A COMPREHENSIVE STRUCTURAL DESIGN FOR STABILIZED PAVEMENT LAYERS

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Evaluation of Tensile Properties of Subbases
for Use in New Rigid Pavement Design

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PREFACE

This is the thirteenth report in a series dealing with research findings concerned with the evaluation of the properties of stabilized subbase materials. This report describes a design system for the structural design of stabilized pavement layers.

This report is a product of the combined efforts of many individuals. The assistance of the Texas Highway Department contact representative Mr. Larry Buttler is gratefully appreciated and the support of the Federal Highway Administration, Department of Transportation, is acknowledged.

The assistance of the staff of the Center for Highway Research is appreciated. Special appreciation is due to Messrs Pat Hardeman, James N. Anagnos, and Harold Dalrymple and Dr. Raymond K. Moore for their suggestions and help in development of testing apparatus and techniques required in evaluation of stabilized materials. The authors are also thankful to Stanley Stokes and Thomas Nash for their help in completing the various computer analyses. The assistance of Professor Jimmy Holmes, who prepared the graphics portion of the report, is also acknowledged.

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LIST OF REPORTS

Report No. 98-1, "An Indirect Tensile Test for Stabilized Materials," by W. Ronald Hudson and Thomas W. Kennedy, summarizes current knowledge of the indirect tensile test, reports findings of limited evaluation of the test, and describes the equipment and testing techniques developed.

Report No. 98-2, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, discusses factors important in determining the tensile strength of asphalt-treated materials and reports findings of an evaluation of eight of these factors.

Report No. 98-3, "Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials," by Humberto J. Pendola, Thomas W. Kennedy, and W. Ronald Hudson, presents factors important in determining the strength of cement-treated materials and reports findings of an evaluation by indirect tensile test of nine factors thought to affect the tensile properties of cement-treated materials.

Report No. 98-4, "Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials," by S. Paul Miller, Thomas W. Kennedy, and W. Ronald Hudson, presents factors important in determining the strength of cement-treated materials and reports findings of an evaluation by indirect tensile test of eight factors thought to affect the tensile properties of lime-treated materials.

Report No. 98-5, "Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials," by Walter S. Tulloch, II, W. Ronald Hudson, and Thomas W. Kennedy, presents a detailed investigation by indirect tensile test of five factors thought to affect the tensile properties of lime-treated materials and reports findings of an investigation of the correlation between the indirect tensile test and standard Texas Highway Department tests for lime-treated materials.

Report No. 98-6, "Correlation of Tensile Properties with Stability and Cohesiometer Values for Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents a detailed correlation of indirect tensile test parameters, i.e., strength, modulus of elasticity, Poisson's ratio, and failure strain, with stability and cohesiometer values for asphalt-treated materials.

Report No. 98-7, "A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents the development of equations for estimating material properties such as modulus of elasticity, Poisson's ratio, and tensile strain based upon the theory of the indirect tensile test and reports verification of the equations for aluminum.

Report No. 98-8, "Evaluation and Prediction of Tensile Properties of Cement-Treated Materials," by James N. Anagnos, Thomas W. Kennedy, and W. Ronald Hudson, investigates, by indirect tensile test, six factors affecting the tensile properties of cement-treated materials, and reports the findings of an investigation of the correlation between indirect tensile strength and standard Texas Highway Department tests for cement-treated materials.

Report No. 98-9, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, presents a detailed investigation by indirect tensile test of seven factors thought to affect the tensile properties of asphalt-treated materials and reports findings which indicate the important factors affecting each of the tensile properties and regression equations for estimation of the tensile properties.

Report No. 98-10, "Practical Method of Conducting the Indirect Tensile Test," by James N. Anagnos and Thomas W. Kennedy, describes equipment and test procedures involved in conducting the indirect tensile test along with a method of analyzing the test results.

Report No. 98-12, "Tensile Behavior of Stabilized Subbase Materials Under Repetitive Loading," by Raymond K. Moore and Thomas W. Kennedy, summarizes the findings of an investigation of the fatigue properties of asphalt-treated, cement-treated, and lime-treated materials subjected to repeated tensile stresses using the indirect tensile test.

Report No. 98-13, "A Comprehensive Structural Design for Stabilized Pavement Layers," by William O. Hadley, W. Ronald Hudson, and Thomas W. Kennedy, describes a design method which can be used for the structural design of stabilized pavement layers and which is based on the prevention of tensile failures in the surface and subbase layers of the pavement.

ABSTRACT

A system is presented which can be used for the structural design of stabilized pavement layers. The basis for the system is primarily the prevention of tensile failures in the surface and subbase layers of a three-layer pavement structure and can be applied to take full advantage of those highway materials which possess cohesion, or tensile strength.

The design system is composed of a series of design equations and several techniques for characterizing the properties of the materials proposed for use in the pavement layers. Linear elastic layered theory was used in the development of design equations for computing

(1) tensile stress in the surface layer,
(2) tensile strain in the surface layer,
(3) tensile stress in the subbase layer,
(4) tensile strain in the subbase layer, and
(5) compressive strain in the subgrade.

Separate equations were developed for the design of high modulus portland cement concrete rigid pavements (the modulus of elasticity of the surface layer exceeds 3.5×10^6 psi) and for the design of flexible pavements and low modulus portland cement concrete pavements (the modulus of elasticity of the surface layer is less than 3.5×10^6 psi). Procedures for proper application of the design equations are presented and include a method for selection of a critical design thickness and practical solutions of the design equations through the use of nomographs.

Characterization techniques are also provided for estimating material properties as well as limiting design criteria for the materials proposed for the various pavement layers. Based on the results of laboratory tests, the indirect tensile test is recommended as the principal method of characterizing the highway materials in the laboratory. Also, a technique is presented for estimating the design-stress criteria, based on indirect tensile test results and repeated loading considerations. In addition, minimum design-strain criteria are recommended for various cohesive highway materials. A special

characterization technique is provided for the design of asphaltic materials for winter and summer temperature conditions.

The application of the total design system to the structural design of various types of subbase layers is illustrated in three example problems.

The design system presented here is based on a practical interpretation of layered theory which emphasizes the contribution of each individual layer to the behavior of the total pavement structure. The system, because of its dependence on layered theory, is subject to validation through field observations. It can be corrected and updated by comparing designs based on the method against observed pavement performance.

KEY WORDS: design, subbase, layered theory, tensile stress criteria, tensile strain criteria, modulus of elasticity, portland cement concrete, asphalt-treated materials, cement-treated materials, lime-treated materials, indirect tensile test, repeated loading, test temperature, loading rate, system, regression equations, nomographs.

SUMMARY

This report presents a system for use in the structural design of stabilized pavement layers. The thickness requirements provided by this system are not intended to supersede established requirements, such as those resulting from expected depth of frost penetration, which may require a thicker layer.

The basis for the design system is the prevention of tensile failures in the surface and subbase layers of a pavement structure involving one or more layers of stabilized materials and is composed of a series of design equations as well as techniques for characterizing the properties of the materials proposed for use in the various pavement layers.

The system involves a practical interpretation of layered theory which emphasizes the contribution of each layer to the behavior of the total pavement structure. The new system, because of its dependence on layered theory, requires verification through trial use and field observation. This theoretical design system, however, offers the basis for correcting and updating by comparing designs based on the theoretical equations against observed pavement performance.

Layered theory was used in the development of design equations for

(1) tensile stress in the surface layer,
(2) tensile strain in the surface layer,
(3) tensile stress in the subbase layer,
(4) tensile strain in the subbase layer, and
(5) compressive strain in the subgrade layer.

Separate equations were developed for the design of high modulus portland cement concrete rigid pavements (the modulus of elasticity of the surface layer exceeds 3.5×10^6 psi) and for the design of flexible pavements and low modulus portland cement concrete pavements (the modulus of elasticity of the surface layer is less than 3.5×10^6 psi). Procedures for proper application of these

design equations were developed and include a method for selection of a critical design thickness and practical solutions of the design equations through the use of nomographs.

Characterization techniques were developed also, to provide necessary estimates of material properties as well as limiting design criteria for the materials proposed for the various pavement layers. The indirect tensile test is recommended as the principal method of characterizing the highway materials in the laboratory, and a special characterization technique was developed to allow for the design of asphaltic materials for summer and winter temperature conditions.

The application of the total design system to the structural design of various types of stabilized subbase layers is illustrated in three example problems.

IMPLEMENTATION STATEMENT

The design system presented here can be used by state highway departments and other agencies for the structural design of various cohesive highway materials. The design equations included in the report can be solved utilizing a computer, and when cost functions are introduced, the most economical design section can be obtained using optimization techniques. Agencies with access to computer facilities have the greatest capability for the continuing correction and updating of the design system based on long term observation of pavement performance.

The practical solutions of the design equations can be obtained in the nomographs used for design purposes by agencies which do not have access to computer facilities. For example, city and county traffic departments can make use of the nomographs for the design of facilities which are expected to have high truck traffic.

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CHAPTER 1. INTRODUCTION

In recent years there has been an increase in the use of pavements involving one or more layers of stabilized materials. Most pavement design methods, unfortunately, do not provide adequate means for the structural design of stabilized layers, and, in fact, the choice of thicknesses of these layers in some methods is often influenced only by depth of frost penetration or some minimum thickness established from experience. The structural design of a subbase for a rigid pavement is based primarily on the improvement in the support value for the surface layer and generally does not consider the expected stresses and strains in either the subbase layer or subgrade. On the other hand, flexible pavement design procedures generally include some consideration of subbase strength characteristics but do not assess the contribution of each layer to the ability of the total pavement structure to withstand the expected traffic. For these pavements to be used effectively, there should be a design method which is based on fundamental considerations and emphasizes the contribution of each individual layer to the behavior of the total pavement structure.

The purpose of this study was to develop a design method for selecting the thickness of each layer in a pavement structure necessary to insure adequate tensile resistance to a large number of applications of vehicle loads. The system is, therefore, applicable to the design of cohesive pavement materials, i.e., those which have tensile strength.

The design system is composed of a series of design equations for a simulated three-layer pavement as well as techniques for characterizing the properties of materials proposed for the layers of the pavement structure. Layered theory* was used in the development of design equations which relate the tensile stresses and strains in the bottom fibers of the upper two layers and the vertical strain in the top of the subgrade layer to the moduli and thicknesses of the various pavement layers. Procedures for proper application

*For brevity, the notation layered theory is used throughout this document in place of the more complete description, linear elastic layered theory.

of these equations to the structural design of stabilized subbase layers were also developed, including a method of selection of design thickness and practical solutions of the equations through use of nomographs.

