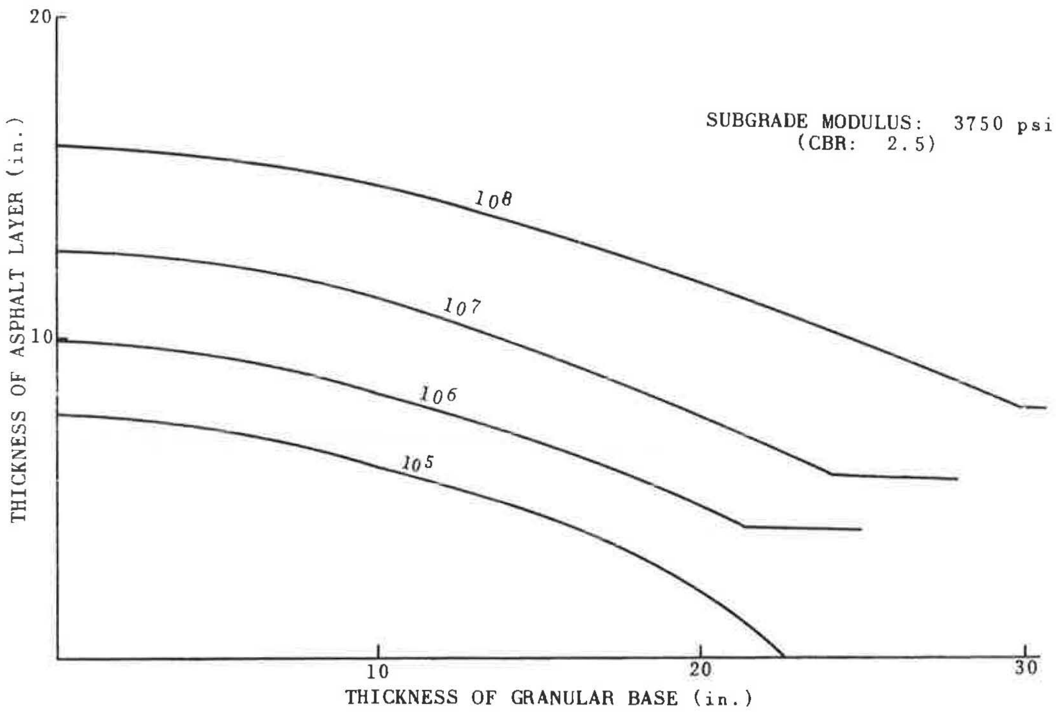

Figure 11. Design curves, 18,000-lb axle load.

