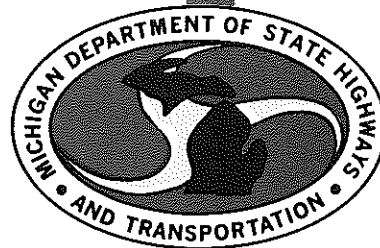# DEVELOPMENT OF BASE LAYER
THICKNESS EQUIVALENCY

TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

DEVELOPMENT OF BASE LAYER
THICKNESS EQUIVALENCY

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SUMMARY

Two current projects in the Research Laboratory's Soils Research Unit, "Comparative Study on Performance of Bituminous Stabilized Bases (M 66 and M 20)" and "Comparison of Cracked and Uncracked Flexible Pavements in Michigan," deal with performance of flexible pavement sections built with 'black bases.' It has been felt that a better knowledge of the interaction of black bases with the rest of the pavement system would be a valuable tool in assessing and designing a flexible pavement.

The purpose of this study is to establish a 'thickness equivalency' of the base layer on the basis of: a) elastic layer theory; and, b) limiting strains at critical locations in the pavement. The elastic layer theory considers the pavement to be a system of homogeneous layers of infinite horizontal extent spread over a semi-infinite depth subgrade and is, therefore, a static linear-elastic boundary-values problem. The limiting strains are the horizontal tensile strain at the bottom of any asphaltic layer and the compressive strain at the top of the subgrade. Control of these strain values provides control over the ability of the pavement to resist fatigue cracking and subgrade failure.

The Chevron CHEV 5L computer program, whose algorithm is based on the elastic layer theory, was used to calculate all critical strains in this study. The allowable values for tensile strain are based on fatigue data established by Santucci (22) and modified to be compatible with Michigan's mix design by equations developed by Pell and Cooper (24) and Epps (25). The subgrade compressive strain criteria developed by Monismith and McLean (26) are used in this study.

The determination of appropriate modulus values for computer input parameters in bituminous concrete, black base, and subgrade soils is discussed. The moduli of granular base and subbase materials are determined from subgrade modulus by stress-dependent concepts, which consider the modulus of a base or subbase layer to be a function of the modulus of the layer below it. All granular base and subbase materials are assumed to have adequate drainage characteristics so that variations in moisture conditions do not affect the strength and stiffness of these materials.

With the use of computer data obtained from models of two standard Michigan flexible pavement sections subjected to 5×10^5, 1×10^6, and 2×10^6 18-kip equivalent axle load repetitions, thickness equivalency curves were developed; each curve defining the relationship between the base thickness h_2 and the base modulus E_2 for given pavement and loading systems.

With these equivalency curves, highway engineers should be able to design the thickness of a granular or asphalt-treated base which will satisfy the strain restrictions in a flexible pavement section with known bituminous concrete and subgrade moduli. Procedures for designing theoretical thickness combinations of granular base and black base pavements are also presented as design alternatives in this report. An example problem is provided to illustrate the procedures for using the thickness equivalency charts and the procedures for development of design alternatives.

One of the other uses of the thickness equivalency charts developed in this study is in determining whether or not a black base is needed in a pavement section, or whether a black base may be substituted for a granular base, as results of the study indicate that black bases have an economic advantage only when the subgrade is weak. Another use is for predicting the remaining years of performance life in an existing flexible pavement.

This investigation considers only load-related failures, i.e., those failures associated with fatigue cracking and surface rutting. Other failures caused by frost heave, thermal cracking, etc., are not taken into account here but will be considered in another study.

This study has yielded considerable groundwork which is readily applicable to future investigations in the design and performance of black base for pavement sections in which the subgrade is weak, or in which the subbase layer is omitted.

INTRODUCTION

Purpose and Scope

The purpose of this study is to establish a thickness equivalency of the base layer of a flexible pavement on the basis of: a) elastic layer theory; and, b) limiting strains at critical locations in the pavement.

Thickness equivalency curves for the base layer define the relationship between the thickness and the resilient modulus of a base layer necessary for optimum pavement performance. By their use, not only can the thickness of a base layer of a material with known modulus, E_2, be determined, but decisions can also be made regarding the use of granular or asphalt-treated bases or combinations of both for a given set of loading conditions.

An 18-kip equivalent axle load (EAL) was used for this study. On the basis of results obtained in fatigue studies by numerous investigators, it was assumed that a 2.5-in. thick bituminous concrete layer would be expected to carry from one-half to one million 18-kip EAL repetitions before failing and a 4.5-in. thick bituminous concrete layer would carry from one to two million 18-kip EAL repetitions before failure.

The study is limited to two typical Michigan flexible pavement designs with the loading condition and layer characteristics shown in Figure 1. Only load-related failures—fatigue cracking and surface rutting—are considered in the calculations for pavement damage.

Furthermore, all granular base and subbase materials are assumed to have adequate drainage characteristics so that variations in moisture conditions do not have a significant effect on the strength and stiffness of these materials. However, moisture conditions which influence the stiffness and strength characteristics of the subgrade soils need to be taken into consideration.

Background of the Study

Research Laboratory interest in base layer equivalencies dates back to 1971 when I. AlNouri, of the Soils Research Unit, proposed a 'quasi-elastic' modulus 'E*' for 'black bases' (1). In 1976, F. Hsia, also of the Soils Research Unit presented charts of thickness equivalencies between asphalt-treated and untreated base layers (2). Two current projects in the Unit, "Comparative Study on Performance of Bituminous Stabilized Bases (M 66 and M 20)," (Research Project 75 E-59), and "Comparison of Cracked and Uncracked Flexible Pavements in Michigan" (Research Project 78 D-36),
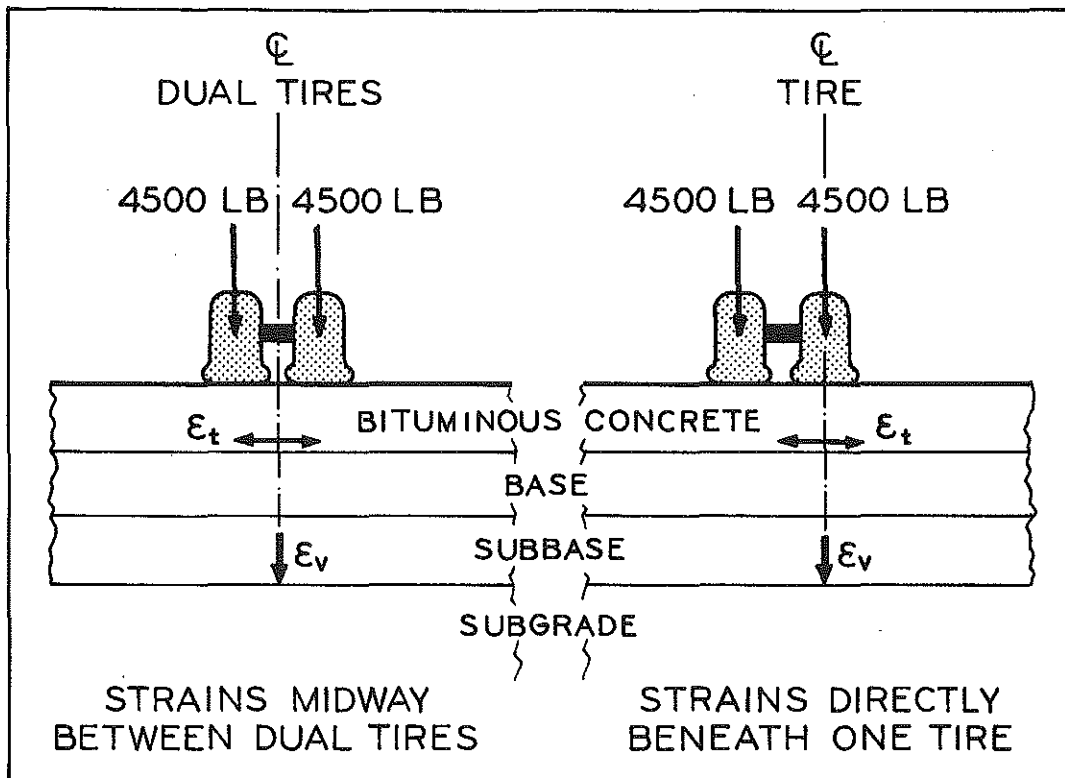
Figure 1. Schematic representation of location of maximum horizontal tensile and vertical compressive strains in flexible pavement structures.

also deal with performance of flexible pavement sections built with black bases. It has been felt that a better knowledge of the interaction of black bases with the rest of the pavement system would be a valuable tool in assessing and designing flexible pavements.

Theoretical Basis of the Study

An essential step in the design of pavements is the evaluation of stresses and strains that are induced in a road structure by traffic loads. One of the methods used today to determine a pavement's response to load is by elastic layer theory which assumes that the pavement is a system of horizontally-infinite homogeneous layers of uniform thickness, resting on a semi-infinite subgrade. If the pavement layers and subgrade respond to traffic loading as linearly elastic solids, the multilayer system of analysis can be used to analyze stresses and strains. Kingham (3) made a study which verified that deflections, vertical strains, and radial strains can be reasonably computed from elastic layer theory. Hicks and Finn (4) have shown that the measured deflections and strains in the San Diego test road

are reasonably close to those computed by the elastic layer system. More recently, investigators have shown that past pavement design experience correlates reasonably well with multilayer, elastic theory computations.

In 1963, Dormon and Metcalf (5) rationalized that the horizontal stress and strain at the bottom of an asphalt layer and the vertical strain at the top of the subgrade layer are critically related to pavement performance. Today, there is general agreement that the horizontal tensile strain at the bottom of the asphalt layer is the controlling criterion for fatigue cracking and that the vertical compressive strain at the surface of the subgrade is the controlling criterion for permanent surface deformation. Control of these strains provides control over pavement performance factors that are related to traffic loading.

In this report, the critical strains under a 9,000-lb equivalent wheel load on dual tires were calculated at two different locations in the wheel load area. One location is midway between the tires, the other directly under one of the tires. Figure 1 illustrates the modes of loading with the location of maximum strain in a typical pavement structure. The values of the strain under one of the dual tires and midway between the tires, are obtained by superimposing the separate strains induced under each of the two locations by one of the tires. The strain values obtained by superposition at the two locations are compared and the greater value is used for analysis purposes.

COMPUTERIZATION OF ELASTIC MULTILAYER SYSTEMS

Characterization of the mechanical behavior of materials is complicated, and stress analysis of a pavement consisting of different types of materials is even more complicated. Without the use of computers, the solutions for stresses, strains, displacements, and other pavement response parameters are tedious and might even be impossible.

There are several elastic layer computer programs that will satisfactorily compute pavement response parameters. CHEV 5L (6) and BISAR (7) computer programs are currently available for use in the Department. Both programs have a similar mathematical development and give essentially the same results. The principal difference between the two programs is that CHEV 5L is restricted to a single normal load while BISAR is capable of analyzing multiple loads.

The CHEV 5L program, which was chosen for this study, was written with the following assumptions:
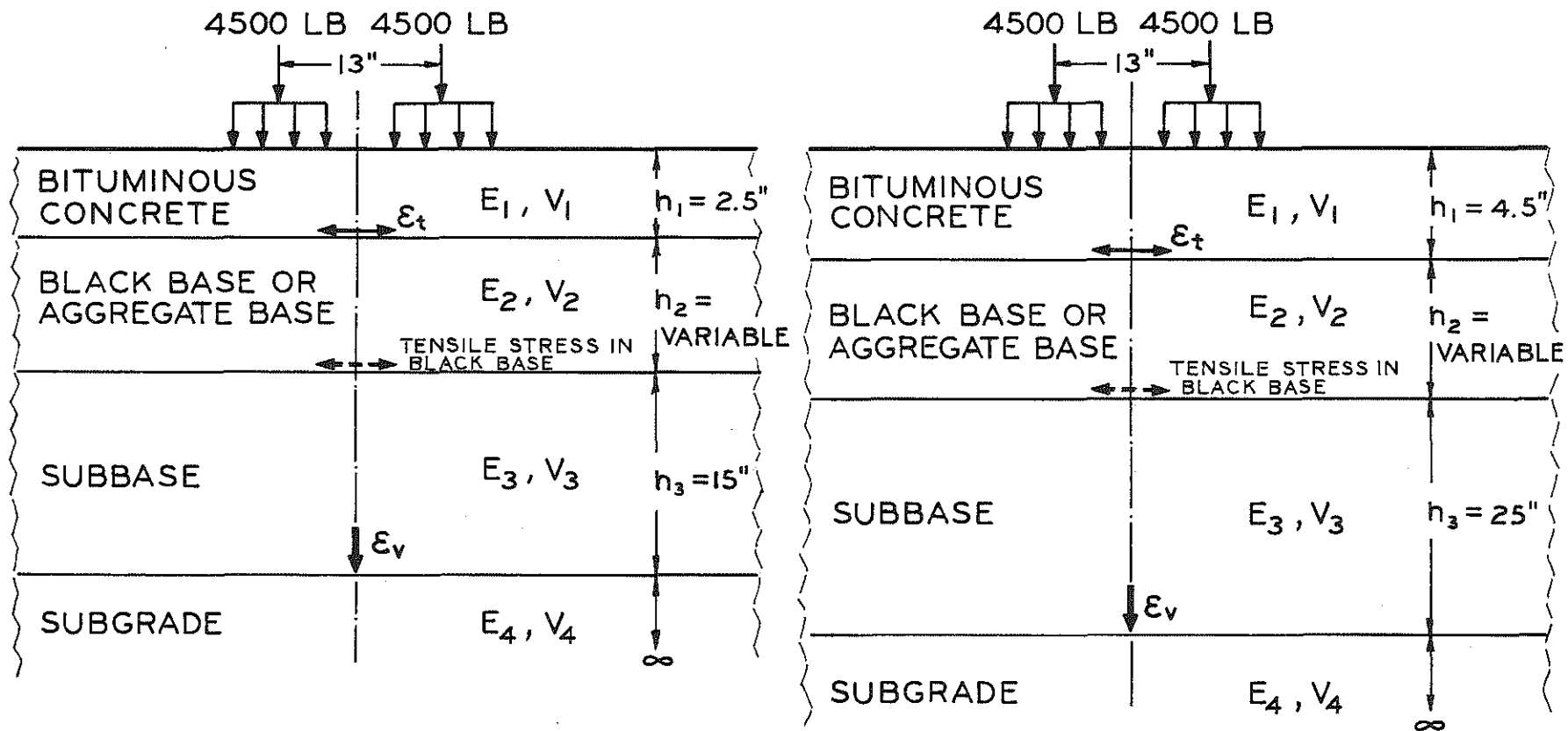
A. This design, with the thinner bituminous concrete surface was used in constructing the thickness equivalency curves shown in Figures 17-22.

B. This design, with the thicker bituminous concrete surface was used in constructing the thickness equivalency curves shown in Figures 23-28.

Figure 2. Schematic representation of two typical Michigan flexible pavement systems.

1) The pavement is a composite of horizontal layers of uniform finite thickness spread over a subgrade layer,

2) The layers are infinite in extent in all horizontal directions, the subgrade layer being infinite in extent in both the horizontal and vertical (downward) directions,

3) The layers are homogeneous and isotropic with respect to their mechanical behavior,

4) The materials of the layers have a linear stress-strain relationship,

5) The components of stress and displacement at interfaces between layers are continuous, and

6) All loads are circular and uniform over the contact area.