Since the design equations were based on linear elastic theory, characterization techniques were also developed to provide necessary estimates of material properties as well as limiting design criteria for each of the proposed materials in the three pavement layers. On the basis of a laboratory study, the indirect tensile test was recommended as the principal method of characterizing the highway materials in the laboratory. A technique was also proposed for estimating the design stress criteria, based on the material properties as determined in the indirect tensile test and repeated loading considerations. In addition, minimum design-strain criteria based on the results of various fatigue studies were recommended. Special material characterization techniques were developed to allow for the design of asphaltic materials for summer and winter temperature conditions.

The combination of the material characterization techniques with the series of design equations completes the design system and therefore provides the necessary vehicle for the structural design of various stabilized pavement layers. Three example problems are presented to illustrate the overall design approach. The examples include (1) the detailed structural design of an asphalt-stabilized subbase layer beneath a portland cement concrete surface layer, (2) the structural design of a cement-stabilized subbase layer for a rigid pavement structure, and (3) the design of an asphalt-stabilized base layer in a flexible pavement structure.

The advantages of such a design approach are many fold. The decision as to which pavement materials and stabilizer to use can then be made on a basis of the most economical design section. For instance, the stabilization of an existing good quality material can produce materials with better fundamental properties, possibly requiring a thinner, more economical pavement design section. In addition, for areas nearly void of good quality highway materials, comparison of costs should be made between

(1) design sections composed of stabilized layers of an in-place marginal material and

(2) design sections including pavement layers of imported, high-quality material.

Chapter 2 contains a brief summary of base and subbase requirements of the Texas Highway Department design methods as well as some other existing design methods and includes a discussion of available theoretical design concepts. Chapter 3 presents the proposed design system and includes a description of the technique used in the development of the series of design equations. Techniques for characterizing the properties of the materials in the various pavement layers are provided in Chapter 4. Examples of the use of the design system are included in Chapter 5, and the summary and recommendations for future improvements to the system are presented in Chapter 6.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

This chapter summarizes base and subbase requirements of the Texas Highway Department design methods as well as some other existing rigid and flexible pavement design methods. A discussion of some of the available theoretical design concepts is also included.

BASE AND SUBBASE REQUIREMENTS: TEXAS HIGHWAY DEPARTMENT DESIGN METHODS

The Texas Highway Department recommends subbase design requirements for rigid pavement structures based on the primary function of the subbase. If the subbase is to provide a working platform on which to construct the concrete slab, the design becomes simply a structural pavement design problem in which the traffic is the construction traffic. The Texas Triaxial method of design as recommended in Texas Test Method 117-E would be used to obtain a design subbase thickness. On the other hand, if the function of the subbase is to provide a reasonably permanent foundation for the concrete slab, a subbase thickness of 4 to 8 inches is recommended, with the top 4 inches stabilized with asphalt or cement to insure a nonpumping subbase. The thinner subbase layer, i.e., 4 inches, would normally be used in conjunction with a lime-stabilized subgrade material (Refs 2.9 and 2.9a).

The Texas Highway Department uses the Texas Triaxial design method (Refs 2.6 through 2.9a) for the structural design of the base and subbase layers of a flexible pavement type. This method uses the triaxial strength class of the materials proposed for the pavement layers as the criterion for selection of the thickness of a better material which is required above the layers within the pavement structure.

The triaxial strength class is obtained from the results of triaxial compression tests by plotting a Mohr rupture envelope on a standard triaxial classification chart. The base design thickness for a given design wheel load and traffic is determined by entering the flexible base design chart with the triaxial strength class of the proposed material to obtain the thickness of better material required.

The full design thicknesses obtained from the design charts are used for interstate and primary highways while reduced thicknesses are used for frontage roads and other facilities. In addition, minimum thicknesses of 8 inches and 6 inches are recommended for highway through lanes and for frontage roads and ramps, respectively. A minimum subbase thickness of 4 inches is recommended when such a layer is required.

In this method stabilized base layers may be used when economically feasible; however, there is no formal method which provides for reduction in base thickness as material properties are improved by stabilization. In fact, it is recommended that reduction in thickness not be allowed for stabilized layers for the following reasons:

(1) Stabilized layers are more difficult to rework in future reconstruction.

(2) Most thickness reduction methods for stabilized layers do not consider the tensile stresses imposed on the stabilized pavement layers.

BASE AND SUBBASE REQUIREMENTS: EXISTING DESIGN METHODS

The role of base and subbase layers in pavement design ranges from the effect on the modulus of subgrade reaction k for rigid pavements to a replacement value for asphaltic concrete based upon equivalency factors in flexible pavements. Base and subbase requirements for some of the more common rigid and flexible pavement design techniques are presented below.

Rigid Pavement Design Methods

Portland Cement Association Method. The Portland Cement Association requires a subbase for rigid pavement structures when encountering subgrades with

(1) nonuniform soil support,

(2) high volume-change soils, and

(3) soils which are susceptible to pumping.

The subbase thickness is arbitrary, with recommended thicknesses equal to one-third to one-half of the depth of frost penetration, 4 to 12 inches in cases of high volume-change soils and 4 to 6 inches when pumping action is anticipated. The finished subbase should provide a modulus of subgrade reaction k of not less than 200 pounds per cubic inch (Ref 2.1).

Corps of Engineers Method. The Corps of Engineers recommends a 4-inch minimum subbase thickness for normal conditions, moderate freezing, and when the water table is deep. For soils subject to severe frost a total thickness of subbase and pavement equal to the depth of frost penetration is used. For soils subject to less severe frost the subbase thickness is obtained using rigid pavement analysis, assuming a subgrade support value k reduced due to frost action (Ref 2.1).

Navy Method. The U. S. Navy uses a subbase thickness which is dependent on the results of plate load tests on the subgrade. The design thickness selected must produce a minimum modulus of subgrade reaction k of 200 pounds per cubic inch for saturated subgrade conditions. For exceptionally difficult frost conditions, the combined thickness of subbase and surface must equal the depth of frost penetration. In areas of limited frost penetration into the subgrade, the subbase thickness should be two-thirds of the difference between the depth of frost penetration and the thickness of the surface course (Ref 2.1).

AASHO Interim Guide. The American Association of State Highway Officials recommends the use of subbases over soil types which can have detrimental effects on the performance of the rigid pavement. The thicknesses recommended are thus dependent on the subgrade soil type, with 6, 9, and 12 inches, respectively, suggested for high bearing (sand and sandy loam soils), medium bearing (silt and silty clay soils), and low bearing (highly active clay soils) soil types. The use of a stabilized subbase does not allow for a reduction in these recommended values (Refs 2.2 and 2.4).

Flexible Pavement Design Methods

Asphalt Institute Method. The Asphalt Institute method for the design of deep-strength asphalt pavements does not provide recommendations concerning specific base or subbase layers. Unstabilized as well as stabilized bases can, however, replace a portion of the design thickness based on general equivalency factors of 1.3 and 1.4 for hot mix sand asphalt bases or liquid and emulsified asphalt bases, respectively, and on substitution ratios of approximately 2.0 and 2.7 for high quality and low quality untreated base materials, respectively (Ref 2.3).

Corps of Engineers Method. The Corps of Engineers recommends minimum base thicknesses which depend on load configuration, type of traffic area, magnitude of load, and CBR value of the base layer. In addition, maximum base and subbase thicknesses for a variety of variables including wheel loads, tire pressure, and gear configurations are obtained from curves relating thickness to the CBR value of the particular layer. Frost penetration and saturation of subgrade are also evaluated in the procedure by reducing the CBR design value (Refs 2.4 and 2.5).

AASHO Interim Guide. The American Association of State Highway Officials recommends minimum thickness values of 4 inches for the base course as well as the subbase course if used. The design thicknesses for base and subbase layers are obtained from an empirical relationship between structural number SN and the thicknesses of the component layers D_1, D_2, and D_3 as expressed by the general equation

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

Estimates of the coefficients a_1, a_2, and a_3 have been established for certain types of surface, base, and subbase courses from the AASHO Road Test and from laboratory tests. The variability which can be expected in these coefficients, created by changes in mixture ingredients, has not been established. In addition, the effects included in the model are simple independent factors; therefore, the assumption must be made that the properties of one layer have no effect on the required thickness of an overlying layer (Refs 2.4 and 2.6). This is a shortcoming of this design technique.

Navy Method. The U. S. Navy uses layered elastic theory in conjunction with plate load test results on the in-place subgrade as well as on a test section of the proposed base material to determine the required base thickness for any condition of loading. The design is based on an arbitrarily selected pavement deflection of 0.2 inch and does not consider the type or depth of the wearing surface (Ref 2.5).

Federal Aviation Agency Method. The Federal Aviation Agency determines base and subbase thickness requirements from comparisons of local conditions with analyses of soil, drainage, frost, and loading conditions for actual behavior and performance of existing in-service airports. The thicknesses of bituminous stabilized, as well as unstabilized, bases and subbases are obtained for a given load and classification of soil, which provides a qualitative measure of drainage and frost conditions. It was assumed in the development of the charts that the subgrade, base, and subbase properties were uniform and unaffected by changes in mixture properties or soil moisture conditions (Ref 2.5).

Shell Oil Company Method. This method is based on the principle of preventing (1) excessive tensile strains in the asphalt bound layer and (2) excessive vertical compressive strains in the subgrade. Design thicknesses obtained by maintaining these strains within safe limits supposedly prevent deformation in the pavement and cracking of the asphalt surface. Design curves indicate a number of different combinations of surface and granular base which will fulfill the strain limitations for an 18,000-pound axle loading. These curves are based on effective moduli of the asphalt bound layer which supposedly represent critical conditions for compressive strain in the subgrade (air temperature of 95^{o} F) and for tensile strain in the asphalt bound layer (air temperature of 50^{o} F) (Refs 2.4 and 2.10). Therefore the design section cannot be checked for other temperature conditions which can occur in the field. The curves, however, do offer some basis for interchanging thickness of surface and granular base to meet economic requirements.