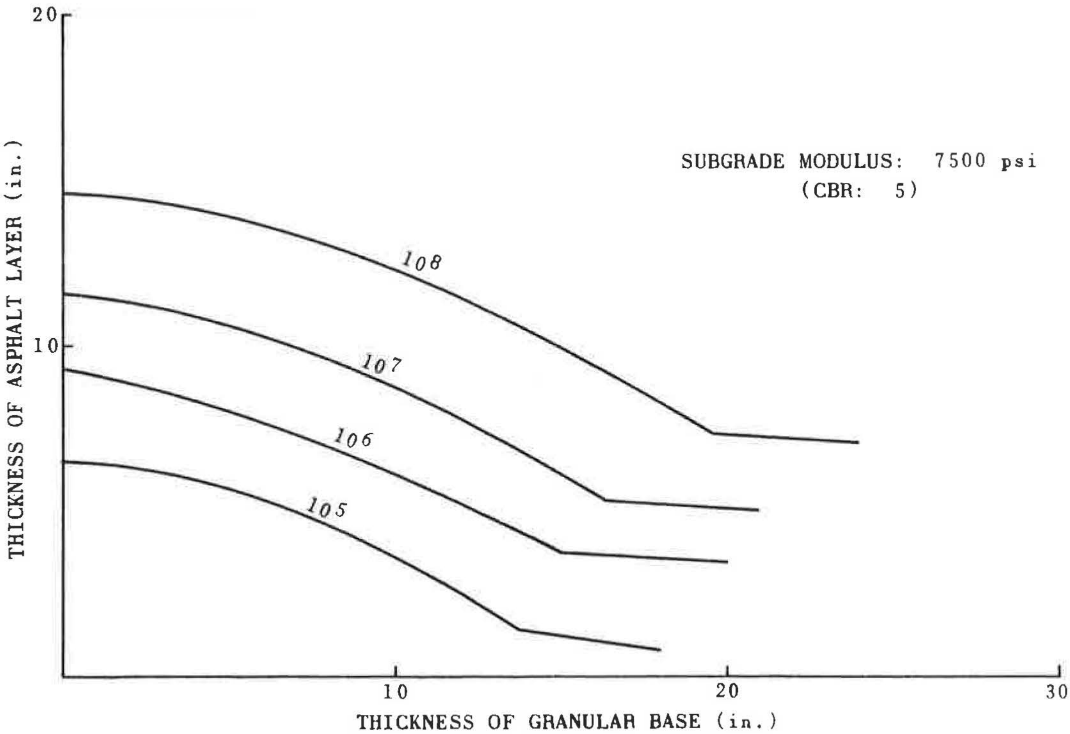

Figure 12. Design curves, 18,000-lb axle load.

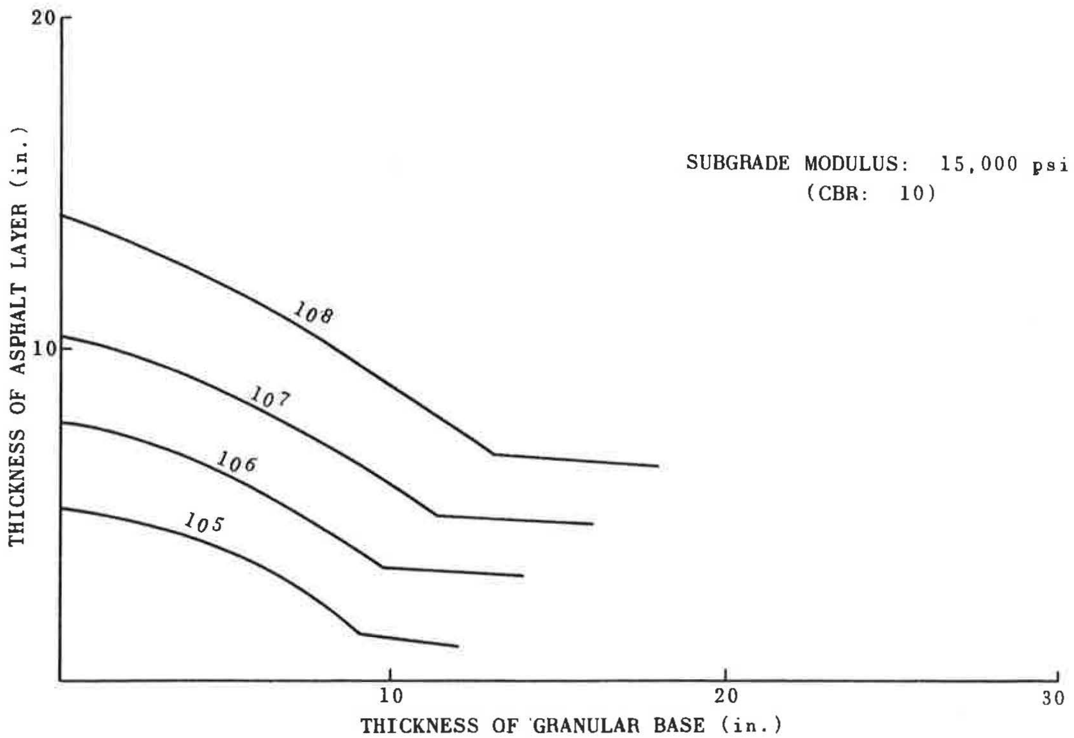

Figure 13. Design curves, 18,000-lb axle load.