These assumptions are, in fact, necessary conditions for pavement design. CHEV 5L enables designers to calculate stresses, strains, and displacements at any position in a multilayer system, with an arbitrary number of layers subjected to a single normal load. In the case of dual tire loadings, CHEV 5L is run for each point load and the effects of the adjacent tire load accounted for by the principle of superposition. The input parameters for the CHEV 5L program are traffic loading, tire pressure, number and thickness of layers in the flexible pavement cross-section, the resilient modulus E, and Poisson's ratio, v, of each component layer. The determination of values to assume for the resilient modulus of each layer was a major portion of this study.

CHARACTERIZATION OF MATERIALS USED IN MICHIGAN FLEXIBLE PAVEMENT SYSTEMS

An investigation was conducted to determine the elastic modulus and Poisson's ratio properties of each layer of two typical four-layer pavement systems used in Michigan (Fig. 2). The base course, of variable depth h_2 in Figure 2, can be constructed of either asphalt-treated material (black base) or unbound granular material. The parameters, h, E, and v shown in Figure 2 are, respectively, layer thickness, modulus of elasticity, and Poisson's ratio, with the numerical subscript denoting the layer order of depth. Note that for the two typical systems used, a 2.5-in. bituminous concrete surface layer, h_1, is assumed to have a 15-in. subbase layer, h_3, (Fig. 2A) and a 4.5-in. bituminous concrete surface layer is assumed to have a 25-in. subbase layer, h_3, (Fig. 2B). The standard subbase layer thicknesses shown are known to provide for satisfactory drainage. Each layer is discussed in the following sections.
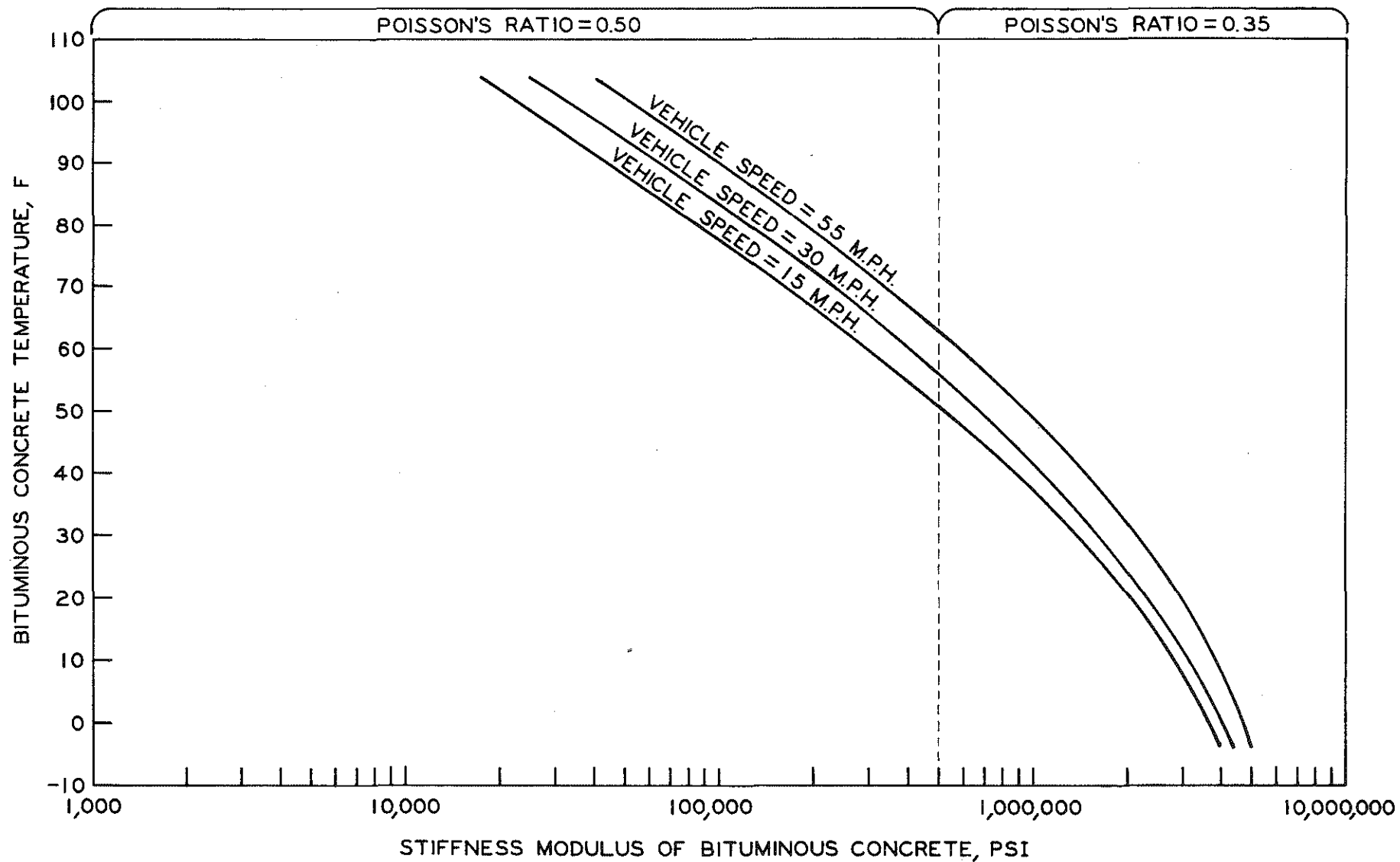
Figure 3. Effect of temperature on stiffness of 120-150 penetration bituminous concrete at various vehicle speeds (after Novak (10)).

Bituminous Concrete

The modulus and the tensile strength of bituminous concrete depend not only on the mix properties such as air void content, aggregate gradation, and bitumen content, but also on pavement temperature and time of loading. On the basis of all these factors, the modulus of bituminous concrete can be determined using the bitumen-stiffness nomograph originally proposed by Van der Poel (8) with later changes by Heukelom and Klomp (9).

Novak (10), using the same stiffness nomograph, developed a series of charts for determining the stiffness modulus of bituminous concrete. Figure 3 illustrates one of Novak's charts for bituminous concrete consisting of 120/150 penetration grade bitumen. Claessen (11) used a similar nomograph for determining the stiffness moduli of bituminous mixes, but his nomograph did not include loading time, which is, essentially, a function of vehicle speed.

Other methods for determining the modulus of a bituminous mix include direct testing methods such as that outlined in ASTM's Annual Book of Standards, Part 15, and by rough estimates from tables such as Table 1 of Ref. (2).

Unbound Granular Base and Subbase Materials

The materials used for highway construction must meet gradation and other requirements as specified in Michigan's "Standard Specifications for Highway Construction."

The method used to determine the modulus values of unbound granular base and subbase materials is based on stress-dependent principles first reported by Izatt, Lettier, and Taylor (12). The modulus values in this report are calculated from mathematical expressions developed at the Waterway Experiment Station (13) from analysis of test track performance data. This method was developed in accordance with the concept that the modulus value of unbound granular materials is stress-dependent and that, since induced stresses decrease with depth, modulus values also decrease with depth. This implies that the modulus of the granular material in each layer is a function of the layer thickness and of the modulus of the underlying layer. Therefore, the modulus of the subbase layer directly over the subgrade is a function of the subgrade modulus and the modulus of the base layer is a function of subbase modulus.

The Waterway Experiment Station equation, applicable to base course material, is:

$$E_n = E_{n+1} (1 + 10.52 \log t - 2.10 \log E_{n+1} \log t) \tag{1}$$

where the base course is layer n. For subbase materials,

$$E_n = E_{n+1} (1 + 7.18 \log t - 1.56 \log E_{n+1} \log t) \tag{2}$$

where the subbase course is layer n. For each equation, E_{n+1} is the modulus value of the lower layer n+1, in psi, t is the thickness of the overlying layer, n, in in., and E_n is the modulus value of layer, n, in psi.

For thick granular base and subbase layers, each layer should be divided into sublayers 6 to 8 in. thick and the modulus of each sublayer assumed to be a function of its thickness and the modulus of the sublayer below it (13).

Eqs. (1) and (2) plotted in Figures 4 and 5 show the relationship of modulus and depth for 2 in. to 10-in. unbound base and 3 in. to 10-in. unbound subbase.

A series of road vibration measurements recorded by Heukelom and Klomp (9) further support the concept that the effective modulus of a granular base course is dependent on the modulus of the underlying subgrade soil. On the average, the modulus of each granular layer is approximately three times greater than that of the layer below it. Klomp and Dormon (14) obtained field measurements that showed the modulus ratios between the overlying unbound layers and the subgrade to be in the range of 1.5 to 2.5. The relationship reflecting the effect of subbase thickness is presented by Klomp and Dormon as follows:

$$E_3 = K_3 E_4 \tag{3}$$

where: $K_3 = 0.206 \, h_3^{0.45}; \; 2 < K_3 < 4$ (4)

h_3 = thickness of unbound layers in millimeters, and
E_4 = known subgrade modulus.

In order to keep the value of K_3 between 2 and 4, h_3 can be assigned only values which are greater than 6.15 in. and less than 28.69 in.

In this study, the two values assigned to the subbase thickness are 15 in. and 25 in., both of which are within the requirement of Eqs. (3) and (4).

For these two subbase thicknesses, a comparison was made between the resulting subbase moduli obtained by using Eqs. (2) and (3) for three

different subgrade modulus values. The calculations were further extended to show how the division into sublayers affect the resulting modulus of a thick subbase. Table 1 shows the results of the comparison. The thickness equivalency charts presented later in this report are based on the average subbase modulus values as determined by division into sublayers and listed in Table 1.

TABLE 1
COMPARISON OF SUBBASE MODULI AS
OBTAINED BY EQS. (2) AND (3)

	Subbase Moduli	Subgrade Modulus, E_4, psi		
		3,000	7,500	15,000
Subbase Thickness, h_3 = 15 in.	Eq. (3), subbase modulus, E_3	8,960	22,400	44,800
	Eq. (2), subbase modulus, E_3	9,180	17,500	26,700
	Eq. (2), subbase modulus (divided into sublayers)			
	h_{31} = 7.5 in., E_{31}	7,590	14,900	23,700
	h_{32} = 7.5 in., E_{32}	15,000	23,600	31,000
	Average subbase modulus, E_3	11,000	19,000	27,000
Subbase Thickness, h_3 = 25 in.	Eq. (3), subbase modulus, E_3	11,280	28,200	56,400
	Eq. (2), subbase modulus, E_3	10,350	19,400	29,000
	Eq. (2), subbase modulus (divided into sublayers)			
	h_{31} = 8 in., E_{31}	7,740	15,150	24,000
	h_{32} = 8 in., E_{32}	15,480	24,000	31,400
	h_{33} = 9 in., E_{33}	24,900	32,000	36,400
	Average subbase modulus, E_3	16,000	24,000	30,000

Asphalt-Treated Material (Black Base)

The term black base is understood to refer to a well-compacted, high stone content hot bituminous mix, having a void content of less than 10 percent and a bitumen content of not less than 4 percent. It is assumed to be a part of the asphalt bond layer. Therefore, the properties of black base are assumed similar to those of bituminous concrete (15). The resilient modulus of the black base is determined on the basis of two concepts. The
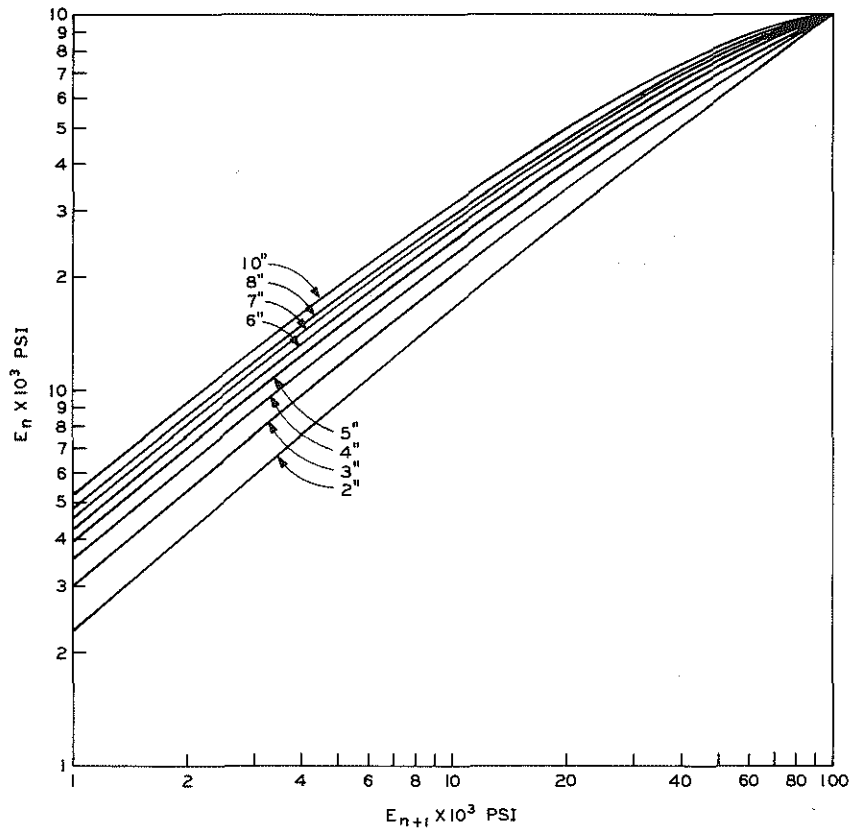
Figure 4. Relationship between modulus of layer n and modulus of layer n+1 for various thicknesses of unbound base course.
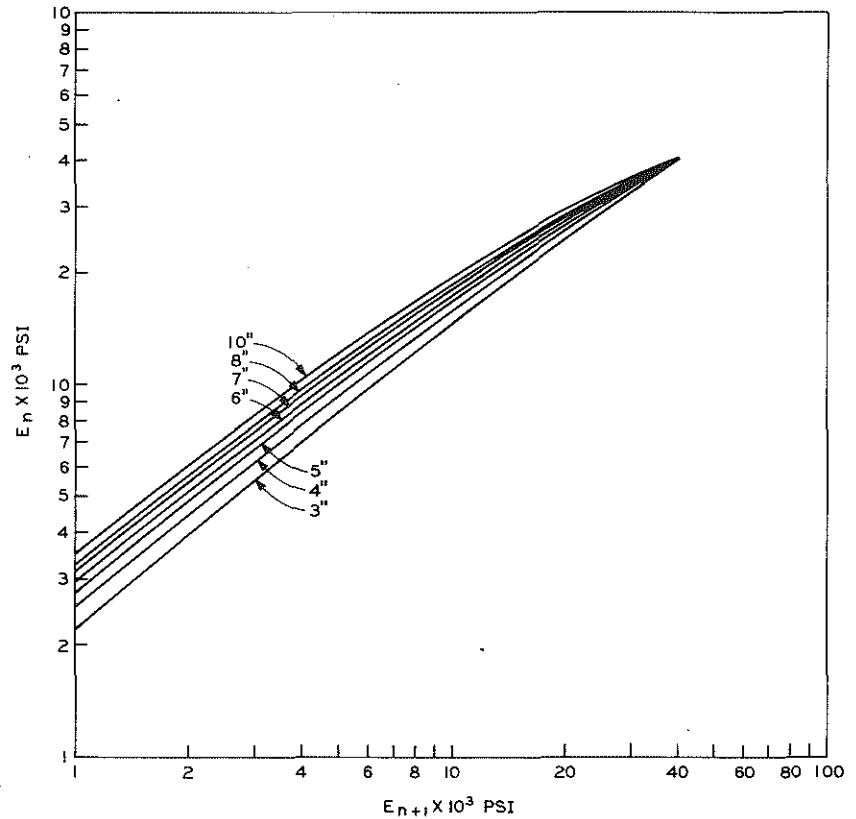

Figure 5. Relationship between modulus of layer n and modulus of layer n+1 for various thicknesses of unbound subbase course.

first concept assumes that the black base will withstand the applied load without development of tensile cracking at the bottom of the black base. Under this concept, the modulus value is determined using the principles described in the "Bituminous Concrete" section of this report. The second concept assumes that tensile cracking will develop, and a reduced modulus value, termed 'black-base cracked section modulus,' is used which is determined by laboratory testing. Barker (13) utilized the unconfined compression test to determine an equivalent cracked section modulus of stabilized base material.