THEORETICAL DESIGN CONCEPTS

One of the more recent developments in pavement design involves the evolution of a pavement design system which provides for continual development and improvement of a working model (Refs 2.1 and 2.2). The complex system used in this design approach can be seen in Fig 2.1 and is based on three limiting distress mechanisms which affect pavement performance. By minimizing each distress response separately, weighting factors can be assigned for a specific pavement structure and location and therefore provide the limiting design criterion for a particular pavement structure. This pavement system lends itself generally to the development of a subsystem for each of the three distress modes, i.e., rupture, distortion, and disintegration. In this general

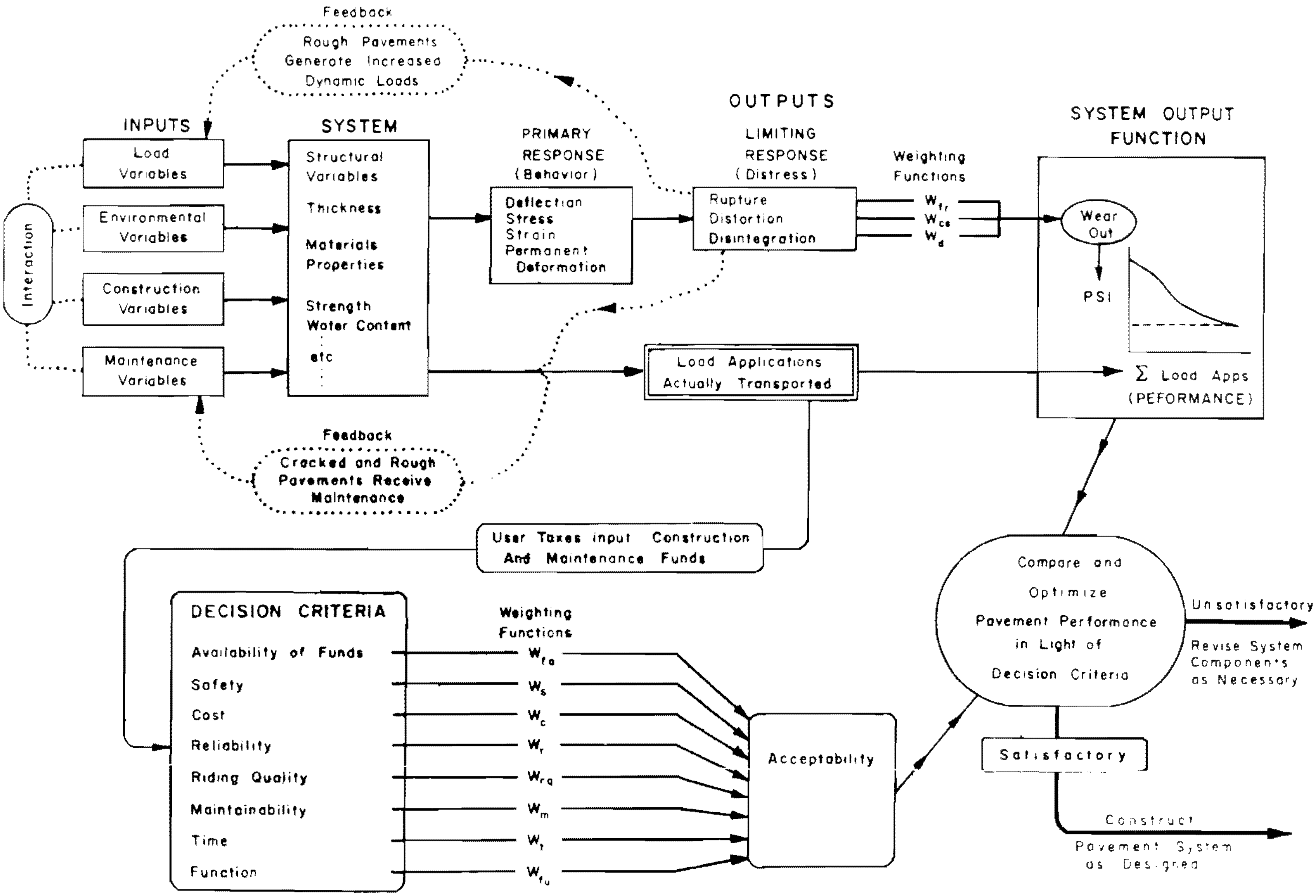


Fig 2.1. Pavement design system (Ref 2.2).

system there is need for

(1) a more rational design theory to provide means of relating the input variables to the primary response and

(2) critical design criteria for primary response to ensure that distress does not occur in the pavement system after a large number of load applications (the design traffic).

Some of the available elastic theories and design criteria which could possibly be used in this system are summarized below.

Elastic Pavement Theories

The complexity of multilayer pavement systems dictates that empirical-correlation and statistical approaches to pavement design alone can not provide adequate representations of the performance of the structural system and that some theory or theories based upon physical laws are required to express relationships between fundamental properties of materials and the performance of the total pavement structure. A theory offers the advantage of incorporating systematic corrections into the design system with some degree of confidence by testing theory against observed pavement performance (Refs 2.11 and 2.12). A theoretical design approach, therefore, provides a basic tool in the development of a pavement design system and, in addition, allows for corrections and updating of the original system based upon observed performance data. The theories considered for use in predicting stresses and deflections in the pavement system included plate theory and layered elastic theory.

In the plate theory, stresses in a surface layer can be obtained from solving Westergaard equations (Ref 2.13) for the three classic load placements or from Hudson and Matlock's discrete-element solutions (Ref 2.14) for any loading configuration. This latter technique (Ref 2.14) also provides the capability of investigating special problems such as special loadings, discontinuities including cracks, nonuniform support, and partial loss of support. Other developments (Refs 2.15 to 2.17) provide the mathematical analyses necessary to predict stresses due to curling and warping as well as load transfer at the joints.

In layered theory a uniform load is applied to a half-space consisting of several layers of finite thickness overlying a layer of infinite depth. The complete state-of-stress may be defined for any location in the pavement structure. This is a distinct advantage of layered theory over plate theory.

Initial solutions for two-layer equations were completed by Burmister (Refs 2.18 and 2.19). Other researchers (Refs 2.20 and 2.21) extended Burmister's work to define completely the stresses and strains in a three-layer pavement structure. In addition, computer programs (Refs 2.22 and 2.23) have been developed which permit the determination of complete state-of-stress and strain at any location in a simulated pavement structure and which allow application of multiple loads to the pavement system.

Each of these theories may provide the most appropriate solution depending upon the type of information desired. The plate theory provides stress information for a surface layer of finite dimensions and includes special advantages provided by Hudson and Matlock's discrete element solution (Ref 2.14). On the other hand, the complete state-of-stress cannot be predicted because the vertical stress is assumed to be zero in plate theory. Therefore, information concerning underlying pavement layers is seriously lacking in the plate theory.

The layered theory more closely represents the actual conditions involved in design and construction of multilayer pavements since it accounts for the layer phenomenon encountered in field construction. The combined surface and base or subbase course layers exhibit an important reinforcing and load-spreading role in protecting the subgrade soil which ultimately must support the stresses imposed by traffic (Refs 2.11 and 2.12). Layered theory has principally been used for design of flexible pavements (Refs 2.11, 2.18, 2.19, 2.21, 2.23, and 2.24) but also increasingly for evaluation and design of composite (Refs 2.25 through 2.28) and concrete pavement systems (Refs 2.12, 2.20 and 2.29).

McCullough and Boedecker (Ref 2.29) found that the tensile stresses at the surface-subbase interface were compatible for the two theories and that stresses predicted by layered theory were slightly higher than those predicted by the Westergaard interior equation. They concluded that the two theories may be used interchangeably with approximately the same degree of confidence.

Design Criteria

Several investigators have proposed critical design criteria for the individual layers in a pavement system. Most have expressed the thought that the tensile stress and strain in the bottom of asphalt layers and the compressive stress and strain in the subgrade are important (Refs 2.10, 2.24, 2.25, 2.30, and 2.31). In addition, tensile stresses are important in lime-treated and cement-treated, as well as portland cement concrete, pavement layers.

CHAPTER 3. DEVELOPMENT OF DESIGN SYSTEM FOR STABILIZED PAVEMENT LAYERS

The design system outlined in the following paragraphs was developed for use in the design of stabilized pavement layers. Its basis is the prevention of tensile failures. It therefore fits within the guidelines of a subsystem for the rupture distress mode of the pavement system illustrated in Fig 2.1 and can be included in the total system with only minor modifications.

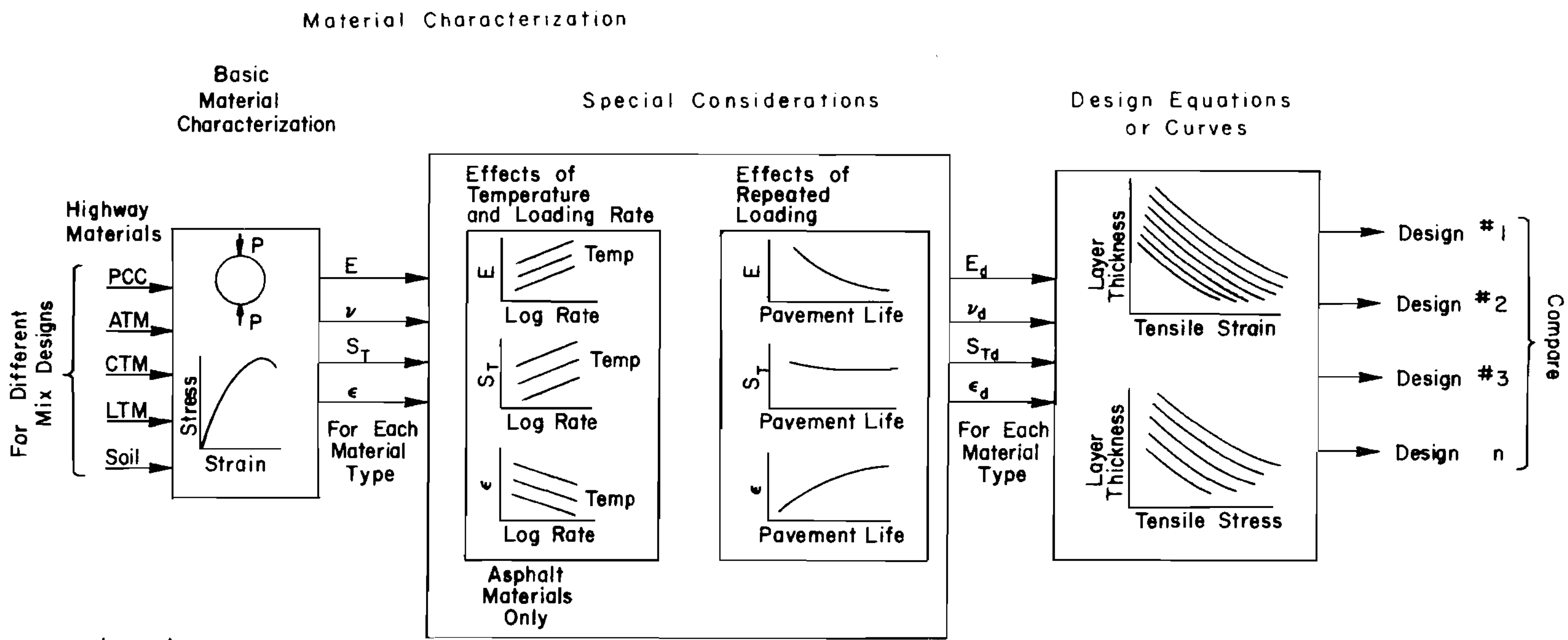
The formalized design system is presented in Fig 3.1 and is broken down into three phases. The first phase is concerned with characterization of the highway materials in the laboratory and requires techniques for estimating fundamental material properties, including modulus of elasticity, Poisson's ratio, tensile strength, and tensile strain for all highway materials.