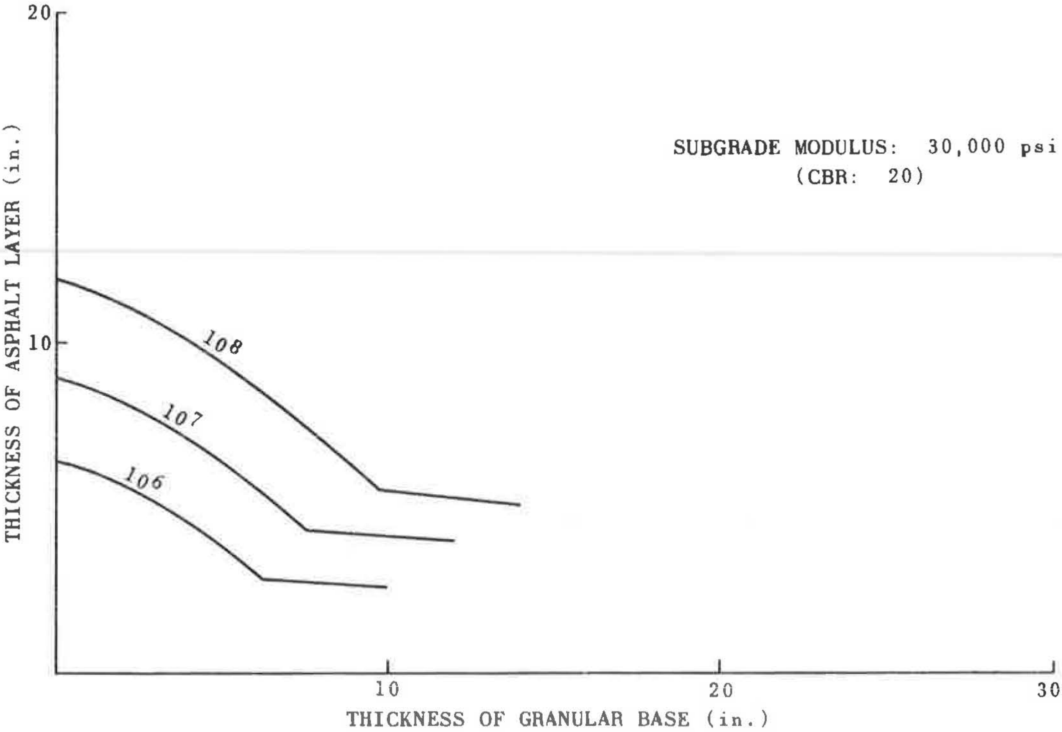

Figure 14. Design curves, 18,000-lb axle load.

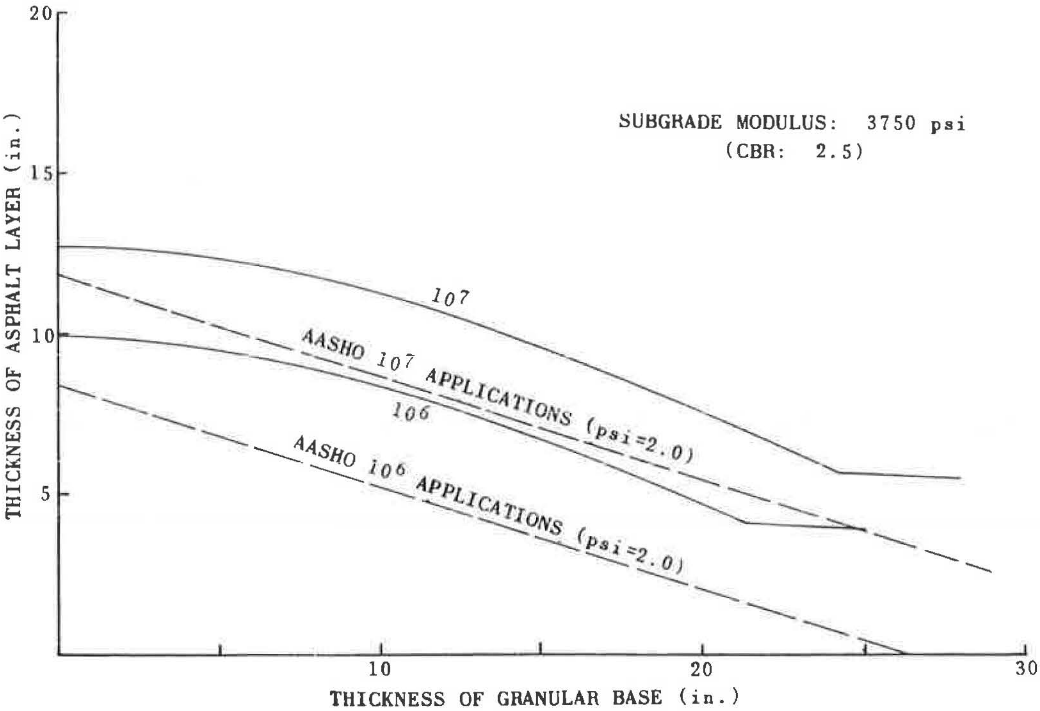

Figure 15. Design curves, 18,000-lb axle load.

in which D represents the structural number for the pavement, and D_1 and D_2 are the thicknesses of the surface and base course, respectively. The strength coefficients, 0.44 and 0.14, are selected from those listed by Liddle for "plant mix surface" and "crushed stone base." These are considered the most representative values for use in the equation. Carey and Irick (12) found that structural numbers of 3.7 and 5.2 correspond to 10^6 and 10^7 load applications for a terminal serviceability index of 2.0. These values are used in plotting the AASHO design lines.