To design a pavement system with black base, an initial black base modulus value is used. The maximum tensile strain at the bottom of the black base layer is computed and compared with the permissible strain indicated by the black base fatigue criteria (Explained in detail on page 27 and Fig. 15). If the black base strain value is smaller than the permissible strain, the black base will not crack before the design number of 18-kip EAL repetitions is applied by traffic. However, if the computed tensile strain is larger than the permissible strain, cracking will occur and a black base cracked section modulus must be used to design the pavements.

In this report, the modulus values of black base used for the computer runs, can be assumed to range from a minimum of 50,000 psi to a maximum of 1,500,000 psi similar to that of bituminous concrete. The high modulus values are used to approximate more closely pavement conditions under moving traffic. The quasi-elastic modulus of black base reported in Ref. (1) is very low compared to values reported by other sources. Ref. (1) results were obtained using the conventional triaxial test equipment in which load cycles were repeated 20 times. The rate of loading is too slow compared with that of moving traffic. Ref. (1) reports that the average black base modulus at a pavement temperature of 77 F is 41,000 psi, while the same mix at the same temperature has, on the basis of Figure 3, a modulus of 150,000 psi for a vehicle speed of 30 mph. The difference is attributed to the rate of loading. It has been reported (16) that long loading periods such as that used in Ref. (1) will change the internal structure of the bituminous mix which, in turn, causes the modulus to differ from that obtained with rapid load cycles. With the use of the MTS electro-hydraulic loading system recently acquired for the Research Laboratory, the determination of black base modulus can be made at rates of loading which better simulate actual traffic loading conditions.

Subgrade Soils

The term 'subgrade' refers to the natural, processed, or fill soils on which the pavement structure is placed. Most subgrades show stress-dependent behavior, and both laboratory and full-scale pavement studies

have demonstrated that linear-elastic theory can be used to describe the pavement response, provided the moduli of all pavement materials are determined under the appropriate loading conditions. Therefore, the subgrade modulus is preferably determined in-situ from surface deflection measurements. There are several different methods of determining subgrade modulus on the basis of surface deflection (17, 18, 19).

Heukelom and Klomp (20) present a relationship between dynamic modulus and California Bearing Ratio (CBR) values which can be used to estimate subgrade modulus when pavement surface deflection or subgrade modulus data are not available.

$$E = 1500 \times CBR \tag{5}$$

This empirical relationship is often used in practice to estimate subgrade modulus.

In this report, three values of subgrade modulus, 3,000 psi, 7,500 psi, and 15,000 psi, are assumed to represent the full range of subgrade conditions found in Michigan. Interpolation procedures can be used to estimate results for other subgrade moduli.

Poisson's Ratio

Hills and Heukelom (16) conducted an investigation to determine how much of an effect Poisson's ratio has on the computed tensile strain at the bottom of the bituminous concrete layer and on the compressive strain at the subgrade surface. The value of Poisson's ratio can vary with stress, temperature, etc. Generally speaking, changes in Poisson's ratio have little effect on the maximum tensile and compressive strains, as shown in Figures 6 through 13. Figure 6 shows that changes in subgrade modulus have little effect on tensile strains; whereas, changes in the modulus of either the bituminous concrete surface layer or the base layer have a significant effect on tensile strain.

Poisson's ratio for bituminous concrete is known to approach a value of 0.5 as the modulus of bituminous concrete decreases. Kingham and Kallas (21) used 0.45 when the modulus was below 500,000 psi. Barker, et al, (13) assigned values of 0.5 and 0.3, respectively, for moduli less than and greater than 500,000 psi while Santucci (22) uses a value of 0.4 regardless of the modulus of the mix. In this study, a Poisson's ratio of 0.5 is used for conditions when the bituminous modulus is less than 500,000 psi, and 0.4 when the modulus is greater than 500,000 psi.
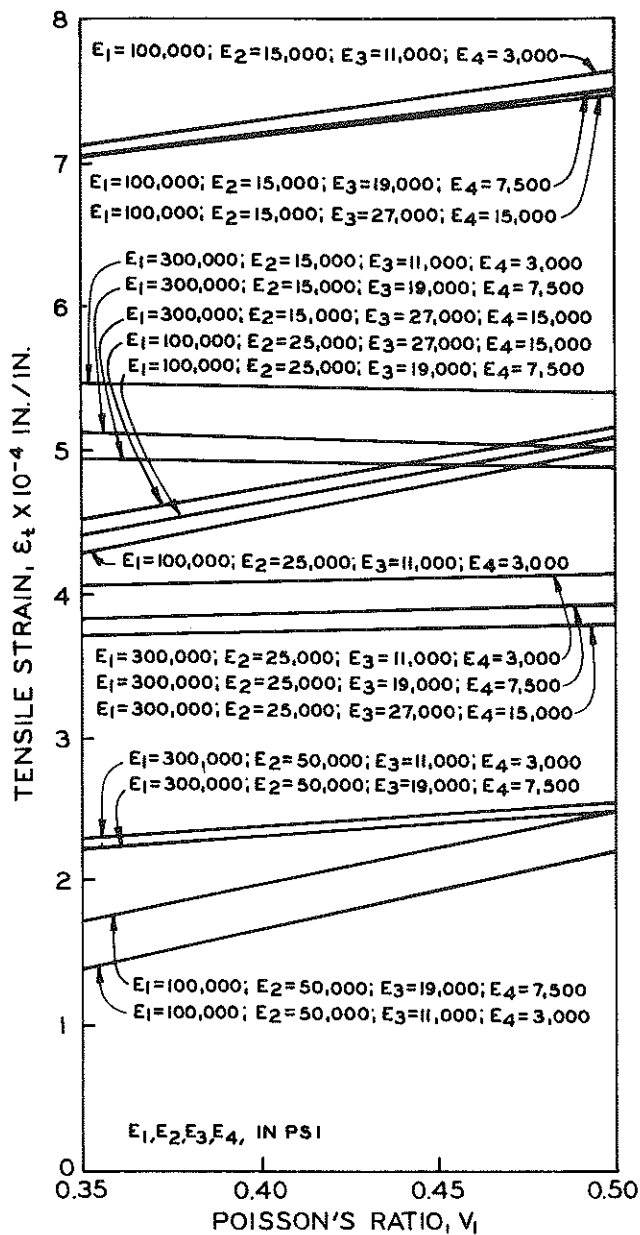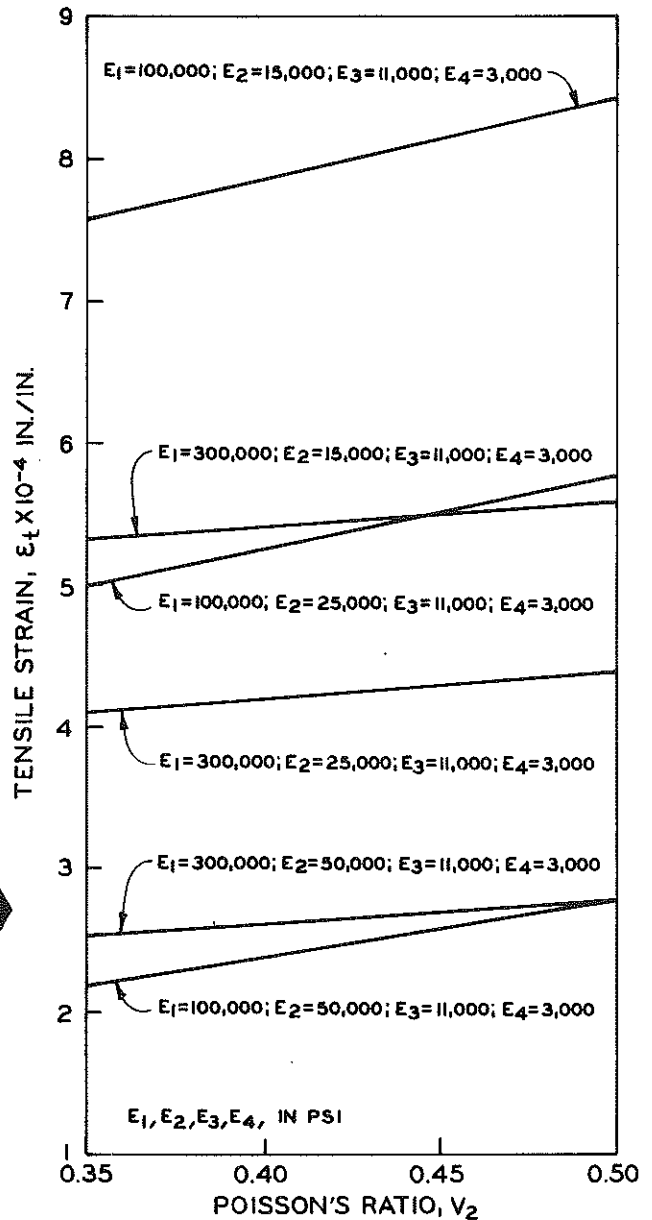
Figure 6. Effect of Poisson's ratio, V_1, on tensile strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where h_1 = 2.5-in., h_2 = 6-in., h_3 = 15-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.

In Figure 6 plot, the curves are labeled:
E_1=100,000; E_2=15,000; E_3=11,000; E_4=3,000
E_1=100,000; E_2=15,000; E_3=19,000; E_4=7,500
E_1=100,000; E_2=15,000; E_3=27,000; E_4=15,000
E_1=300,000; E_2=15,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=15,000; E_3=19,000; E_4=7,500
E_1=300,000; E_2=15,000; E_3=27,000; E_4=15,000
E_1=100,000; E_2=25,000; E_3=27,000; E_4=15,000
E_1=100,000; E_2=25,000; E_3=19,000; E_4=7,500
E_1=100,000; E_2=25,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=25,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=25,000; E_3=19,000; E_4=7,500
E_1=300,000; E_2=25,000; E_3=27,000; E_4=15,000
E_1=300,000; E_2=50,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=50,000; E_3=19,000; E_4=7,500
E_1=100,000; E_2=50,000; E_3=19,000; E_4=7,500
E_1=100,000; E_2=50,000; E_3=11,000; E_4=3,000
E_1,E_2,E_3,E_4, IN PSI

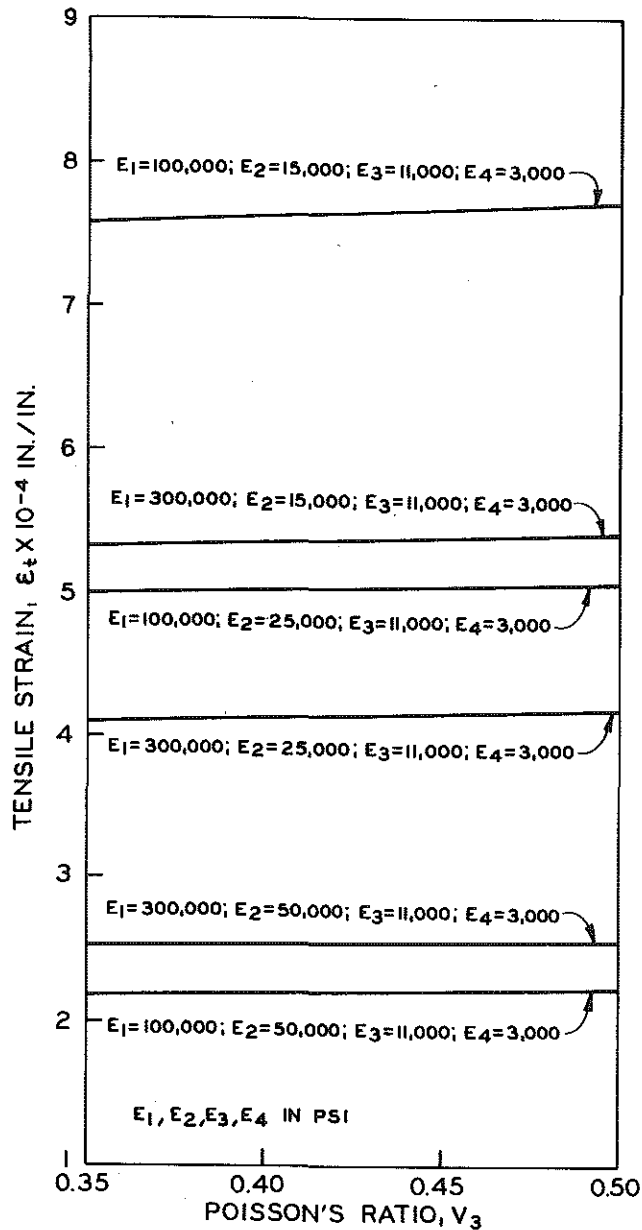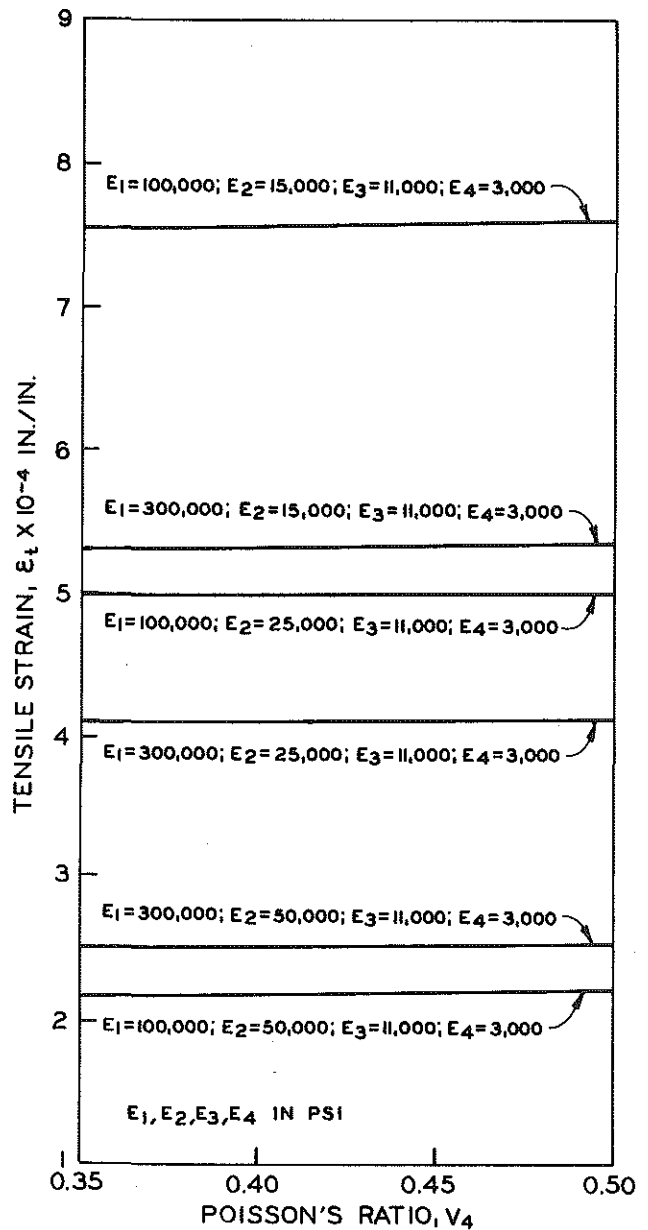Axes: TENSILE STRAIN, $\varepsilon_t \times 10^{-4}$ IN./IN. vs POISSON'S RATIO, V_1

Figure 7. Effect of Poisson's ratio, V_2, on tensile strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where h_1 = 2.5-in., h_2 = 6-in., h_3 = 15-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.