The second phase involves special characterization considerations for such factors as temperature, loading rate, and repeated load applications. The effects of temperature and loading rate on the properties of asphaltic materials are considered in this phase, to provide flexibility in the design. The other major special consideration involves the establishment of minimum allowable stress and strain values for each of the highway materials, based on repeated load studies.

The culmination of the design process occurs in the third phase where the minimum design criteria established in the second phase are used with design equations or curves to obtain the required layer thickness. Since the thickness requirement of a stabilized layer can be affected by changes in the material properties of the layers, the design process can produce a large number of adequate design sections from which to choose. Economics can then be injected into the process for selection of the final design section.

SELECTION OF PAVEMENT THEORY

Layered theory has been selected as the basic design theory in this design system for the following reasons: (1) the state of stress in all pavement layers was necessary in order to develop design equations for the individual layers and (2) the fact that the tensile stresses at the interface between



Legend

PCC - Portland Cement Concrete
HMAC - Hot Mix Asphaltic Concrete
ATM - Asphalt-Treated Material
CTM - Cement-Treated Material
LTM - Lime-Treated Material
E - Modulus of Elasticity
ν - Poisson's Ratio
S_T - Tensile Strength
ϵ - Tensile Strain

$E_d, \nu_d, S_{Td}, \epsilon_d$ - fundamental properties considering effects of temperature, loading rate, and repeated loading which are used in thickness design selection process

Fig 3.1. Block diagram of a system for structural design of stabilized pavement layers.

the surface and subbase for the two theories (Ref 2.29) indicated that layered theory may be compatible with rigid pavement theory.

Layered theory has been used extensively since its development by Burmister in 1943; however, little has been done to incorporate the theory into a structural design system. The design system presented here is based on a practical interpretation of layered theory which emphasizes the contribution of each individual pavement layer to the behavior of the total pavement structure.

One disadvantage in the use of layered theory is that there are insufficient field data available to provide a check on the design equations generated from the theoretical equations. In addition, the validation of the design equations for a given pavement structure cannot readily be accomplished because of the difficulty in measuring the stresses and strains in the various pavement layers. As a consequence the validation of the design system can best be accomplished from long-term observations of pavements designed in accordance with the design method.

The hypothetical pavement design section adopted for this design system, illustrated in Fig 3.2, consists of three layers, i.e., a surface course, a subbase course, and the subgrade. The pavement is assumed to be loaded by two 4500-pound loads uniformly distributed over circular areas and located 12 inches apart, center to center. This loading represents the present single axle legal load limit of 18,000 pounds.

There are certain assumptions which are necessary for the solution of the three layer problem illustrated in Fig 3.2. The materials in each of the layers are assumed to be homogeneous, isotropic, and elastic. The surface and subbase layers are assumed to be infinite in extent in the lateral direction but of finite depth, while the subgrade layer is assumed to be infinite in both the horizontal and vertical directions. In addition, the continuity conditions require that there be continuous contact between the surface and subbase layers and between the subbase and subgrade layers.

In the future, there may be a combination of the plate theory with the layered theory. The design, according to layered theory, would be applicable as long as the pavement structure remains intact. In fact, the design provided by this approach is based on prevention of just such a loss of integrity.

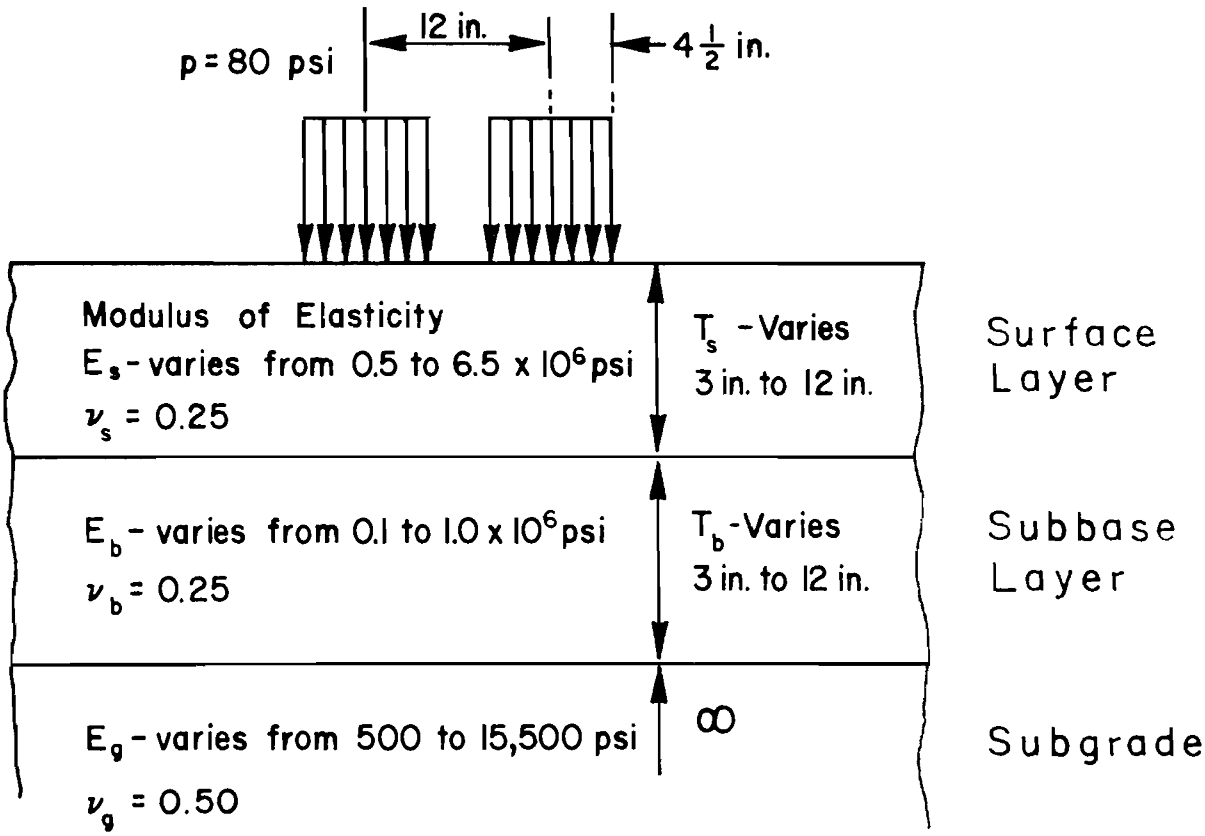


Fig 3.2. Hypothetical Pavement Section.

However, upon loss of integrity, exemplified by loss of support or development of a crack in the slab, subsequent analysis of pavement structure by plate theory could provide information concerning increased pavement cracking or loss of support, thereby providing an estimate of remaining pavement life prior to total pavement failure, i.e., when it can no longer serve its purpose. The plate theory can also be useful for special problems such as pavement designs near bridge abutments.

DEVELOPMENT OF DESIGN EQUATIONS

Since layered theory provides a deterministic model for predicting stresses, strains, and deflections in a given pavement system, it has direct application to evaluation of existing pavement sections. The inputs required in the theory, i.e., number and thickness of layers, moduli, and Poisson's ratio, can be estimated for existing pavement materials.

On the other hand, layered theory cannot be used directly to design structurally the individual layers of a pavement system since the thicknesses of the layers are required as input for the theory. Iterative solutions of layered theory equations for variations in the pavement section could be used in the design process; however, this technique would be feasible for only the simplest of design problems. The greatest value of layered theory in design of pavement structures appears to be its use in development of design equations relating stresses and strains to the important variables of the design section, i.e., layer thickness and modulus of elasticity. These equations can then be used to obtain the combination of layer thickness and modulus of elasticity corresponding to a specified critical design stress or strain. A simplified method for relating important properties of the layers of a pavement structure to critical design criteria is a necessity for this approach.

The task then involves the development of a simplified mathematical model or algorithm which can produce results that agree closely with those obtained from the original theory. A replacement model was developed for this design system by approximating the layered theory results with a polynomial mathematical equation which includes all the important variables of the design section. Regression analysis techniques were used to develop the approximate models from a series of solutions obtained from the Chevron STRESS-N computer program (Ref 3.2) for various levels of the design variables. A stepwise regression technique was used to relate specific stresses and strains obtained from the Chevron STRESS-N computer program to the design variables listed in Table 3.1.

Technique of Developing Design Equations

The variables considered in the development of the design equations were modulus of elasticity and thickness of surface layer, modulus of elasticity and thickness of subbase layer, and modulus of elasticity of the subgrade. The ranges in these variables which were used to develop the design equations are shown in Fig 3.2 and Table 3.1. The values of modulus of elasticity in the surface layer provided for evaluation of low modulus as well as high modulus layers while the range of modulus values for the subbase layer spanned the range expected for lime-treated, asphalt-treated, and cement-treated materials. The thicknesses selected were considered to be representative of those normally used in highway pavements.

The effects of modulus of elasticity and thicknesses of the layers were considered to be much more important than Poisson's ratio; therefore, Poisson's ratio was assumed to be 0.25 for the upper two layers and 0.5 for the subgrade. The effect of the changes in Poisson's ratio on the stresses and strains obtained from layered theory analysis was investigated, however, and is included in Appendix I, for information only. In this analysis it was found that for a realistic range of Poisson's ratios in the surface and subbase layers (0.125 to 0.375) the maximum differences in tensile stresses and strains were 15 percent and 8 percent, respectively.

A similar analysis concerning the effects of contact pressure and magnitude of vehicle load on the stresses and strains in the pavement layers was also conducted and is included in Appendix 2. The results presented in these appendices can be used later to expand the application of the structural design system to the design of a variety of highway pavements subjected to various traffic loads.

Location of Maximum Stresses and Strains for Dual Wheel Configuration

The stresses and strains for the dual wheel configuration were obtained from superposition of results for two separate 4500-pound loads each uniformly distributed over a circular area with a contact pressure of 8C psi. One of

TABLE 3.1. FACTORS AND LEVELS USED IN DEVELOPMENT OF DESIGN EQUATIONS

Variables	Levels 1	2	3	4	5
Modulus of Elasticity of Surface E_s					
(a) Low modulus, 10^6 psi	0.5	1.5	2.5	3.5	-
(b) High modulus, 10^6 psi	3.5	5.0	6.5	-	-
Thickness of Surface Layer T_s, inches	3	6	9	12	-
Modulus of Elasticity of Subbase Layer E_b					
(a) Low modulus pavement, 10^5 psi	1	2.5	4	7	10
(b) High modulus pavement, 10^5 psi	1	4	7	10	-
Thickness of Subbase Layer T_b, inches	3	6	9	12	-
Modulus of Elasticity of Subgrade Layer, 10^3 psi	0.5	5.5	10.5	15.5	-

the problems encountered in the superposition of results was the variation in the location of maximum values of stresses and strains.