Although the AASHO lines are somewhat below the theoretical curves, it must be noted that the AASHO designs shown here are based on a relatively low serviceability index of 2.0. The development of the theoretical designs depends on a relatively higher serviceability of 3.0 or higher.

The slope of the AASHO designs is roughly equal to the average trend of the theoretical curves. The AASHO designs, however, which plot as straight lines, have a constant equivalency ratio between surface and base of 3.1. No allowance is made for the change in equivalency ratio of different thicknesses of base shown by the theoretical designs. Otherwise, the distance separating the AASHO lines for the different magnitudes of load application is approximately the same as for the theoretical curves. This lends support to the belief that fatigue criteria developed for the theoretical method are reasonable.

CONCLUSION

A series of pavement design curves has been prepared on the basis of the principles of theoretical layered system analysis. The results demonstrate how theoretical methods can be utilized in the design of pavement for different subgrade strengths. Introduction of fatigue criteria to the method permits pavement design to be adjusted to different traffic intensities.

The guiding principle in the design method is to provide pavements in which the strains at critical locations within the structure do not exceed certain permissible values. In the present analysis, the different combinations of asphalt-bound surface and granular base are calculated to prevent excessive deformation of the subgrade and cracking of the asphalt surface. The method provides a series of design curves which represent equivalent designs for a given subgrade strength and magnitude of traffic. These offer a convenient basis for interchanging thicknesses of surface and base to meet economic requirements.

In the development of the method, it has been necessary to make certain assumptions concerning properties and strengths of materials. This need arises because precise information on these factors is frequently lacking. In these cases, assumptions are made on the basis of existing experience and results of laboratory tests. Use of these assumptions leads to designs that appear to be in reasonable agreement with practice. As additional information is accumulated in the future, specific values for design factors can be more thoroughly investigated. Any needed modifications can be made in accordance with these studies.

An example of this is the effect of climatic conditions. Because the design curves are drawn up on the basis of severe conditions (i.e., low soil strength and low dynamic modulus of the asphalt layer), it is probable that constructions will tend to be overdesigned, particularly for the thicker asphalt layers in temperate areas. It is felt undesirable, however, to apply a theoretical correction for such conditions until there is more confirmation from experience.

For the present, it is believed that the theoretical method provides a reliable basis for design and accurately reflects the influence of important design variables. It should be clear that work on the method is not concluded and modification of the proposals is a continuing process.

REFERENCES

1. Acum, W. E. A., and Fox, L. Geotechnique, Vol. 2, pp. 293-300, 1951.
2. Jones, A. Tables of Stresses in Three-Layer Elastic Systems. Highway Research Board Bull. 342, pp. 176-214, 1962.

3. Peattie, K. R. Stress and Strain Factors for Three-Layer Elastic Systems. Highway Research Board Bull. 342, pp. 215-253, 1962.
4. Peattie, K. R. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 403, 1962.
5. Dormon, G. M. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 785, 1962.
6. Fox, L. Road Res. Tech. Paper No. 9, D. S. I. R., H. M. S. O., 1948.
7. Whiffin, A. C., and Lister, N. W. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 499, 1962.
8. Heukelom, W., and Klomp, A. J. G. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 667, 1962.
9. The AASHO Road Test, Highway Research Board Spec. Rept. 61E, 1962.
10. Heukelom, W., and Foster, C. R. Proceedings, ASCE, Vol. 86, 1960.
11. Liddle, W. J. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 42, 1962.
12. Carey, W. N., and Irick, P. E. Proc. Int. Conf. on the Structural Design of Asphalt Pavements, p. 22, 1962.