In Figure 7 plot, the curves are labeled:
E_1=100,000; E_2=15,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=15,000; E_3=11,000; E_4=3,000
E_1=100,000; E_2=25,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=25,000; E_3=11,000; E_4=3,000
E_1=300,000; E_2=50,000; E_3=11,000; E_4=3,000
E_1=100,000; E_2=50,000; E_3=11,000; E_4=3,000
E_1,E_2,E_3,E_4, IN PSI

Axes: TENSILE STRAIN, $\varepsilon_t \times 10^{-4}$ IN./IN. vs POISSON'S RATIO, V_2

Figure 8. Effect of Poisson's ratio, V_3, on tensile strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where h_1 = 2.5-in., h_2 = 6-in., h_3 = 15-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.
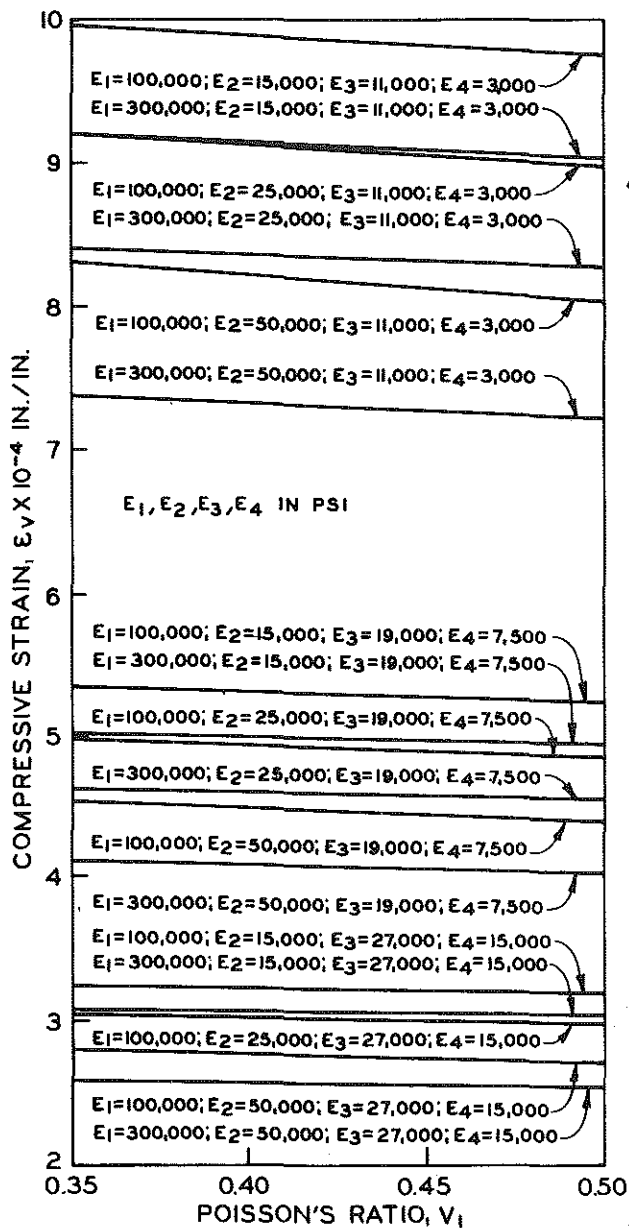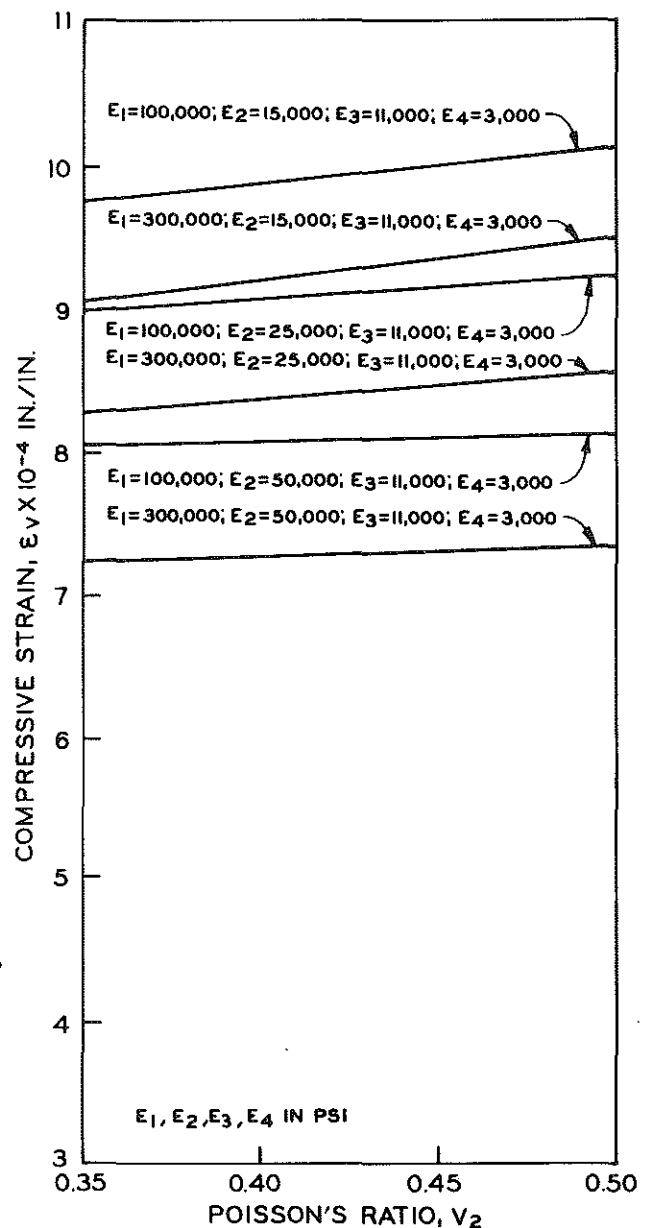
Figure 9. Effect of Poisson's ratio, V_4, on tensile strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where h_1 = 2.5-in., h_2 = 6-in., h_3 = 15-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.

Figure 10. Effect of Poisson's ratio, V_1, on compressive strain at the bottom of the bituminous concrete for various combinations of m o d u l i in a four-layer system where $h_1 = 2.5$-in., $h_2 = 6$-in., $h_3 = 15$-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.
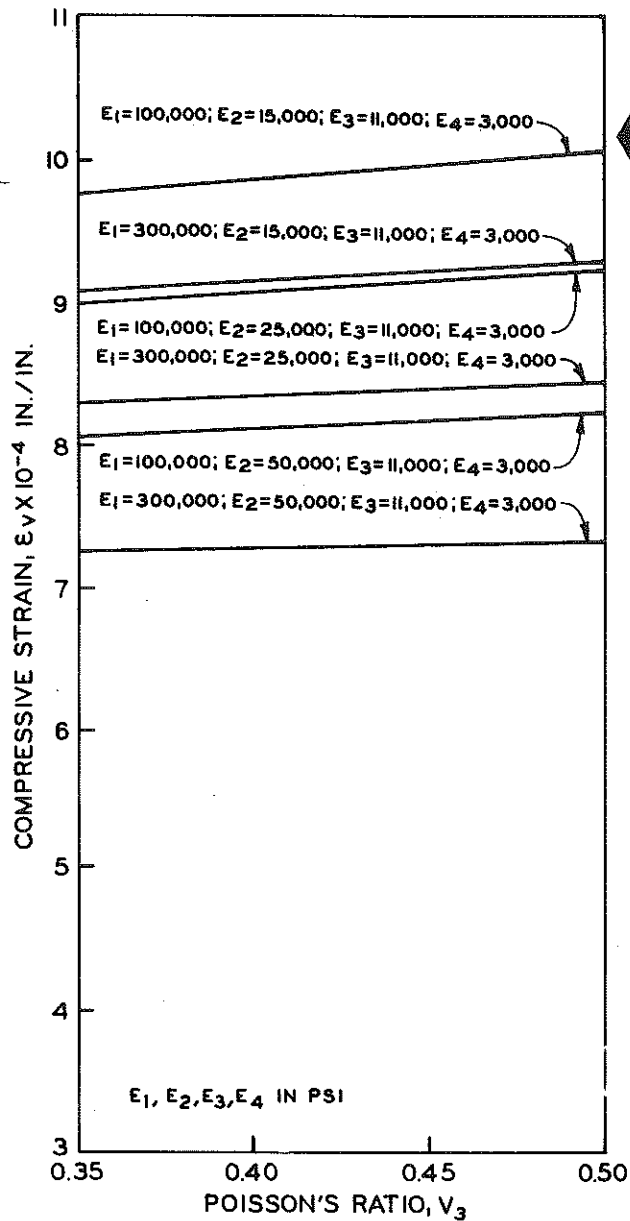

Figure 11. Effect of Poisson's ratio, V_2, on compressive strain at the bottom of the bituminous concrete for various combinations of m o d u l i in a four-layer system where $h_1 = 2.5$-in., $h_2 = 6$-in., $h_3 = 15$-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.

Figure 12. Effect of Poisson's ratio, V_3, on compressive strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where $h_1 = 2.5$-in., $h_2 = 6$-in., $h_3 = 15$-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.

Figure 13. Effect of Poisson's ratio, V_4, on compressive strain at the bottom of the bituminous concrete for various combinations of moduli in a four-layer system where $h_1 = 2.5$-in., $h_2 = 6$-in., $h_3 = 15$-in., h_4 = semi-infinite, axle load = 18,000 lb, tire pressure = 70 psi.
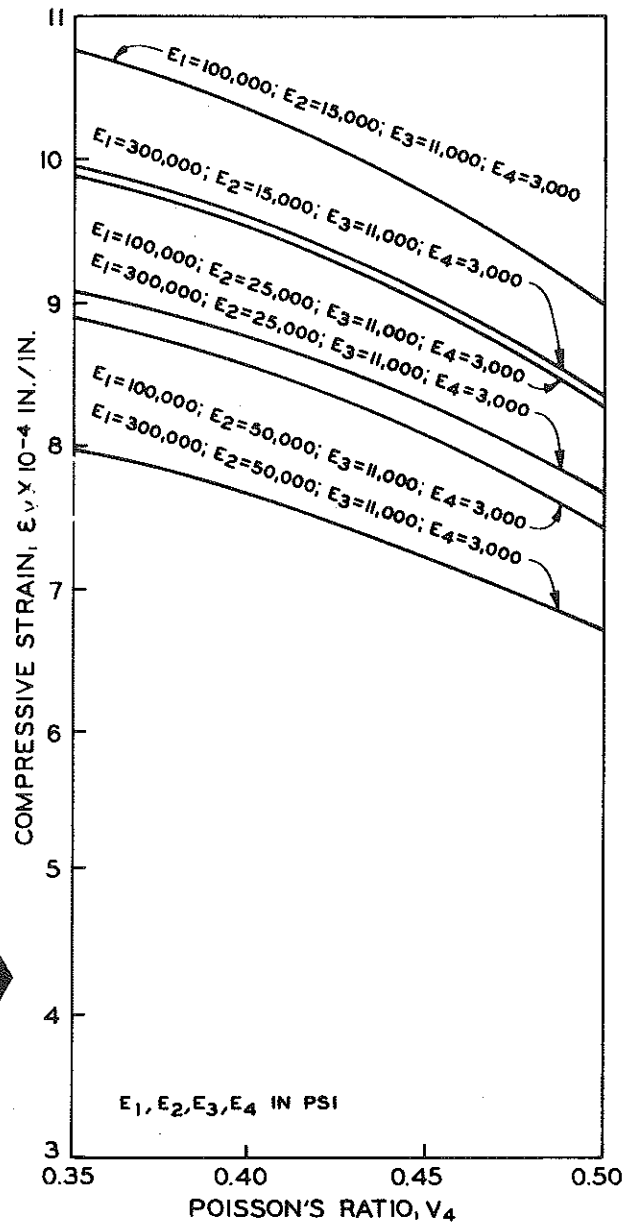
Dormon and Edwards (23) reported that Poisson's ratio for subgrade soils and granular material lies in the range of 0.35 and 0.45. In this study, a value of 0.45 for subgrade soils and 0.35 for base and subbase granular materials were chosen.

FATIGUE CRITERIA FOR BITUMINOUS CONCRETE AND BLACK BASE

The literature on asphalt technology is filled with research evidence to show that bituminous concrete, when subjected to repeated or fluctuating stress, will fail under stresses lower than those that would cause failure under static conditions. This decrease in resistance is known as fatigue failure.

The fatigue criterion for bituminous concrete and black base is based on permissible strains which are a function of the number of load repetitions and modulus values. Several direct laboratory test procedures exist for evaluating the permissible strain. These test procedures involve applying a repetitive load to a specimen, under controlled stress or strain conditions, until failure of the specimen occurs. With such test procedures, limiting horizontal tensile strains can be determined for the normal modulus range of a given bituminous mix.