A series of 28 different design sections which covered the range of the variables listed in Table 3.1 was selected at random to investigate the possibility of a single location for the maximum stresses and strains. From this analysis it was found, however, that the location of the maximum values varied from one design section to another. This posed a problem in the development of the design equations, because of the time and effort required to obtain the maximum values for a large number of model design sections. As a consequence of these results it was necessary to adopt a simple technique for selection of the most likely location for maximum stresses and strains.

A survey of the same computer solutions was made to find the most likely location for each of the maximum stress and strain values. The locations were designated as shown in Fig 3.3 and Table 3.2. The preselected location which occurred the most times in this survey was considered to be the most likely location for the different maximum values. The results of the survey can be seen in Table 3.3, along with the average difference and percentage difference between the actual maximum stress or strain and the values at the selected locations. The closeness of the agreement between maximum stresses and strains and the corresponding stresses and strains at the most likely location of the maximums for the 28 different computer solutions can be seen in Figs 3.4 through 3.8. Based on the results of this survey, the locations used for determination of stresses and strains for dual wheel configuration were

(1) directly beneath the center of one of the loads for tensile stress and tensile strain in the surface layer,

(2) halfway between the two loads for tensile stress in the subbase layer, and

(3) directly beneath the edge of one of the loads for tensile strain in the base layer and compressive strain in the subgrade.

Design Equations

Regression techniques were used to obtain equations for tensile stresses and strains in the bottom fibers of the upper two layers and vertical strain in the top of the subgrade in terms of the moduli and thicknesses of the pavement layers. The general form of the equations is $\log_{10}(Y) = f(X_1, X_2, X_3, \ldots X_n)$ where $\log_{10}(Y)$ is the logarithm of the dependent

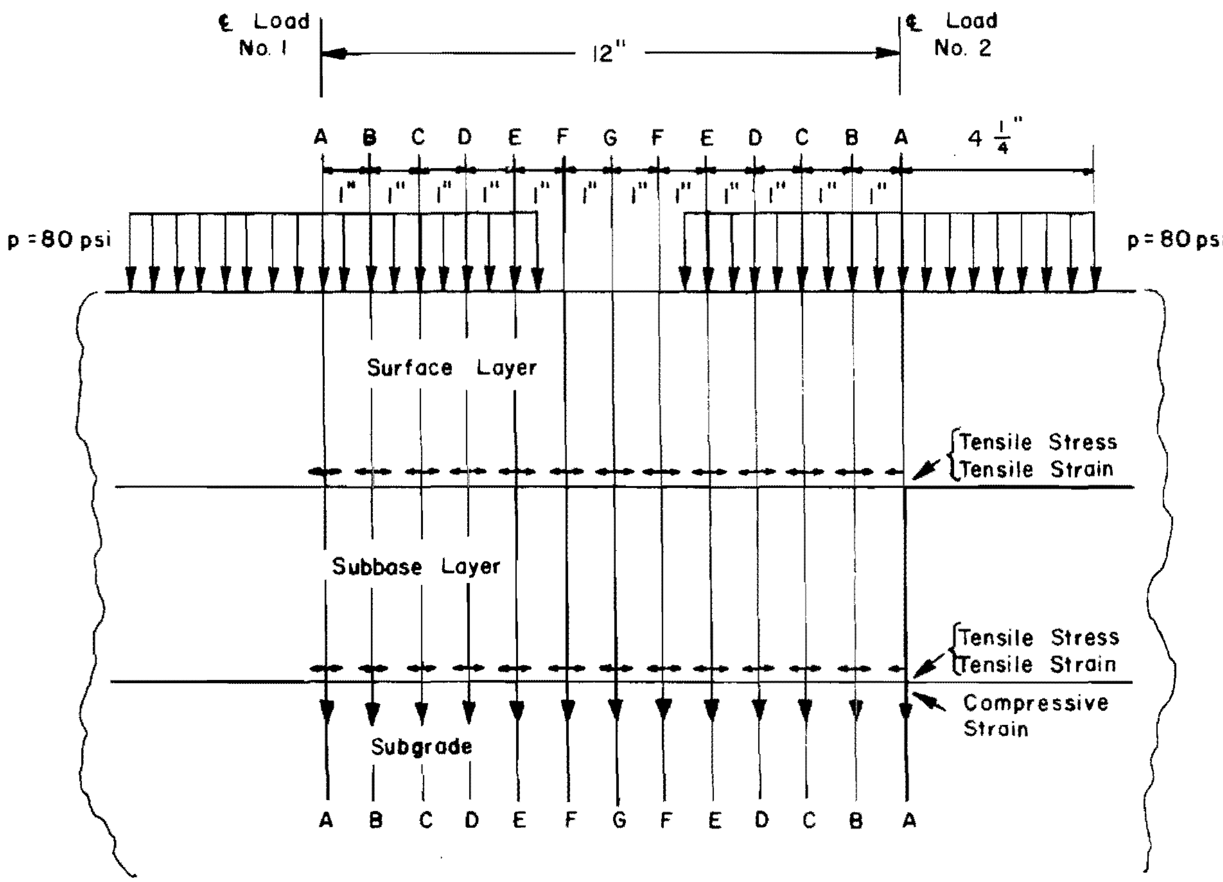


Fig 3.3. Scheme for selection of most likely location for maximum stresses and strains in the pavement layers.

TABLE 3.2. DESIGNATED LOCATIONS FOR SURVEY OF MAXIMUM STRESS AND STRAIN VALUES

Designated Location	Distance in Inches From ℄ of Load No. 1	Distance in Inches From ℄ of Load No. 2
A	0	12
B	1	11
C	2	10
D	3	9
E	4	8
F	5	7
G	6	6

TABLE 3.3. LOCATIONS SELECTED FOR DETERMINATION OF STRESSES AND STRAINS FOR DUAL WHEEL LOAD CONFIGURATION

Variable	Selected Location	Average Difference**	Average Percent Difference*, **
Tensile stress in base layer σ_b	G	0.7 psi	1.3
Tensile strain in base layer ε_b	E	4.8 microunits	2.3
Compressive strain in subgrade ε_c	E	3.4 microunits	1.0
Tensile stress in surface layer σ_s	A	2.4 psi	2.8
Tensile strain in surface layer ε_s	A	0.2 microunits	0.8

*Percent difference = $\frac{V_{MAX} - V_{SELECT}}{V_{MAX}} \times 100\%$ where V_{MAX} is the maximum stress or strain and V_{SELECT} is the corresponding stress or strain at the most likely location.

**Average of 28 different design sections.

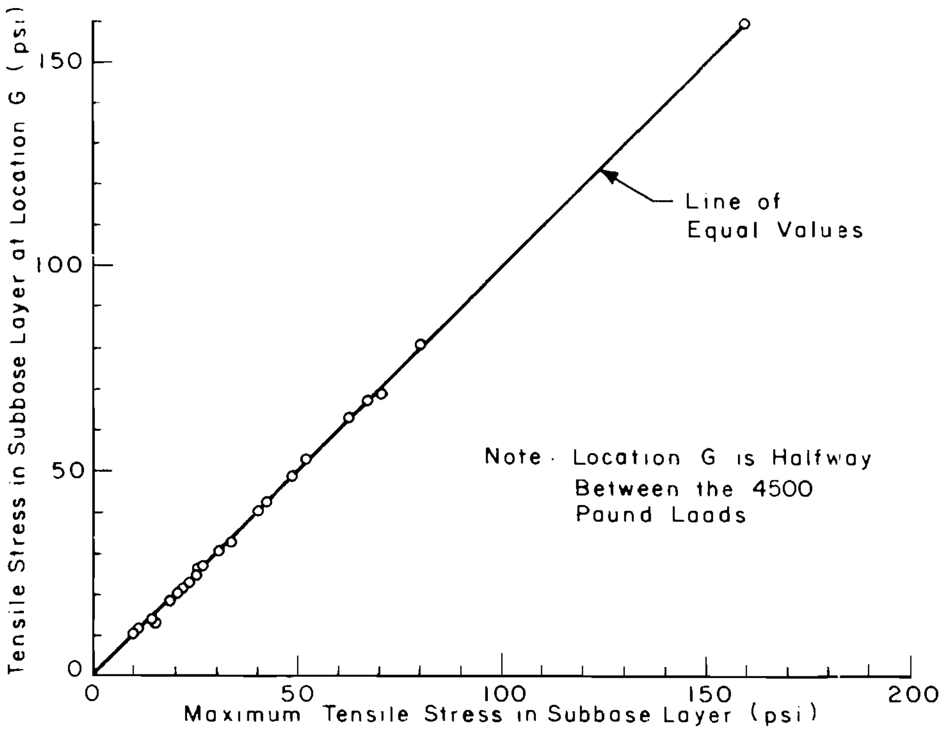


Fig 3.4. Comparison of tensile stress in subbase layer: maximum stress versus stress at location G .

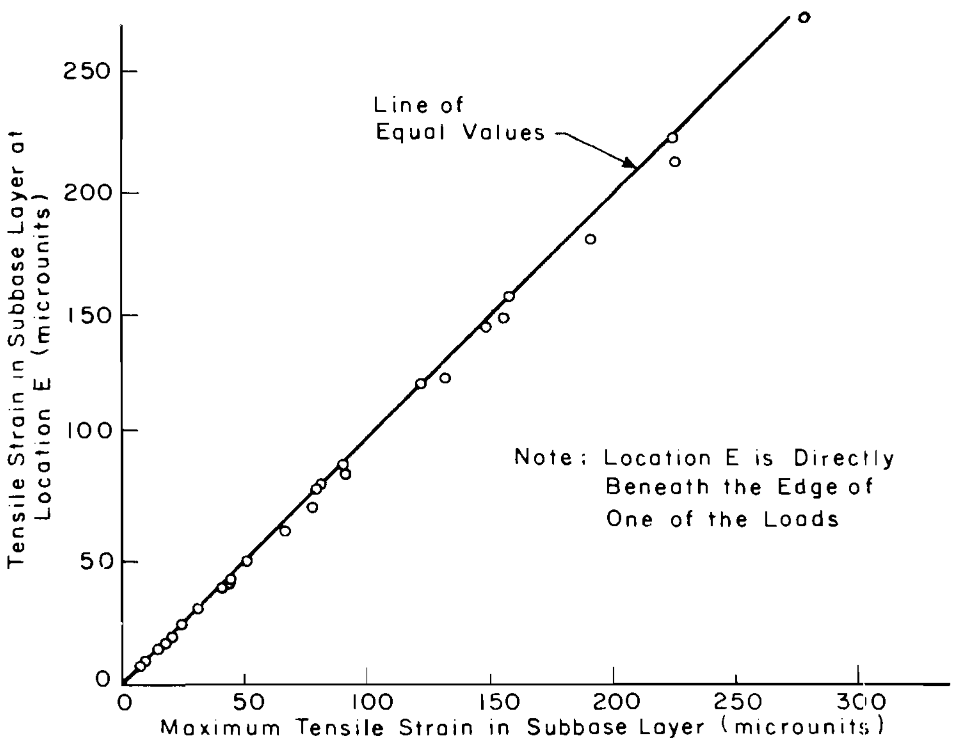


Fig 3.5. Comparison of tensile strain in subbase layer: maximum strain versus strain at location E .