Appendix

NOMENCLATURE

E_1 = elastic modulus of top (surface) layer,

E_2 = elastic modulus of second (base) layer,

E_3 = elastic modulus of third (subgrade) layer,

K_1 = modular ratio E_1/E_2,

K_2 = modular ratio E_2/E_3,

h_1 = thickness of top layer (in.),

h_2 = thickness of second layer (in.),

a = radius of loaded area (in.),

A = thickness ratio a/h_2,

H = thickness ratio h_1/h_2,

σ = unit contact pressure (psi),

ZZ1 = vertical stress at bottom of top layer,

ZZ2 = vertical stress at bottom of second layer,

RR1 = radial stress at bottom of top (surface) layer, and

RR3 = radial stress at top of third (subgrade) layer.

SAMPLE CALCULATIONS FOR DESIGN CURVES

Calculations apply to curves in Figure 10, i.e., $E_3 = 3,750$ psi, with 10^6 load applications of an 18,000-lb wheel load.

Subgrade Strain

Wheel Load.—Total load = 9,000 lb; contact pressure = 80 psi (σ); and radius of loaded area (a) = 6.0 in.

Permissible Strain. —6.5×10^{-4} (Fig. 5). Strain factor (ZZ2 - RR3) = strain × $E/\sigma = (6.5 \times 10^{-4})(3,735/80) = 0.0305$.

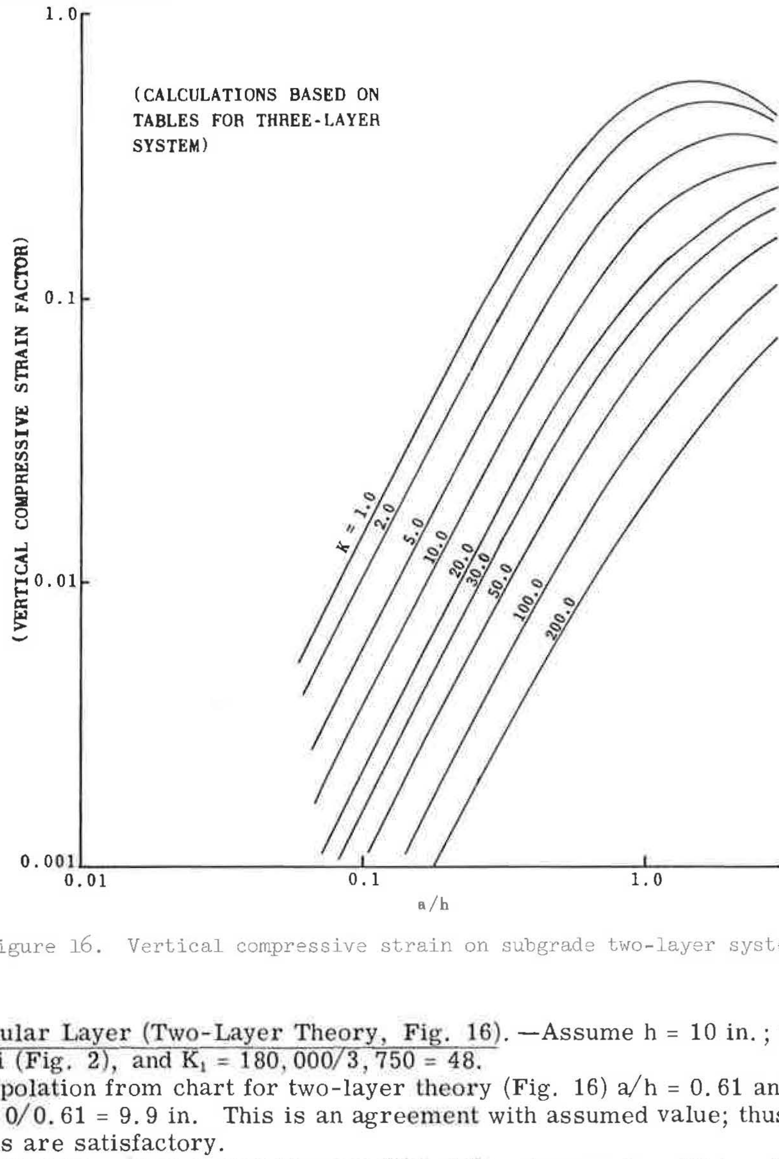

Figure 16. Vertical compressive strain on subgrade two-layer system.

No Granular Layer (Two-Layer Theory, Fig. 16). —Assume h = 10 in.; then E_1 = 180,000 psi (Fig. 2), and K_1 = 180,000/3,750 = 48.

By interpolation from chart for two-layer theory (Fig. 16) a/h = 0.61 and h = a/0.61 = 6.0/0.61 = 9.9 in. This is an agreement with assumed value; thus, provisional assumptions are satisfactory.