The fatigue criteria used in this study are based on Santucci's (22) results. The fatigue curves shown in Santucci's report are based on data derived from bituminous mixtures with air voids and bitumen contents by volume, of 5 and 11 percent, respectively. For Michigan's standard mix design, air void and bitumen contents are 3 and 13.8 percent, respectively, for bituminous concrete, and 6 and 10.5 percent for black base. An equation developed by Pell and Cooper (24) and Epps (25) was used to adapt Santucci's fatigue data to fatigue curves for Michigan's bituminous concrete and black base. This equation is:

$$N_c = N_f \times 10^M \tag{6}$$

where: N_c = corrected number of repetitions to failure,
N_f = number of repetitions to failure at a given strain level and modulus from Santucci's fatigue curves.

$$M = 4.84 \left(\frac{V_b}{V_a + V_b} - 0.688 \right) \tag{7}$$

and: V_a = air void content in percent,
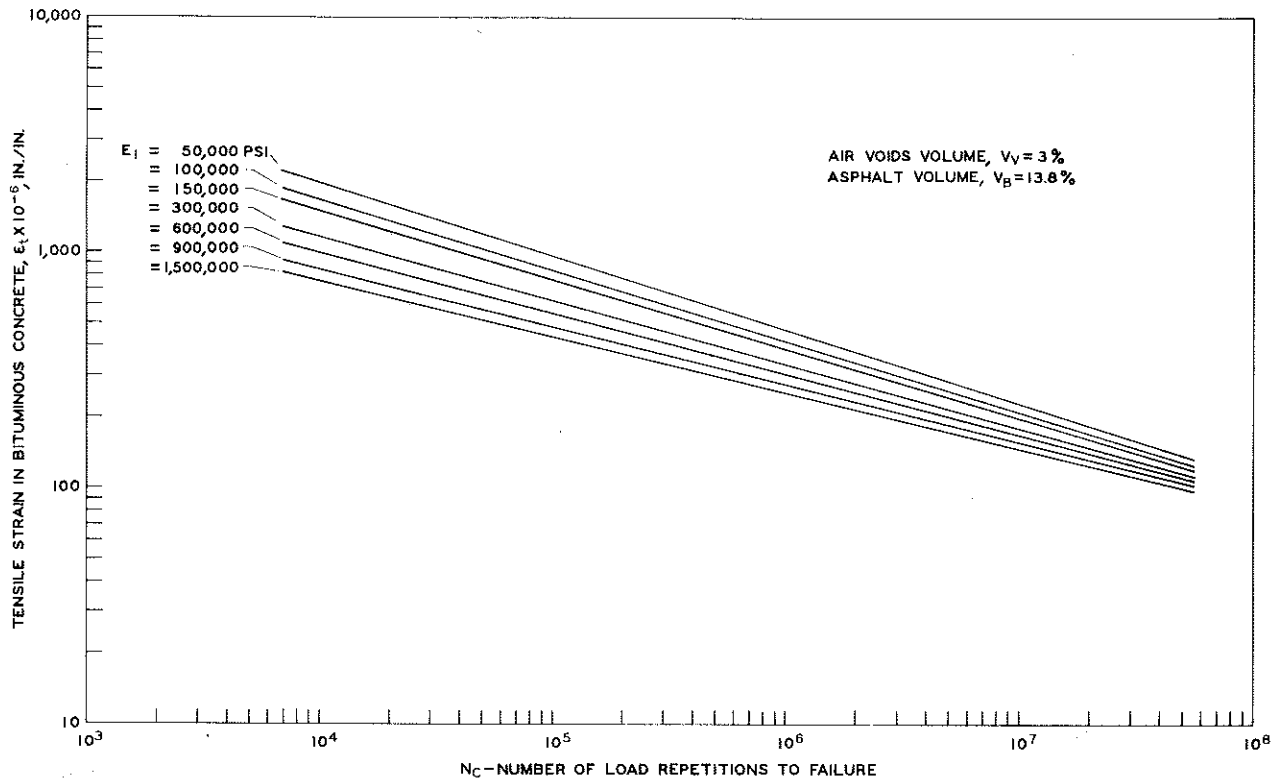V_b = bitumen content by volume in percent.

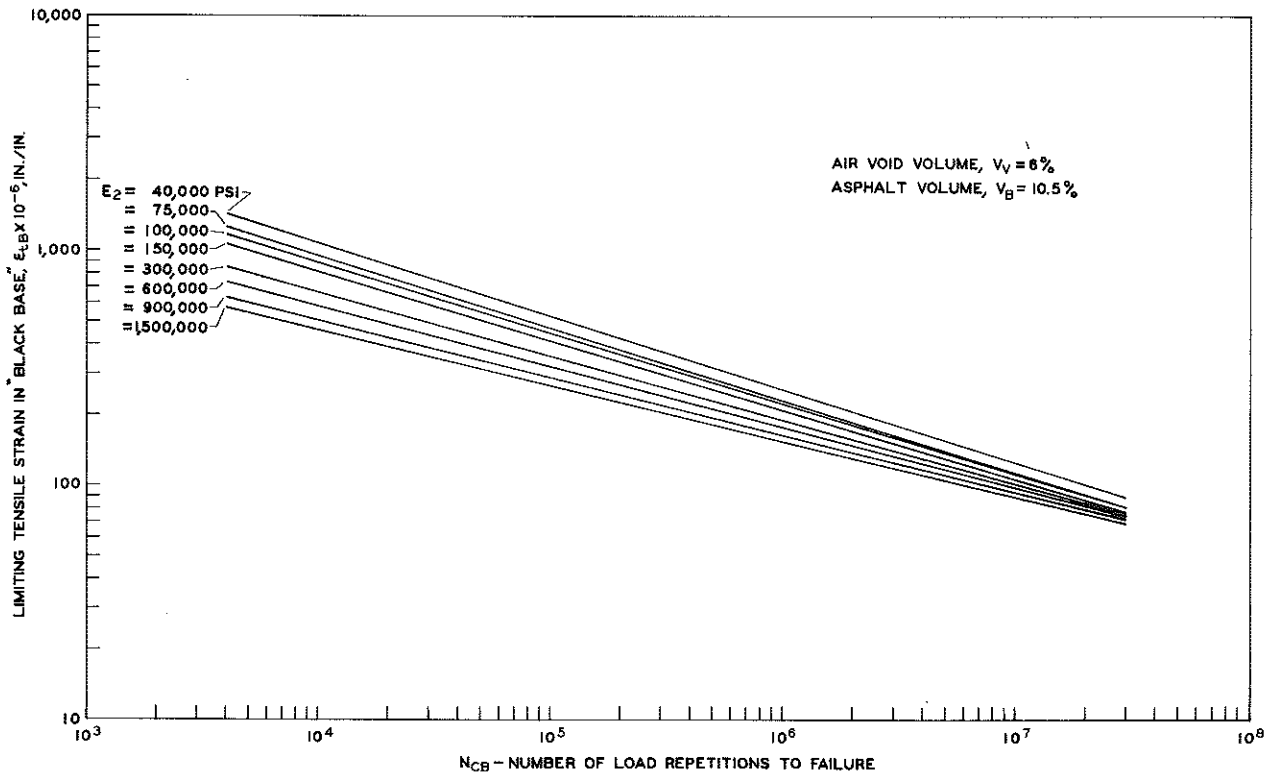Figure 14. Fatigue criteria for a Michigan bituminous mix.

Figure 15. Fatigue criteria for Michigan asphalt-treated black base.

Figures 14 and 15 represent the corrected fatigue curves for Michigan's bituminous concrete and black base, respectively, and may be used for Michigan's bituminous concrete and black base until actual fatigue properties are established by direct laboratory tests. Table 2 summarizes the bituminous concrete fatigue data used to develop the thickness equivalency charts presented in this report.

TABLE 2

PERMISSIBLE TENSILE STRAINS (ε_t) AND COMPRESSIVE STRAINS (ε_v) FROM FIGURES 14 AND 16 FOR THREE DIFFERENT LOAD APPLICATIONS (N_c) AND VARIABLE E_1

Type of Strain		Pavement Thickness (h_1) and Number of Load Applications (N_c)		
		$h_1 = 2.5$ in., $N_c = 5 \times 10^5$	$h_1 = 2.5$ and 4.5 in., $N_c = 1 \times 10^6$	$h_1 = 4.5$ in., $N_c = 2 \times 10^6$
Tensile Strain for $\varepsilon_t \times 10^{-4}$	$E_1 = 50,000$ psi	5.77	4.64	3.75
	$E_1 = 100,000$ psi	5.10	4.15	3.38
	$E_1 = 300,000$ psi	4.00	3.33	2.77
	$E_1 = 600,000$ psi	3.60	3.02	2.53
	$E_1 = 900,000$ psi	3.24	2.73	2.30
	$E_1 = 1,000,000$ psi	2.95	2.51	2.13
Compressive Strain, $\varepsilon_v \times 10^{-4}$		5.65	4.82	4.12

SUBGRADE STRAIN CRITERIA

The basic hypothesis regarding rutting of a pavement surface is that if the maximum compressive vertical strain at the top of the subgrade is less than a critical (permissible) value, then surface rutting will be within tolerable limits for a specified number of 18-kip EAL applications. The relationship between the number of load applications and permissible subgrade compressive strain shown in Figure 16 was originally developed by Monismith and McLean (26) and is in good agreement with other results (13). Table 2 also summarizes the limiting vertical subgrade compressive strains used to develop the thickness equivalency charts presented in this report.

PROCEDURE USED FOR CONSTRUCTING
THICKNESS EQUIVALENCY CHARTS

Step A - The CHEV 5L computer program was run with 720 different modulus and thickness data combinations to calculate tensile strains at the bottom of the bituminous concrete surface layer and compressive strains at the top of the subgrade for each of the two standard pavement designs shown in Figure 2. These pavements are assumed to have layer properties as summarized in Table 1 and permissible tensile and compressive strains as listed in Table 2.
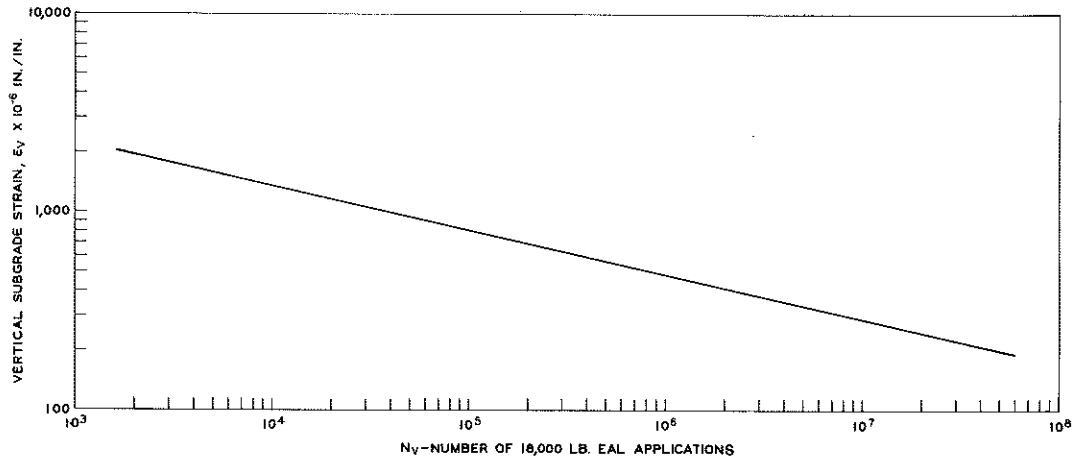
Figure 16. Subgrade strain criteria.

Step B - The results of the computer runs were summarized as strain-modulus curves which relate key permissible tensile and compressive strains to the full range of layer modulus values. Seventy-two sets of curves were drawn, two typical sets of which are presented in the Appendix; the others are available in the investigator's files. Of the 70 sets of curves, 31 sets showed the strain developed in the pavement system to be far below the permissible strains; these are being preserved for a future study.

Step C - The permissible strain values presented in Table 2 are plotted on the strain-modulus curves (Appendix Figs. 1A and 2A are examples). The intersection of permissible strain with the desired base thickness, h_2, will give the base modulus, E_2, required to carry, without failure, the number of 18-kip EAL indicated. As an example, Appendix Figure 1A shows that, for the pavement and loading system in the figure, a 6-in. base would need to have a modulus E_2 of 21,600 psi for 500,000 load repetitions or 26,000 psi for 1,000,000 load repetitions to enable it to carry the loading shown without failure.

Step D - The base modulus E_2 for each corresponding h_2 obtained from the strain-modulus curves are replotted (Figs. 17 through 28) with the base modulus, E_2, as the ordinate and the base thickness, h_2, as the abscissa for each bituminous concrete modulus listed in Table 2 and for each of the two standard pavement cross-sections shown in Figure 2. The curves in Figures 17 through 28, also identified as the thickness equivalency curves, define the relationship between E_2 and h_2 necessary to obtain optimum pavement performance.
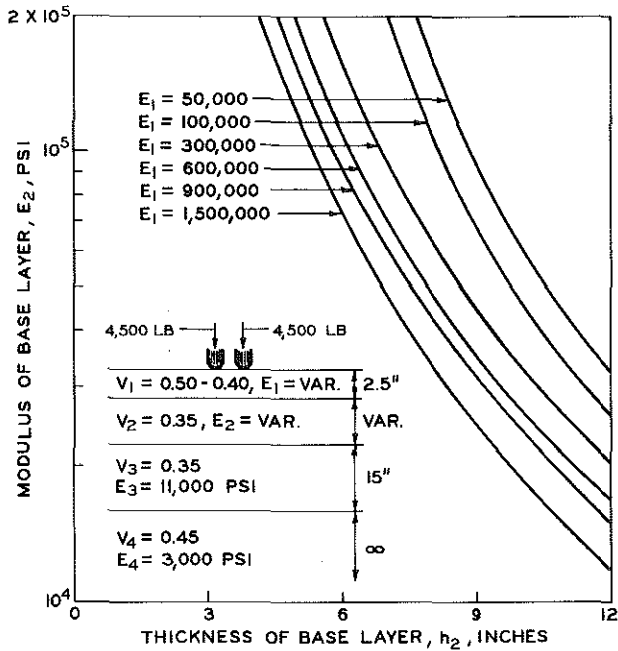
Figure 17. Thickness equivalency chart, loading = 500,000, 18 kip EAL repetitions.
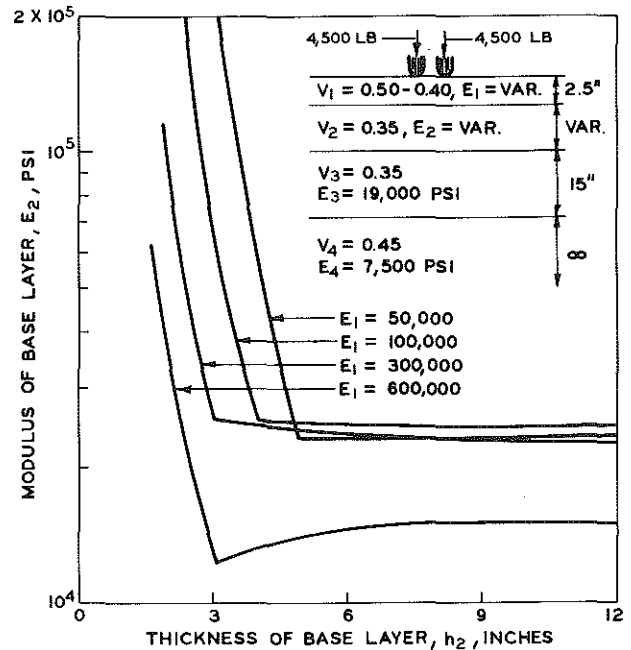
Figure 18. Thickness equivalency chart, loading = 500,000, 18 kip EAL repetitions.