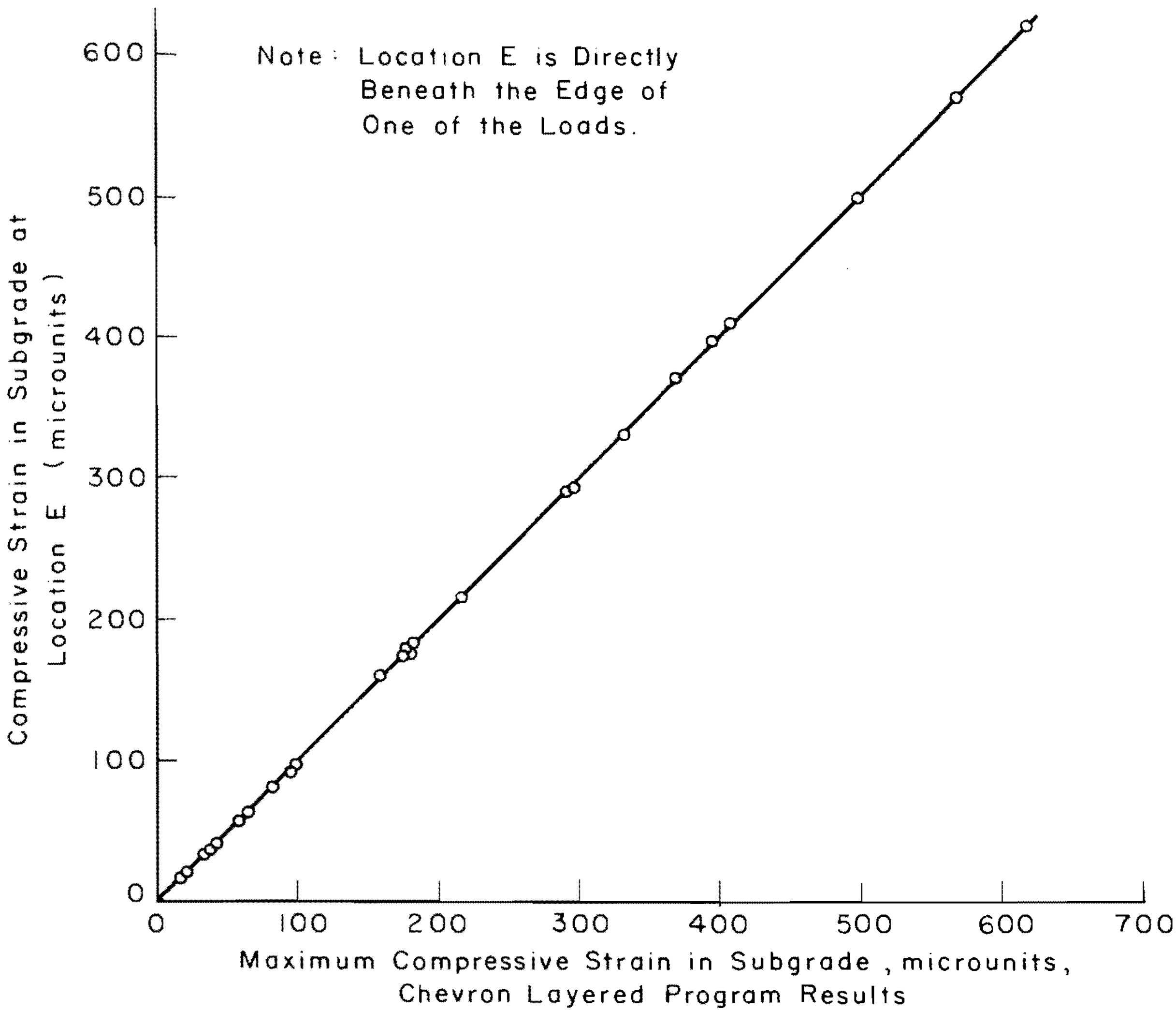


Fig 3.6. Comparison of compressive strain in the subgrade: maximum strain versus strain at location E .

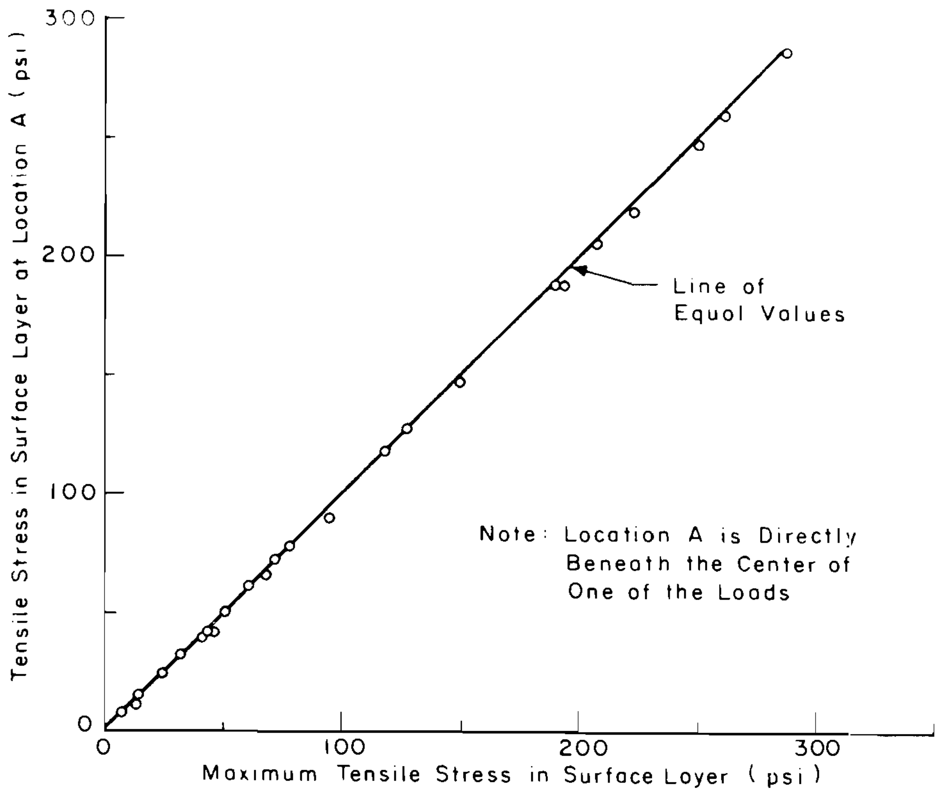


Fig 3.7. Comparison of tensile stress in surface layer: maximum stress versus stress at location A .

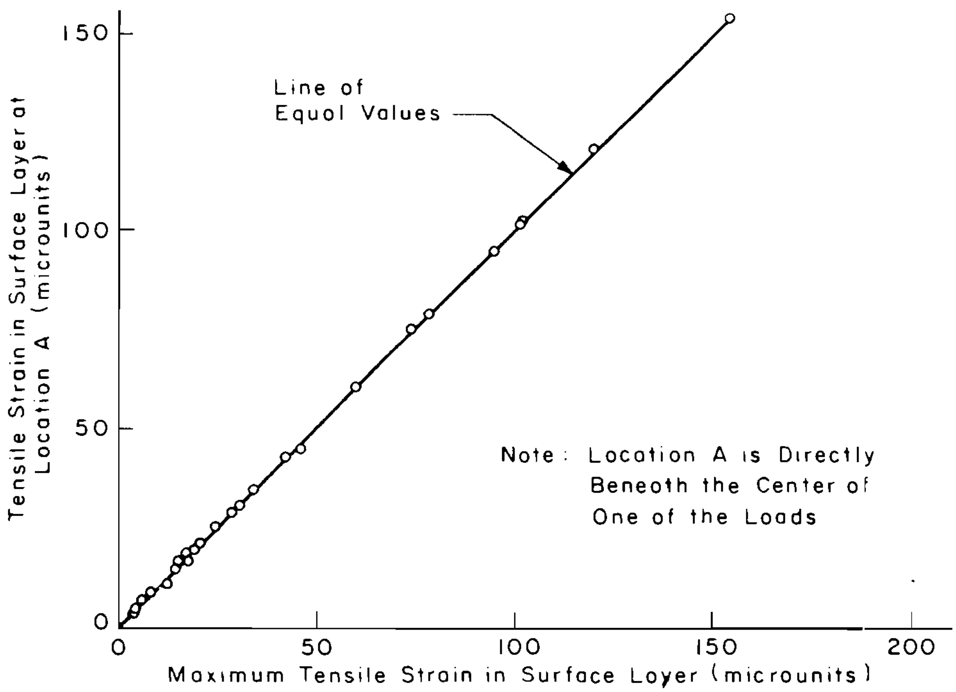


Fig 3.8. Comparison of tensile strain in surface layer: maximum strain versus strain at location A .

variable Y , i.e., stress or strain in a particular layer, and X_1, X_2, X_3,...X_n are the independent variables under consideration, i.e., layer moduli and thicknesses. All possible combinations of the levels of the variables listed in Table 3.1 were used in the development of the design equations.

Separate equations were obtained for low and high modulus layers, as indicated in Table 3.1, to provide flexibility in the type of highway pavement to be designed. The equations for low modulus layers can be used for design of flexible pavements as well as for design of low modulus portland cement concrete pavements, while the equations for high modulus layers can be used for design of high strength portland cement concrete pavements.

The following symbols are used in all of the design equations:

(1) E_s = modulus of elasticity of surface layer, 10^6 psi;

(2) T_s = thickness of surface layer, inches;

(3) E_b = modulus of elasticity of base layer, 10^5 psi;

(4) T_b = thickness of base layer, inches;

(5) E_g = modulus of elasticity of subgrade, 10^3 psi.

Design of High Modulus Surface Layers

The regression equations for pavement structures with surface layers exhibiting modulus of elasticity values in the range of 3.5×10^6 psi to 6.50×10^6 psi are presented below. The pertinent statistical information concerning the equations is included in Table 3.4.