No Asphalt Layer (Two-Layer Theory, Fig. 16). —Assume h_2 = 28 in.; then K_2 = 4.0 (Fig. 4).

By interpolation from chart for two-layer theory (Fig. 16), a/h = 0.217, and h_2 = 6.0/0.217 = 27.5 in. Therefore, the provisional assumptions are satisfactory.

Intermediate Points. —When h_2 = 6 in. (A = 1.0), K_2 = 2 (Fig. 4). Assume h_1 = 9.0 in., then E_1 = 175,000 psi (Fig. 2), and K_1 = 175,000/7,500 = 23.4. By interpolation from three-layer data (2), H = h_1/h_2 = 1.55, and h_1 = 1.55 × 6.0 = 9.3 in.

When h_2 = 15 in. (A = 0.4), K_2 = 3 (Fig. 4). Assume h_1 = 7.0 in.; then E_1 = 165,000 psi (Fig. 2), and K_1 = 165,000/11,250 = 14.7. By interpolation from three-layer data (2), H = h_1/h_2 = 0.45, and h_1 = 0.45 × 15 = 6.75. Therefore, the provisional assumptions are satisfactory.

Tensile Strain in Asphalt Layer

Wheel Load. —Load is assumed to consist of one wheel of a dual-wheel pair. Total load = 9,000/2 = 4,500 lb; contact pressure = 80 psi; contact area = 56.2 sq in.; and radius of area = 4.2 in.

Permissible Strain. —1.45×10^{-4}. Strain factor $\frac{1}{2}$ (RR1 - ZZ1) = strain × E/σ = $(1.45 \times 10^{-4})(900,000/80) = 1.63$. A graphical representation of strain factors is contained in Ref. 3.

Tensile Strain Curve. —Points are determined by interpolation from three-layer data (2, 3). Calculations are made for several different thicknesses of granular base:

When $h_2 = 5.25$ in. ($A = 0.8$), $K_2 = 1.9$ (Fig. 4), $E_1 = 900,000$ psi, and $K_1 = 126$. By interpolation from tensile strain charts, $H = 0.92$, and $h_1 = 4.8$ in.

When $h_2 = 10.5$ in. ($A = 0.4$), $K_2 = 2.6$ (Fig. 4), $E_1 = 900,000$ psi, and $K_1 = 92$. By interpolation from tensile strain charts, $H = 0.43$, and $h_1 = 4.5$ in.

Discussion

K. R. PEATTIE, Esso Petroleum Co. Ltd., England. —The writer would like to comment on the use by Dormon and Metcalf of resultsfrom the AASHO Road Test in order to introduce the effects of repeated loads on the subgrade into a design method for flexible pavements.

The AASHO Road Test curves (9) showing the effect of numbers of axle loads on the thickness index were obtained by taking into account all the factors that reduced the serviceability indexes to the approporiate level. That is, they include the effect of repeated loads on the subgrade, the base courses, and the bituminous layers. However, Dormon and Metcalf have apparently used these curves as a basis for introducing the effect of repeated loads on subgrades alone because they treat the effect on the bituminous layers separately as a question of fatigue of bituminous materials.

Data relating to the effect of repeated applications of axle loads on the subgrade could be obtained from the results of the AASHO Road Test by calculating the stress or strain developed in the subgrade under the design load in pavement sections that were known to have failed by excessive deformation of the subgrade. These stresses or strains may then be plotted against the number of axle loads corresponding to the end value of the serviceability index. This has been done to a very limited extent by the writer (4). The main difficulty in extending this is the lack of knowledge of the mode of failure of the individual sections.

Furthermore, there are perhaps some doubts about the wisdom of applying the results of the AASHO Road Test in this way. In the first place, the climate and the types of construction used at the Road Test are not necessarily typical of those occurring in other regions. Secondly, the incidence of failures at the AASHO Road Test was not regular throughout the duration of the test. Most of the failures in the flexible sections occurred during the spring periods of 1959 and 1960, although the number of axle load applications increased smoothly throughout the test. There was no smooth relationship between axle applications and damage to the subgrade.

There is an urgent need to introduce the effect of repeated loads on the subgrade into design methods for flexible pavements. This may be done by using the results of laboratory tests on soils in conjunction with road trials in which damage is known to have increased smoothly with the buildup of axle loads.