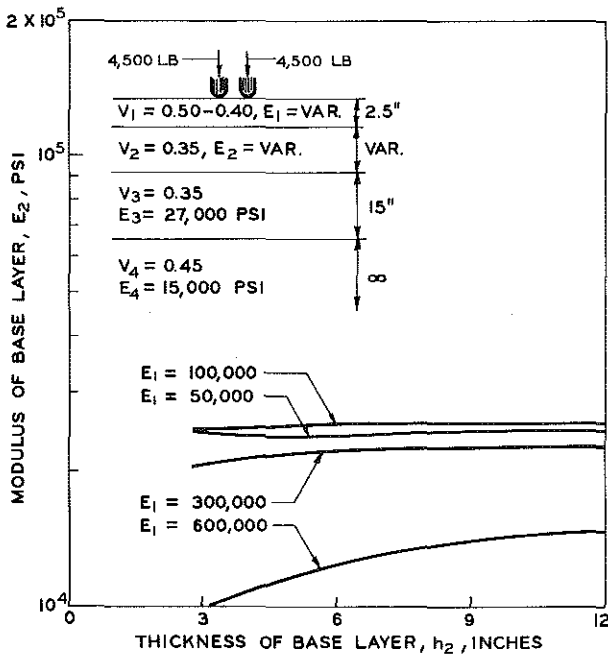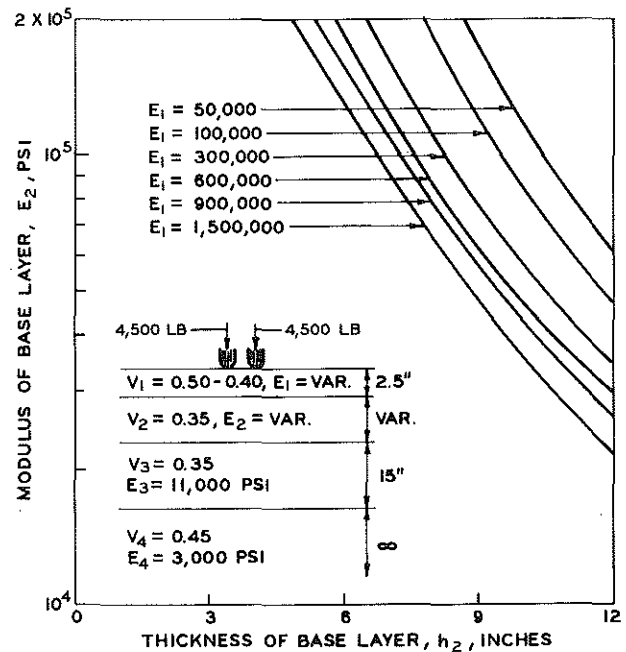Figure 19. Thickness equivalency chart, loading = 500,000, 18 kip EAL repetitions.

Figure 20. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.

Figure 22. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.
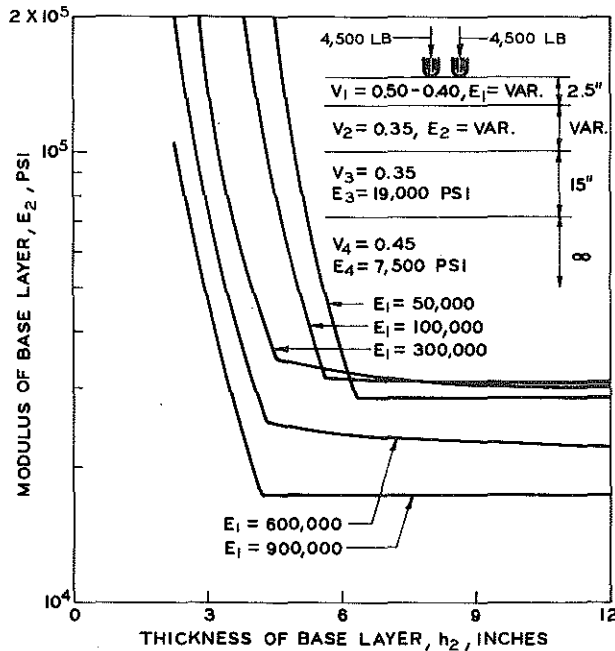
Figure 21. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.

Figure 23. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.

Figure 24. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.

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Figure 25. Thickness equivalency chart, loading = 1,000,000, 18 kip EAL repetitions.

Figure 26. Thickness equivalency chart, loading = 2,000,000, 18 kip EAL repetitions.

Figure 27. Thickness equivalency chart, loading = 2,000,000, 18 kip EAL repetitions.

Figure 28. Thickness equivalency chart, loading = 2,000,000, 18 kip EAL repetitions.
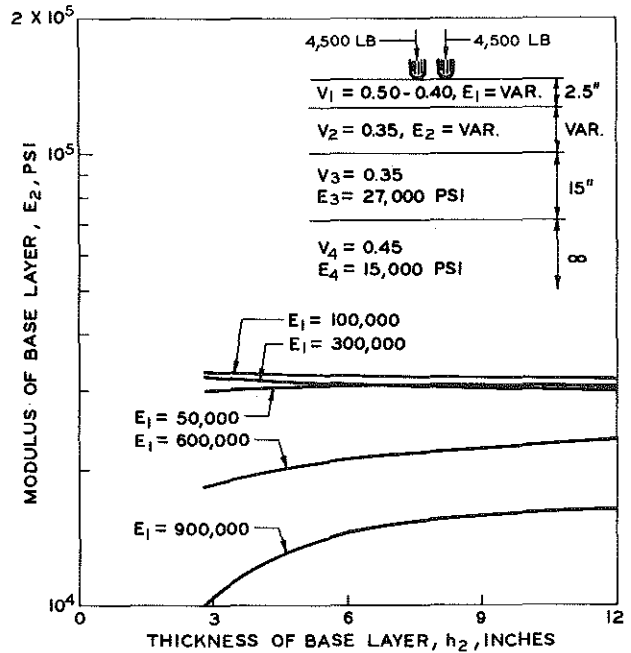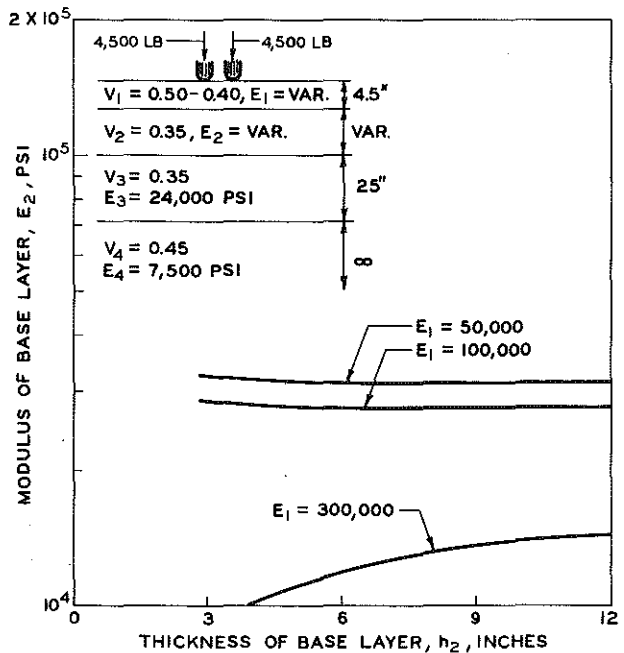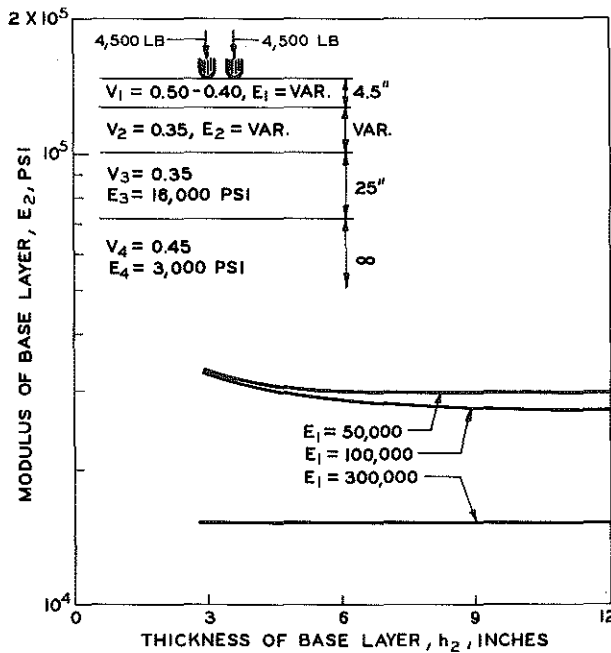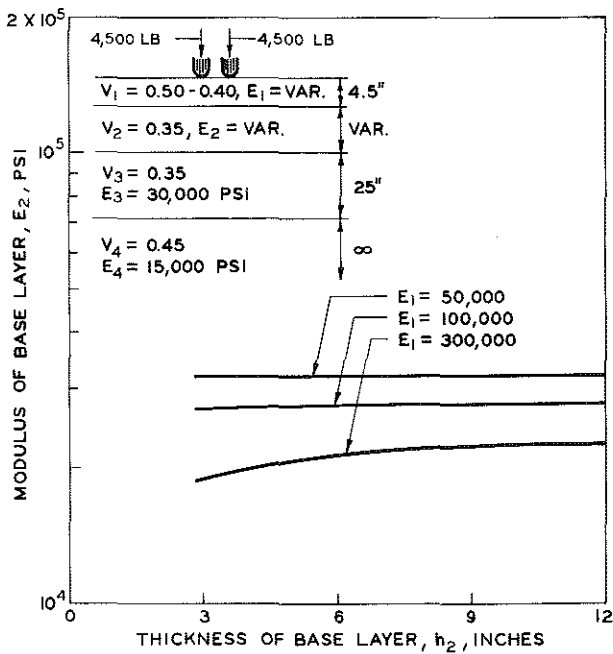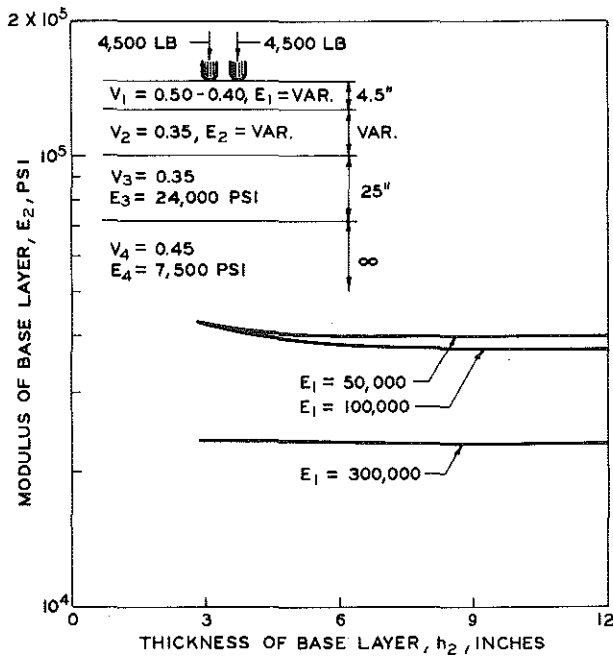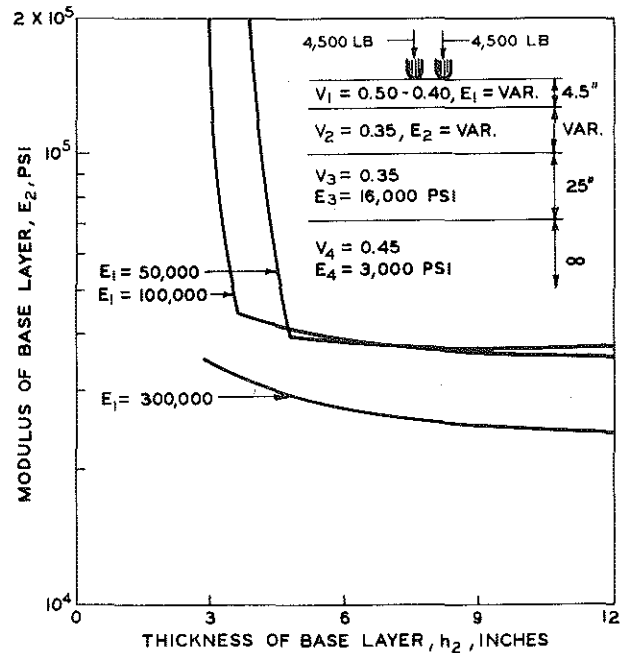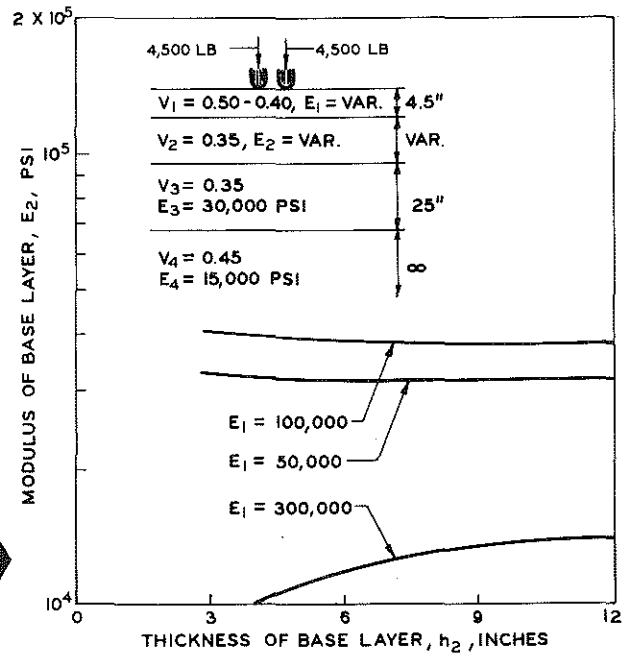
INTERPRETING THE THICKNESS EQUIVALENCY CHARTS

The steep curves seen in Figures 17 and 20 indicate that base thickness equivalency is dependent on the subgrade compressive strain, i.e., base thickness is needed to prevent or minimize pavement surface rutting. The flat curves seen in Figures 19, 22, 23, 24, 25, 27, and 28 indicate that base thickness equivalency is dependent on the asphaltic tensile strain, i.e., base thickness is needed to prevent or minimize pavement surface cracking. Other figures having a combination of steep and flat curves indicate that both compressive and tensile strains influence pavement performance.

As a specific example: Figures 19, and 22 to 28 indicate that when the pavement's subgrade modulus is over 15,000 psi or the bituminous concrete thickness is over 4.5 in., tensile strain controls, i.e., failure would be in the form of fatigue cracking. For the pavement systems in this study, a 3-in. granular base is adequate and a black base is not needed. Increasing base thickness over 3 in. has virtually no effect on improving performance. However, when the subgrade modulus value is less than 15,000 psi, increasing the base thickness to over 3 in. may be necessary to prevent subgrade failure. When the required base thickness is greater than 3 in., black bases may have economic benefits. In Michigan, where firm subgrades predominate, pavement analysis using the procedures described here is necessary to determine where the use of black bases would result in improved performance.

Application of Thickness Equivalency Charts

The thickness equivalency curves (Figs. 17 through 28) developed in this study make possible the design of base layer thickness for any material whose modulus, E_2, is known or can be reasonably estimated. The thickness equivalency curves can also be used to determine the thickness of asphalt-treated black base needed to replace standard thicknesses of granular base material. A sample application is given below.