TABLE 3.4. STATISTICAL DATA FOR REGRESSION EQUATIONS: HIGH MODULUS SURFACE LAYERS

Response Variable	Log Form	Coefficient of Determination R^2	Standard Error of Estimate $\hat{S}_r$
Tensile stress in base layer	$\text{Log}(\sigma_b)$	0.989	±.04635
Tensile strain in base layer	$\text{Log}(\epsilon_b)$	0.983	±.04388
Compressive strain in subgrade	$\text{Log}(\epsilon_c)$	0.991	±.03321
Tensile stress in surface layer	$\text{Log}(\sigma_s + 26.4)$	0.680	±.18694
Tensile strain in surface layer	$\text{Log}(\epsilon_s + 5.15)$	0.635	±.1716

Tensile Stress in Bottom of Base Layer σ_b .

$$\text{Log}_{10}(\sigma_b) \times 10^3 =$$

$$1333.84 + 46.868\ (E_b - 5.5) - 23.774\ (T_b - 7.5)$$

$$-3.3610\ (E_b - 5.5)(T_b - 7.5) - 11.008\ (E_b - 5.5)^2$$

$$+ 1.6306\ (E_b - 5.5)^3 + 4.3026\ (T_s - 7.5)(T_b - 7.5)$$

$$- 39.310\ (E_s - 5.0) - 21.572\ (E_g - 8.0) + 1.7254\ (E_g - 8.0)^2$$

$$- 80.972\ (T_s - 7.5) + 4.0607\ (E_b - 5.5)(T_s - 7.5)$$

$$+ 3.4019\ (T_s - 7.5)^2 \qquad (1)$$

Tensile Strain in Bottom of Base Layer ϵ_b .

$$\text{Log}_{10}(\epsilon_b) \times 10^3 =$$

$$1412.12 - 34.516\ (E_b - 5.5) - 19.891\ (T_b - 7.5)$$

$$- 3.3677\ (E_b - 5.5)(T_b - 7.5) + 2.0650\ (E_b - 5.5)^2$$

$$+ 3.9519\ (T_s - 7.5)(T_b - 7.5) - 37.103\ (E_s - 5.0)$$

$$- 21.293\ (E_g - 8.0) + 1.7920\ (E_g - 8.0)^2 - 76.216\ (T_s - 7.5)$$

$$+ 3.9517\ (E_b - 5.5)(T_s - 7.5) + 2.7973\ (T_s - 7.5)^2 \qquad (2)$$

Compressive Strain in Subgrade ε_c .

$$\text{Log}_{10}(\varepsilon_c) \times 10^3 =$$

$$1744.52 - 34.206\ (E_b - 5.5) - 17.860\ (T_b - 7.5)$$

$$- 3.3359\ (E_b - 5.5)(T_b - 7.5) + 2.09191\ (E_b - 5.5)^2$$

$$- 74.426\ (T_s - 7.5) + 4.1675\ (T_s - 7.5)(T_b - 7.5)$$

$$+ 3.1465\ (T_s - 7.5)^2 - .44062\ (T_s - 7.5)^2(T_b - 7.5)$$

$$+ 3.9401\ (E_b - 5.5)(T_s - 7.5) - .44431\ (E_b - 5.5)^2(T_s - 7.5)$$

$$- 11.482\ (E_g - 8.0) + 1.7026\ (E_g - 8.0)^2 - .16881\ (E_g - 8.0)^3$$

$$- 38.520\ (E_s - 5.0) - 3.5104\ (E_s - 5.0)(T_s - 7.5) \qquad (3)$$

Tensile Stress in Bottom of Surface Layer σ_s .

$$\text{Log}_{10}(\sigma_s + 26.4) \times 10^3 =$$

$$2084.50 - 31.179\ (E_b - 5.5) - 37.176\ (T_b - 7.5)$$

$$- 4.9726\ (E_b - 5.5)(T_b - 7.5) + 6.5353\ (T_s - 7.5)(T_b - 7.5)$$

$$- 24.615\ (T_s - 7.5) - 1.2956\ (E_b - 5.5)(T_s - 7.5)^2$$

$$+ 8.2011\ (E_b - 5.5)(T_s - 7.5) - 9.3803\ (E_s - 5.0)(T_s - 7.5)$$

$$- 7.2608\ (E_g - 8.0) \qquad (4)$$

Tensile Strain in Bottom of Surface Layer ϵ_s .

$$\text{Log}_{10} (\epsilon_s + 5.15) \times 10^3 =$$

$$1233.72 - 40.073 (E_b - 5.5) - 35.042 (T_b - 7.5)$$

$$- 4.1767 (E_b - 5.5)(T_b - 7.5) + 6.1426 (T_s - 7.5)(T_b - 7.5)$$

$$- 15.756 (T_s - 7.5) + 7.0680 (E_b - 5.5)(T_s - 7.5)$$

$$- 8.1402 (E_g - 8.0) \tag{5}$$

Design of Low Modulus Surface Layers

The regression equations for pavement structures with surface layers exhibiting modulus of elasticity values in the range of 0.5 to 3.5 $\times 10^6$ psi are presented below. The pertinent statistical data concerning the equations are included in Table 3.5. From these results, it is obvious that the equation for tensile strain in the surface layer ($R^2 = 0.100$) is not as good as the others in approximating layer theory equations; however, the equation can provide general design information.

Tensile Stress in Bottom of Base Layer σ_b .

$$\text{Log}_{10}(\sigma_b) \times 10^3 =$$

$$1532.25 - 66.290 (T_s - 7.5) - 35.264 (T_b - 7.5)$$

$$+ 3.6935 (T_s - 7.5)(T_b - 7.5) - 89.256 (E_s - 2.0)$$

$$- 8.3627 (E_s - 2.0)(T_s - 7.5) + 44.289 (E_b - 4.90)$$

$$- 12.508 (E_b - 4.90)^2 + 1.7468 (E_b - 4.90)^3 + 2.9460 (E_b - 4.90)$$

$$(T_s - 7.5) - 21.341 (E_g - 8.0) + 1.7005 (E_g - 8.0)^2 \tag{6}$$

TABLE 3.5. STATISTICAL DATA FOR REGRESSION EQUATIONS: LOW MODULUS SURFACE LAYER

Response Variable	Log Form	Coefficient of Determination R^2	Standard Error of Estimate $\hat{S}_r$
Tensile stress in base layer	$\text{Log}(\sigma_b)$	0.969	±.06649
Tensile strain in base layer	$\text{Log}(\epsilon_b)$	0.964	±.06212
Compressive strain in subgrade	$\text{Log}(\epsilon_c)$	0.965	±.06323
Tensile stress in surface layer	$\text{Log}(\sigma_s + 55.0)$	0.847	±.10570
Tensile strain in surface layer	$\text{Log}(\epsilon_s + 56.4)$	0.100	±.40665

Tensile Strain in Bottom of Base Layer ϵ_b .

$$\mathrm{Log}_{10}(\epsilon_b) \times 10^3 =$$

$$1614.23 - 60.373\ (T_s - 7.5) - 30.108\ (T_b - 7.5)$$
$$+ 3.1786\ (T_s - 7.5)(T_b - 7.5) - 81.580\ (E_s - 2.0)$$
$$- 8.9055\ (E_s - 2.0)(T_s - 7.5) - 50.011\ (E_b - 4.9)$$
$$+ 3.7758\ (E_b - 4.9)^2 + 2.7682\ (E_b - 4.9)(T_s - 7.5)$$
$$- 21.619\ (E_g - 8.0) + 1.7407\ (E_g - 8.0)^2 \qquad (7)$$

Compressive Strain in Subgrade ϵ_c .

$$\mathrm{Log}_{10}(\epsilon_c) \times 10^3 =$$

$$1949.16 - 64.339\ (T_s - 7.5) - 33.750\ (T_b - 7.5)$$
$$+ 3.5397\ (T_s - 7.5)(T_b - 7.5) - 86.598\ (E_s - 2.0)$$
$$- 8.4973\ (E_s - 2.0)(T_s - 7.5) - 49.905\ (E_b - 4.9)$$
$$+ 3.7417\ (E_b - 4.9)^2 + 2.8438\ (E_b - 4.9)(T_s - 7.5)$$
$$- 20.156\ (E_g - 8.0) + 1.6349\ (E_g - 8.0)^2 \qquad (8)$$

<u>Tensile Stress Function for Surface Layer σ_s.</u>

$$\text{Log}_{10}(\sigma_s + 55.0) \times 10^3 =$$

$$2043.83 - 27.372\ (T_b - 7.5) - 4.3388\ (T_s - 7.5)^2$$

$$+ 3.66404\ (T_s - 7.5)(T_b - 7.5) + 126.90\ (E_s - 2.0)$$

$$- 15.756\ (E_s - 2.0)(T_s - 7.5) - 35.357\ (E_s - 2.0)^2$$

$$- 47.247\ (E_b - 4.90) + 3.9371\ (E_b - 4.90)^2$$

$$+ 6.6099\ (E_b - 4.9)(T_s - 7.5) \qquad (9)$$

<u>Tensile Strain Function for Surface Layer ϵ_s.</u>

$$\text{Log}_{10}(\epsilon_s + 56.4) \times 10^3 =$$

$$1845.4 - 13.892\ (T_b - 7.5) - 26.686\ (E_b - 4.90)$$

$$+ 14.129\ (E_s - 2.0)(E_b - 4.90) - 15.177\ (E_s - 2.0)(T_s - 7.5)$$

$$+ 4.9443\ (E_b - 4.90)(T_s - 7.5) \qquad (10)$$

COMPARISONS BETWEEN DESIGN EQUATIONS AND LAYERED THEORY EQUATIONS

The statistical information presented in Tables 3.4 and 3.5 indicates that regression Eqs 1 through 9 provide adequate approximations of layered theory solutions. These results, however, represent good agreement for the levels of the five variables used in the development of the design equations (see Table 3.1). Since the equations will be used to approximate theoretical stresses and strains over the total range of the variables, it was necessary to investigate the adequacy of the design equations at some intermediate levels which were not used in the original development.

As a result, a series of 20 design sections was selected for a comparison of stresses and strains obtained from layered theory with those obtained from the design equations. The design sections were selected so that one-half of them met the requirements of a high modulus pavement (Eqs 1 through 5) and the other one-half met the requirements of a low modulus pavement (Eqs 6 through 10).

The results of a comparison of stresses and strains obtained by the two methods are presented in Table 3.6. In addition, Figs 3.9 through 3.13 illustrate the close relationship between the stresses and strains estimated from the design equations and those obtained from layered theory equations. It was observed from Fig 3.13 that there was good agreement between those equations for tensile strains in a low modulus surface layer, i.e., modulus of elasticity of the surface layer less than 3.50×10^6 psi, up to a tensile strain of approximately 50 microunits. Based on this survey, design Eqs 1 through 9 are considered to provide a good approximation of layer theory solutions over the range of the variables listed in Table 3.6. In addition, design Eq 10 apparently provides an adequate approximation of layer theory equations for surface layer tensile strains less than approximately 50 microunits.

APPLICATIONS TO DESIGN

Application of Design Equations

Because of the number of terms involved, each of the equations presented in this study could best be solved in a computer. The equations can be solved for any one of the following six variables as long as estimates of the other five are available:

(1) critical design stress or strain,

(2) modulus of elasticity of the surface layer E_s ,

(3) thickness of the surface layer T_s ,

(4) modulus of elasticity of the subbase layer E_b ,

(5) thickness of the subbase layer T_b , and

(6) modulus of elasticity of the subgrade E_g .