A standard Michigan flexible pavement consists of a 2.5-in. bituminous concrete surface and a 15-in. subbase. If this pavement is constructed on a sandy subgrade, and is to be designed to carry a traffic loading of one million (1×10^6) 18-kip EAL applications over the life of the pavement, what is the required granular base thickness? Assume, on the basis of Figure 3, the bituminous concrete modulus to be 300,000 psi for 72 F design temperature and the subgrade modulus to be 7,500 psi. If asphalt-treated black base is to be used in place of standard granular base, what is its required thickness? Assume the elastic modulus of black base to be 100,000 psi at 72 F design temperature.

The solution to the first part of the problem is as follows:

Step A - Dividing the subbase into sublayers and using Eq. (2) or Figure 5, the average subbase modulus, E_3, is 19,000 psi when the subgrade modulus, E_4, is 7,500 psi.

Step B - Select the thickness of the base layer from Figure 21 using the curve for E_1 = 300,000 psi. If h_2 = 4 in. is selected, a stiffness E_2 of 49,000 psi is required.

Step C - Using Figure 4, with E_3 = 19,000 psi, E_2 can only reach 36,500 psi which is well below the required 49,000 psi for h_2 = 4 in. Thus, an h_2 of 4 in. will not be thick enough to carry the one million 18-kip axle load. Try h_2 = 4.4 in. and use Figure 21 again; now the required E_2, from Figure 21, is 36,500 psi. Going back to Figure 4, still using E_3 = 19,000 psi but with h_2 = 4.4 in., E_2 = 36,500 psi, meeting the required modulus value. Therefore, h_2 = 4.4 in. is an adequate thickness of granular base for this pavement system. The granular base thickness of 4.4 in. in this example is controlled by subgrade compressive strain, i.e., pavement surface rutting.

The solution to the second part of the problem is obtained by following the concepts described in the section on "Asphalt-Treated Material (Black Base)."

Step D - Assume the black base will not crack. Then, from Figure 21, with black base modulus = 100,000 psi, a 3.3-in. black base is adequate. However, the horizontal tensile strain, ε_{tB} at the bottom of a 3.3-in. black base layer with the given loading and pavement conditions, is computed by CHEV 5L to be 3.97×10^{-4} in./in.

From Figure 15 (black base fatigue curves), for ε_{tB} = 3.97×10^{-4} in./in., the number of load repetitions, N_{cB}, to failure is 1.5×10^5. This means that 150,000 repetitions of 18-kip EAL will crack the black base. Also, at the end of 150,000 load repetitions, a cumulative damage, DF, to the top of the subgrade is

$$DF = \frac{1.5 \times 10^5}{10^6} = 0.15, \quad \text{on the basis of Miner's hypothesis of damage fatigue.}$$

Once the black base has cracked, it is necessary to determine how many more load repetitions will be needed to either crack the bituminous concrete surface or fail the subgrade.

Step E - Determine the black base cracked section modulus, E_{2c}, from laboratory tests. In this example, the cracked section modulus is assumed to be 60,000 psi. The maximum compressive strain, ε_v, at the top of the subgrade is then computed by CHEV 5L as 5.05×10^{-4} in./in.

From Figure 16, for $\varepsilon_v = 5.05 \times 10^{-4}$ in./in. N_v is 8.2×10^5 repetitions. However, the cumulative damage to the subgrade is DF = 0.15 or 1.5×10^5 repetitions. Thus, the actual load repetitions the pavement can withstand after the black base cracks is 820,000 x (1 - DF) = 697,000.

The total of load repetitions to failure for this pavement system is the sum of the load repetitions before and after cracking of black base, i.e., $1.5 \times 10^5 + 6.97 \times 10^5 = 8.47 \times 10^5$, failure occurring before the design load of one million (10^6) repetitions is reached. Therefore, a thicker black base is needed.

Step F - Following the procedure outlined above and increasing a black base thickness to 3.8 in. the following results are obtained:

$$\varepsilon_{tB} = 3.75 \times 10^4 \text{ in./in.}$$

$$N_{cB} = 1.8 \times 10^5$$

$$DF = 0.18$$

$$\varepsilon_v = 4.81 \times 10^{-4} \text{ in./in.}$$

$$N_v = 10^6$$

10^6 load repetitions are needed to cause subgrade failure. Therefore, a 3.8-in. black base is equivalent to a 4.4-in. unbound granular base.

Step G - A check of tensile cracking of the bituminous concrete layer is not necessary since, with the subgrade modulus less than 15,000 psi and the bituminous concrete thickness less than 4.5 in., the pavement system is controlled by compressive strain, according to the criteria on page 20. However, it is interesting to note how many load repetitions are needed to crack the bituminous concrete after the 3.8-in. black base cracks. The maximum tensile strain, ε_t, at the bottom of the bituminous concrete is computed to be 2.43×10^{-4} in./in. From Figure 14, for $E_1 = 300,000$ psi, N_c is 3.2×10^6. Thus, the total number of load repetitions needed to crack the bituminous concrete surface layer is $3.2 \times 10^6 + 1.5 \times 10^5 = 3.35 \times 10^6$, which is considerably more than the repetitions of traffic load needed to cause rutting failure.

One other method of increasing pavement life without increasing black base thickness is to improve black base quality, i.e., to increase the asphalt content and reduce the air void volume in the black base so that it will

sustain a greater number of load repetitions without failing. The limits will need to be determined by laboratory and field testing.

PAVEMENT DESIGN ALTERNATIVES, SAMPLE APPLICATION

The method presented can also be applied to the design of flexible pavements where a portion of granular base is replaced by black base such that no loss in predicted performance occurs. The basic model becomes a five-layer system instead of a four-layer system. The pavement system and material properties presented in this sample problem are similar to the previous problem except that subgrade moduli of 3,000 psi and 7,500 psi are used.

As in the previous problem, the maximum tensile strains at the bottom of the black base and compressive strains at the top of the subgrade were calculated using the CHEV 5L computer program. From these strain data, Figures 29 through 32 were developed to show the relationship between granular base and black base thickness for a given tensile or compressive strain. Note that the compressive strains are computed in the first sample problem and the information provided by Figures 29 through 32. The thickness relationship between granular base and black base was developed and is summarized in Figure 33 (solid line). The dashed lines, also shown in Figure 33, are results obtained by assuming that the black base will not crack before failure by surface rutting.

The four hypothetical design alternatives summarized in Tables 3 and 4 show that there is little reduction in total base thickness as black base is used to replace granular base. For example, Table 3 shows that 3 in. of black base replaces 3.3 in. of granular base, and 5 in. of black base replaces 5.6 in. of granular base. The 11.8 in. granular base can be replaced by 9.8 in. of black base. For subgrade modulus, $E_5 = 7,500$ psi in Table 4, the equivalency of 3.8 in. of black base to 4.4 in. of granular base has the same solution as was illustrated in the previous example. Figure 33 can be used to determine any combination of granular base and black base thickness when the design load is one million 18-kip EAL and the pavement cross-section and material properties are as shown in the figure.

Development of a series of figures similar to Figure 33 for pavement cross-sections normally encountered in Michigan is suggested. They should cover the full range of bituminous concrete and subgrade moduli, layer thickness, and design range of 18-kip EAL repetitions normally considered for Michigan pavements.
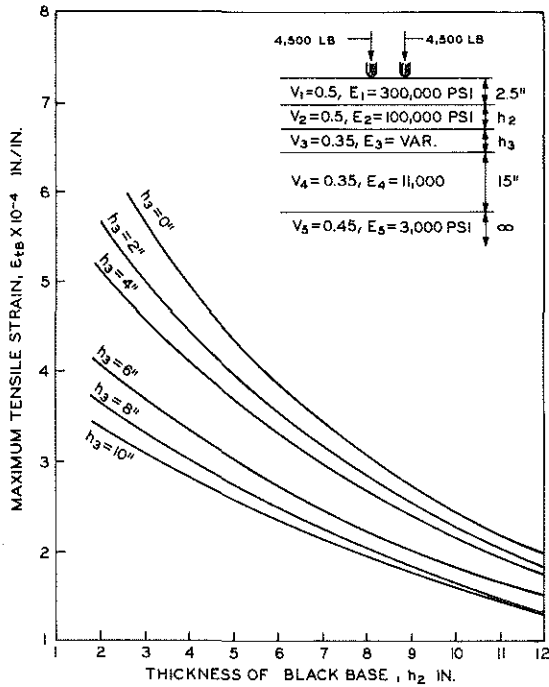
Figure 29. Tensile strain at the bottom of black base as a function of black base thickness, h_2, and granular base thickness, h_3.
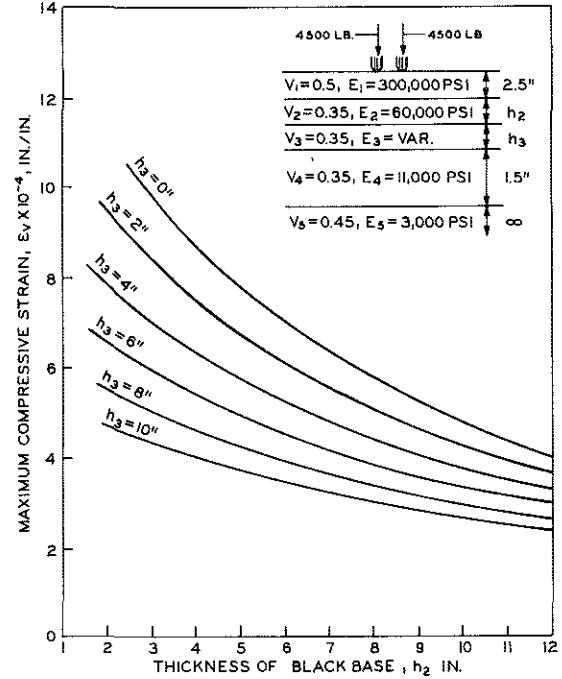
4,500 LB — 4,500 LB

$V_1 = 0.5$, $E_1 = 300,000$ PSI — 2.5"
$V_2 = 0.5$, $E_2 = 100,000$ PSI — h_2
$V_3 = 0.35$, $E_3 = $ VAR. — h_3
$V_4 = 0.35$, $E_4 = 11,000$ — 15"
$V_5 = 0.45$, $E_5 = 3,000$ PSI — ∞

$h_3 = 0"$
$h_3 = 2"$
$h_3 = 4"$
$h_3 = 6"$
$h_3 = 8"$
$h_3 = 10"$

MAXIMUM TENSILE STRAIN, $\varepsilon_{tB} \times 10^{-4}$ IN./IN.

THICKNESS OF BLACK BASE, h_2 IN.

Figure 30. Compressive strain at the top of the subgrade as a function of black base thickness, h_2, and granular base thickness, h_3.

4500 LB. — 4500 LB.

$V_1 = 0.5$, $E_1 = 300,000$ PSI — 2.5"
$V_2 = 0.35$, $E_2 = 60,000$ PSI — h_2
$V_3 = 0.35$, $E_3 = $ VAR. — h_3
$V_4 = 0.35$, $E_4 = 11,000$ PSI — 1.5"
$V_5 = 0.45$, $E_5 = 3,000$ PSI — ∞

$h_3 = 0"$
$h_3 = 2"$
$h_3 = 4"$
$h_3 = 6"$
$h_3 = 8"$
$h_3 = 10"$

MAXIMUM COMPRESSIVE STRAIN, $\varepsilon_V \times 10^{-4}$, IN./IN.

THICKNESS OF BLACK BASE, h_2 IN.

Figure 31. Tensile strain at the bottom of black base as a function of black base thickness, h , and granular base thickness, h .

4500 LB — 4500 LB
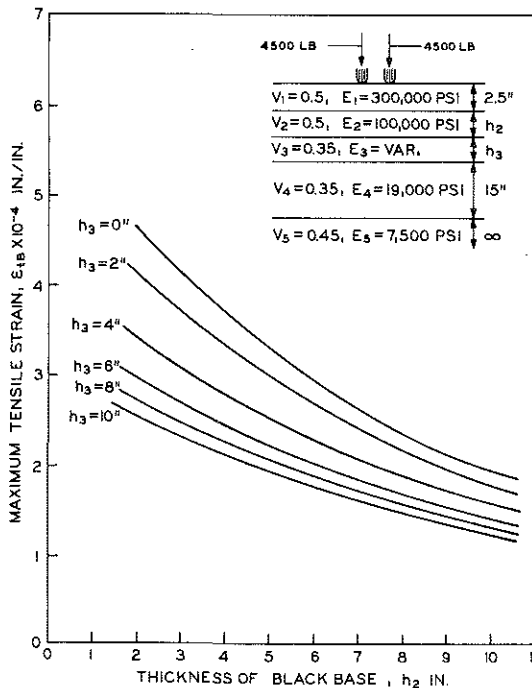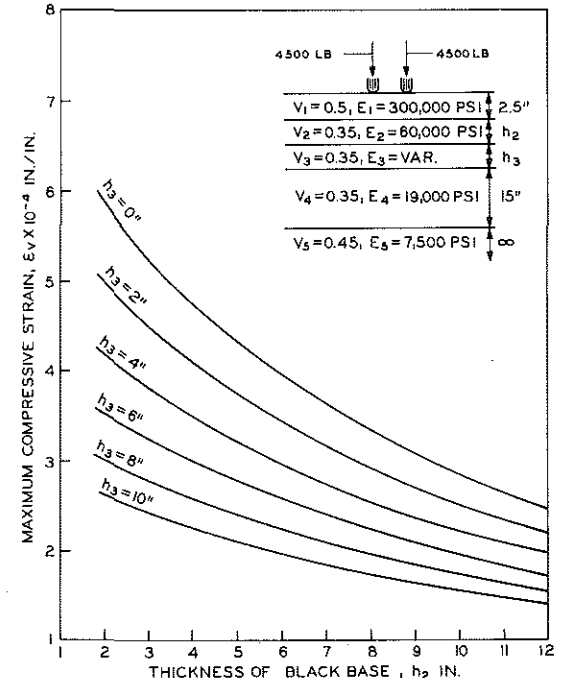
$V_1 = 0.5$, $E_1 = 300,000$ PSI — 2.5"
$V_2 = 0.5$, $E_2 = 100,000$ PSI — h_2
$V_3 = 0.35$, $E_3 = $ VAR. — h_3
$V_4 = 0.35$, $E_4 = 19,000$ PSI — 15"
$V_5 = 0.45$, $E_5 = 7,500$ PSI — ∞

$h_3 = 0"$
$h_3 = 2"$
$h_3 = 4"$
$h_3 = 6"$
$h_3 = 8"$
$h_3 = 10"$

MAXIMUM TENSILE STRAIN, $\varepsilon_{tB} \times 10^{-4}$ IN./IN.

THICKNESS OF BLACK BASE, h_2 IN.

Figure 32. Compressive strain at the top of the subgrade as a function of black base thickness, h_2, and granular base thickness, h_3.

4500 LB — 4500 LB

$V_1 = 0.5$, $E_1 = 300,000$ PSI — 2.5"
$V_2 = 0.35$, $E_2 = 60,000$ PSI — h_2
$V_3 = 0.35$, $E_3 = $ VAR. — h_3
$V_4 = 0.35$, $E_4 = 19,000$ PSI — 15"
$V_5 = 0.45$, $E_5 = 7,500$ PSI — ∞

$h_3 = 0"$
$h_3 = 2"$
$h_3 = 4"$
$h_3 = 6"$
$h_3 = 8"$
$h_3 = 10"$

MAXIMUM COMPRESSIVE STRAIN, $\varepsilon_V \times 10^{-4}$ IN./IN.
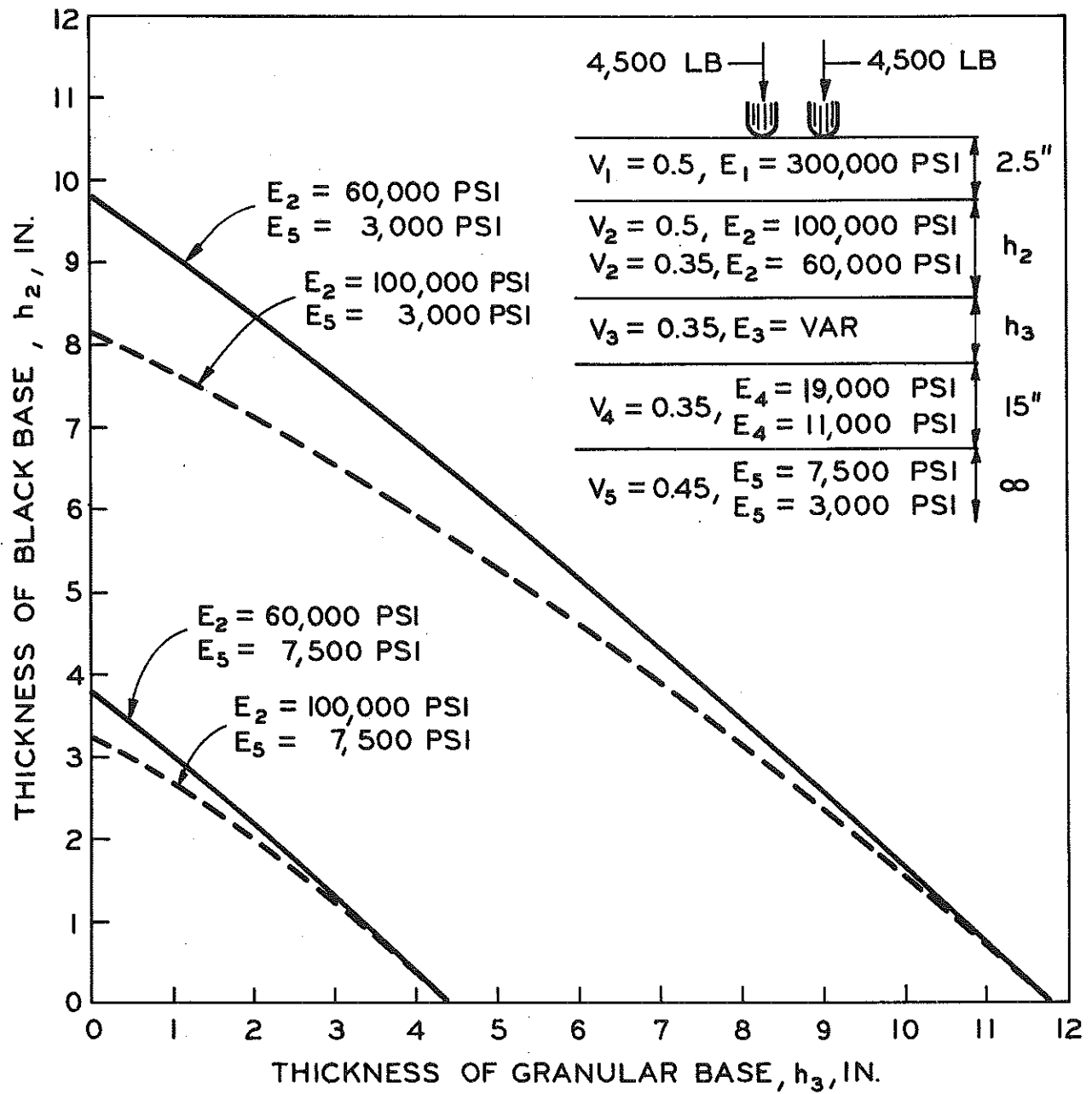
THICKNESS OF BLACK BASE, h_2 IN.

Figure 33. Design alternative curves for combination of black base, h_2, and granular base, h_3.

TABLE 3

DATA ILLUSTRATING USE OF DESIGN ALTERNATIVE CHART
(FIG. 33) FOR $E_5 = 3,000$ psi, 18-kip EAL $= 10^6$

Material	Design Alternatives			
	1	2	3	4
Thickness of bituminous concrete, in.	2.5	2.5	2.5	2.5
Thickness of black base, in.	---	3.0	5.0	9.8
Thickness of granular base, in.	11.8	8.5	6.2	---
Thickness of granular subbase, in.	15.0	15.0	15.0	15.0
Total Thickness, in.	29.3	29.0	28.7	27.3

TABLE 4

DATA ILLUSTRATING USE OF DESIGN ALTERNATIVE CHART
(FIG. 33) FOR $E_5 = 7,500$ psi, 18-kip EAL $= 10^6$

Material	Design Alternatives			
	1	2	3	4
Thickness of bituminous concrete, in.	2.5	2.5	2.5	2.5
Thickness of black base, in.	---	1.0	2.1	3.8
Thickness of granular base, in.	4.4	3.4	2.1	---
Thickness of granular subbase, in.	15.0	15.0	15.0	15.0
Total Thickness, in.	21.9	21.9	21.7	21.3

SUMMARY AND CONCLUSIONS

Summary

1) The elastic layer theory and two limiting strains, the horizontal tensile strain at the bottom of any asphaltic layer and the vertical compressive strain at the top of the subgrade, are used to establish 'thickness equivalency' charts and 'design alternatives.' Chevron's CHEV 5L computer program was used to calculate the critical strains.

2) Determination of appropriate modulus values for bituminous concrete and subgrade soils is discussed. Asphalt-treated black base and bituminous concrete are considered to have similar stiffness, although different fatigue properties. The modulus of base or subbase materials is determined from subgrade modulus by means of stress-dependent principles first reported by Izatt, Lettier, and Taylor (12).

3) Santucci (22) established the fatigue characteristics of bituminous concrete, of a given mix design, on the basis of controlled stress laboratory tests. Santucci's fatigue data were modified to make them compatible with Michigan's mix designs, adapting the equations developed by Pell and Cooper (24) and Epps (25).

4) The subgrade compressive strain criterion (Fig. 15) originally developed by Monismith and McLean (26) was chosen for this study, because it demonstrated good agreement with other results.

5) The thickness equivalency charts were developed on the basis of a design load carrying capacity of 5×10^5, 1×10^6, and 2×10^6 18-kip EAL.

6) Design alternative curves were also developed to illustrate the thickness interchanges possible between granular base and black base for equivalent pavement performance.

7) The design alternative curves shown in Figure 33 are based on a assumption of a 60,000 psi black base cracked section modulus. A limited number of black base samples could be tested in the laboratory to verify this value.

Conclusions

The following conclusions are restricted to the loading and the range of cross-sections, moduli, load repetitions and other materials characteristics assumed in this study. The effects of environmental factors such as frost heave, thermal cracking, etc., are not taken into account.

1) Thickness equivalency charts, Figures 17 through 28, developed in this study for two standard Michigan flexible pavement sections, can be used for thickness design of the base layer.

2) From the thickness equivalency charts developed in this study, it can be inferred that a black base is not needed for the pavement sections where the subgrade modulus is over 15,000 psi or the bituminous concrete thickness is over 4.5 in. and that a granular base thickness of more than 3 in. will not significantly improve pavement performance.

3) The thickness equivalency charts presented, Figures 17 through 28, indicate that the base thickness used for Michigan standard designs are much thicker than needed for pavements expected to carry two million (2×10^6) 18-kip equivalent axle loads or less.

4) The principles used to develop the thickness equivalency charts can also be used to develop alternative design charts for determining the thickness relationship between granular base and black base for equivalent pavement performance. Any combination of granular base and black base thicknesses can be selected from such design alternative charts.

5) For Michigan standard pavement sections, if the analysis shows that a given black base has little or no thickness advantage over granular bases, it is possible to make an 'equivalent' but thinner black base by increasing the asphalt content and reducing the air void volume.

6) This study has yielded considerable groundwork which is readily applicable to future investigations in the design and performance of black base for pavement sections in which the subgrade is weak, or in which the subbase layer is omitted.

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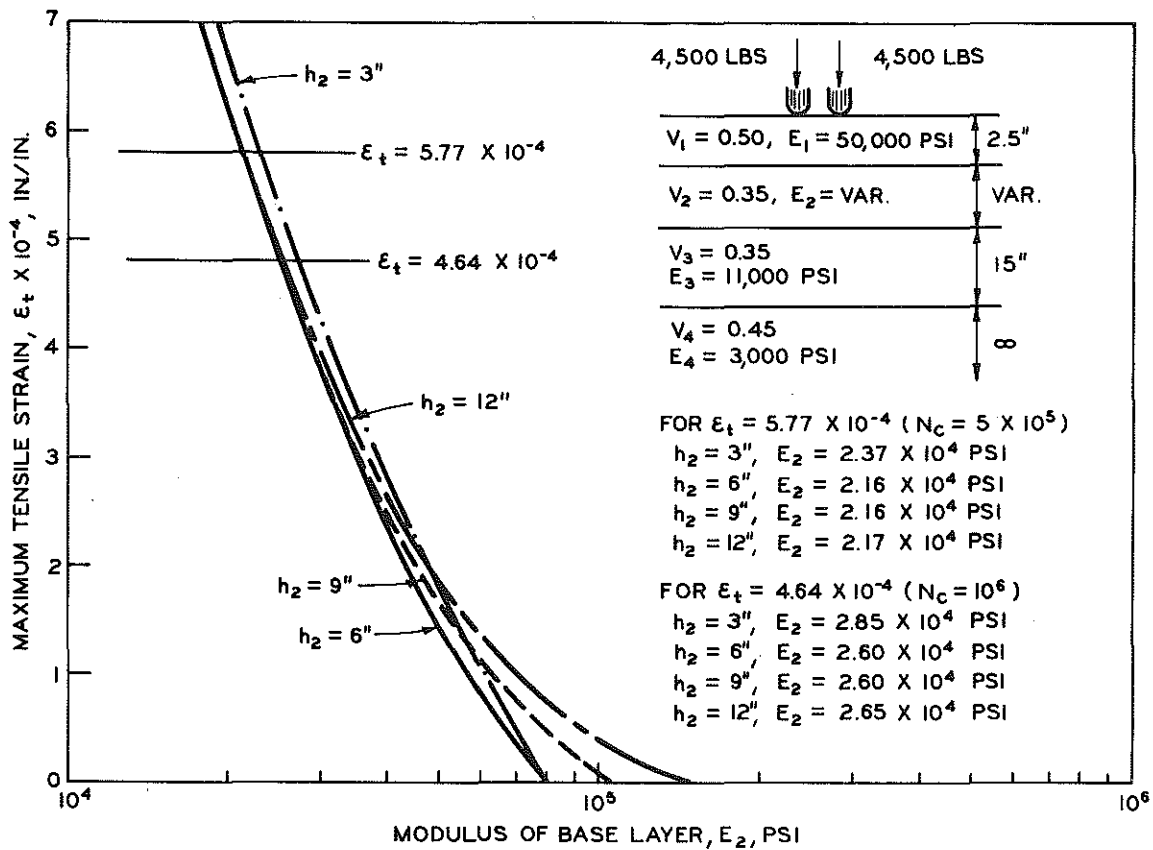
APPENDIX

Figure 1A. Tensile strain at the bottom of bituminous concrete as a function of E_2 and h_2.
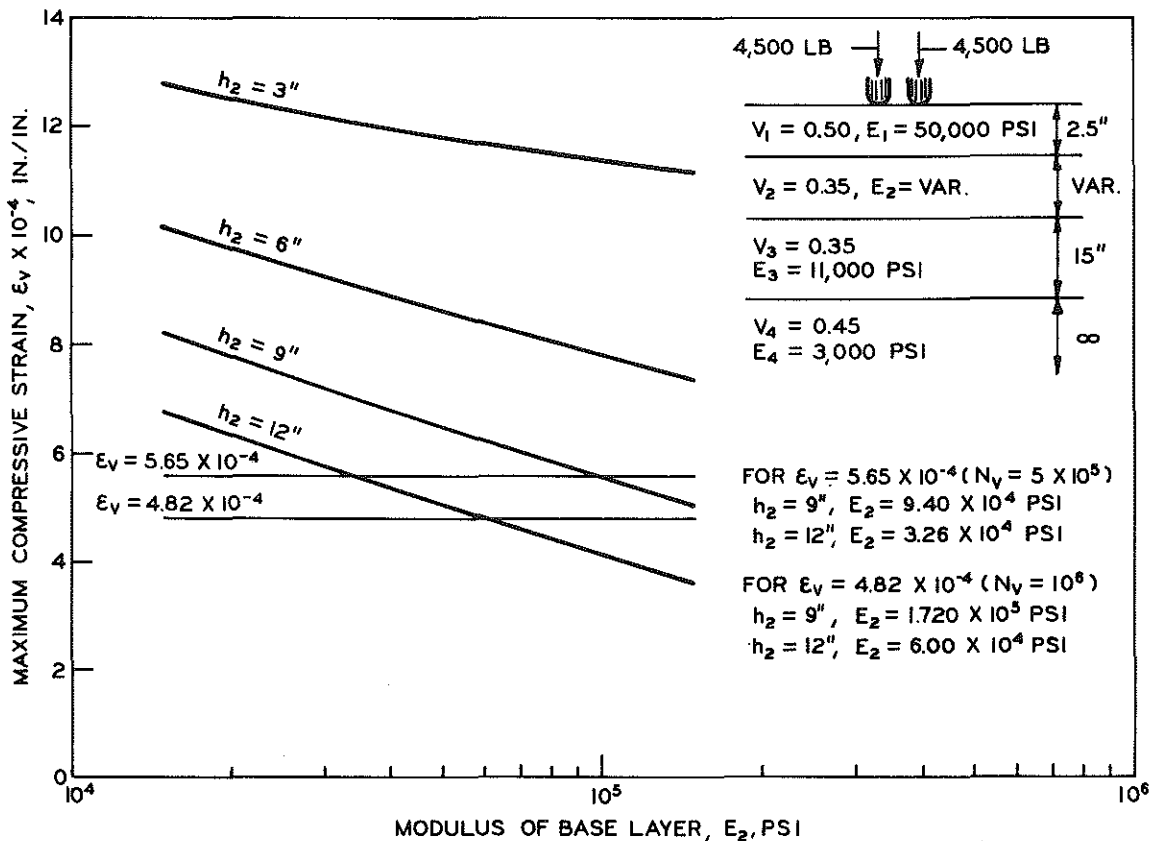

Figure 2A. Compressive strain at the top of the subgrade as a function of E_2 and h_2.