In the general case, the inputs for the equations would include a critical design stress or strain and modulus of elasticity for each of three pavement layers as well as an estimate of surface layer thickness. The resulting output

TABLE 3.6. A COMPARISON OF THE SOLUTIONS TO A SERIES OF DESIGN SECTIONS: DESIGN EQUATION VERSUS LAYERED THEORY EQUATIONS

Design Variable	Difference Between Solutions: Average Difference	Difference Between Solutions: Average Percent Difference
Tensile stress in the subbase layer σ_b , psi		
High modulus surface (1)*	3.0	9.7
Low modulus surface (6)	.8	4.1
Tensile strain in the subbase layer ϵ_b , microunits		
High modulus surface (2)	7.5	8.1
Low modulus surface (7)	4.4	8.6
Compressive strain in the subgrade ϵ_c , microunits		
High modulus surface (3)	13.1	6.4
Low modulus surface (8)	5.0	6.0
Tensile stress in the surface layer σ_s , psi		
High modulus surface (4)	11.4	16.0
Low modulus surface (9)	11.3	13.2
Tensile strain in the surface layer ϵ_s , microunits		
High modulus surface (5)	8.8	23.0
Low modulus surface (10)	1.7	10.1

*Numbers in parentheses designate the applicable design equation.

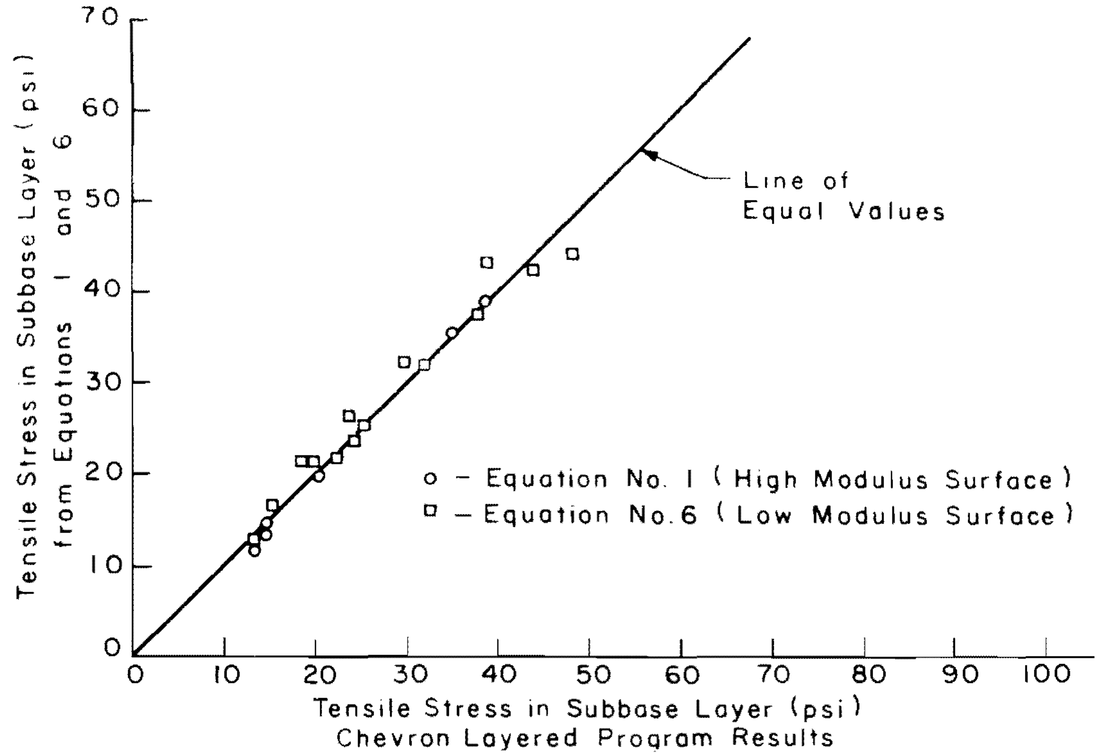


Fig 3.9. A comparison of the tensile stress in the subbase layer: design equations versus layered theory equations.

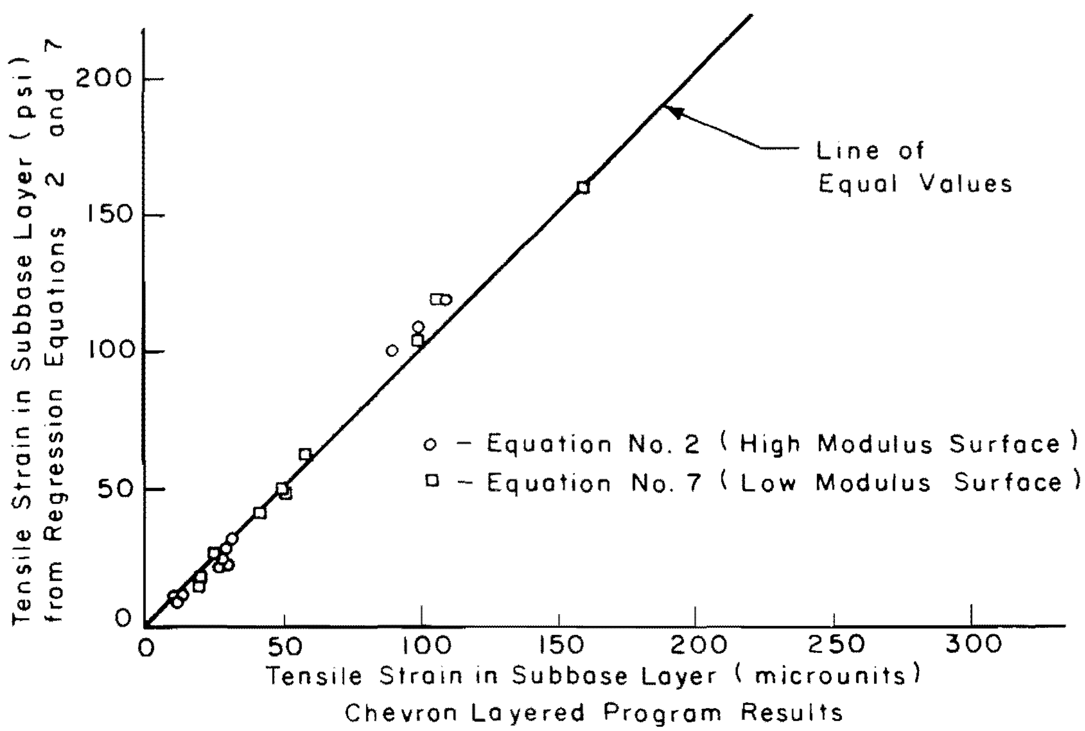


Fig 3.10. A comparison of the tensile strain in the subbase layer: design equations versus layered theory equations.

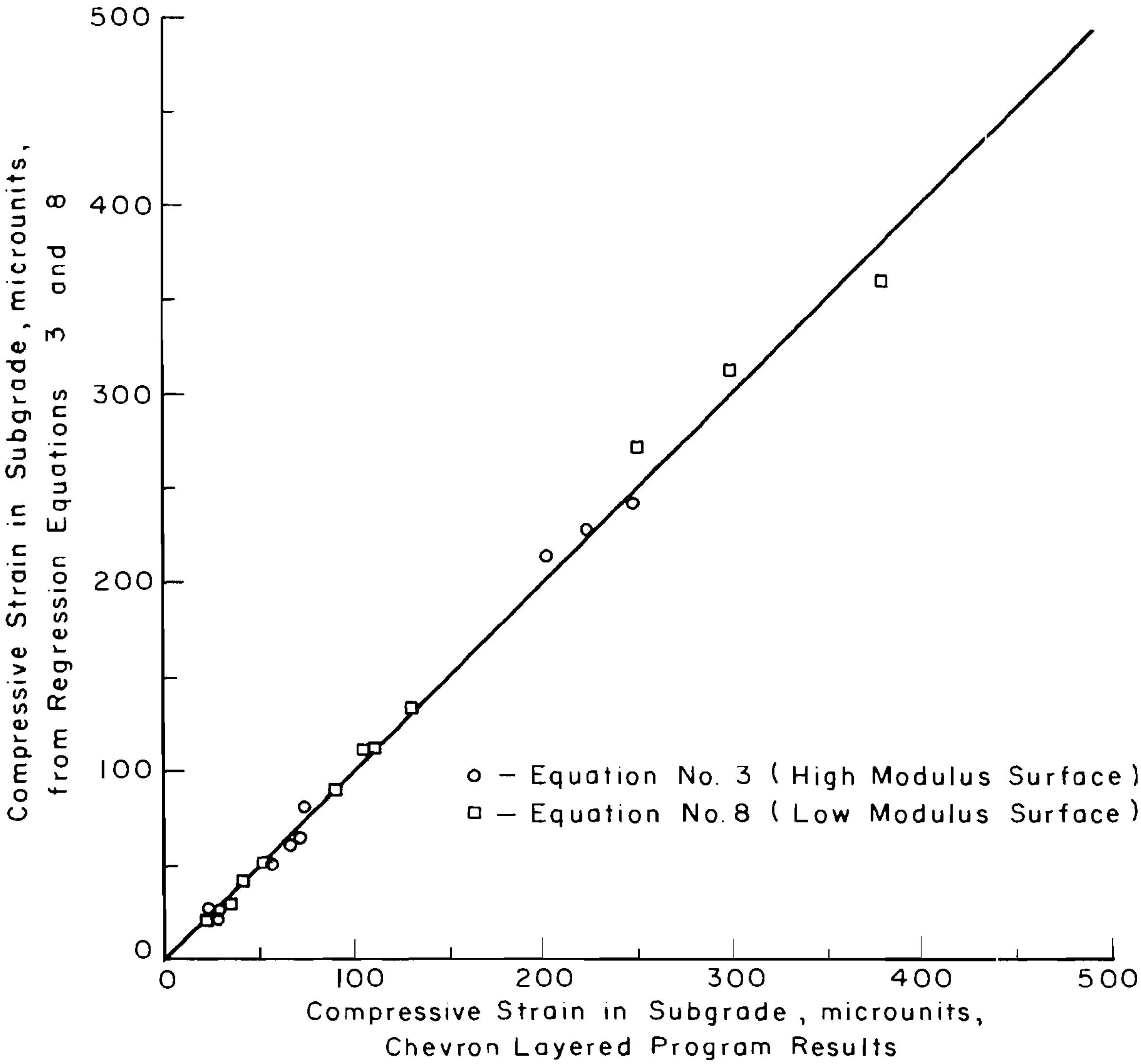


Fig 3.11. A comparison of compressive strain in the subgrade: design equations versus layered theory equations.

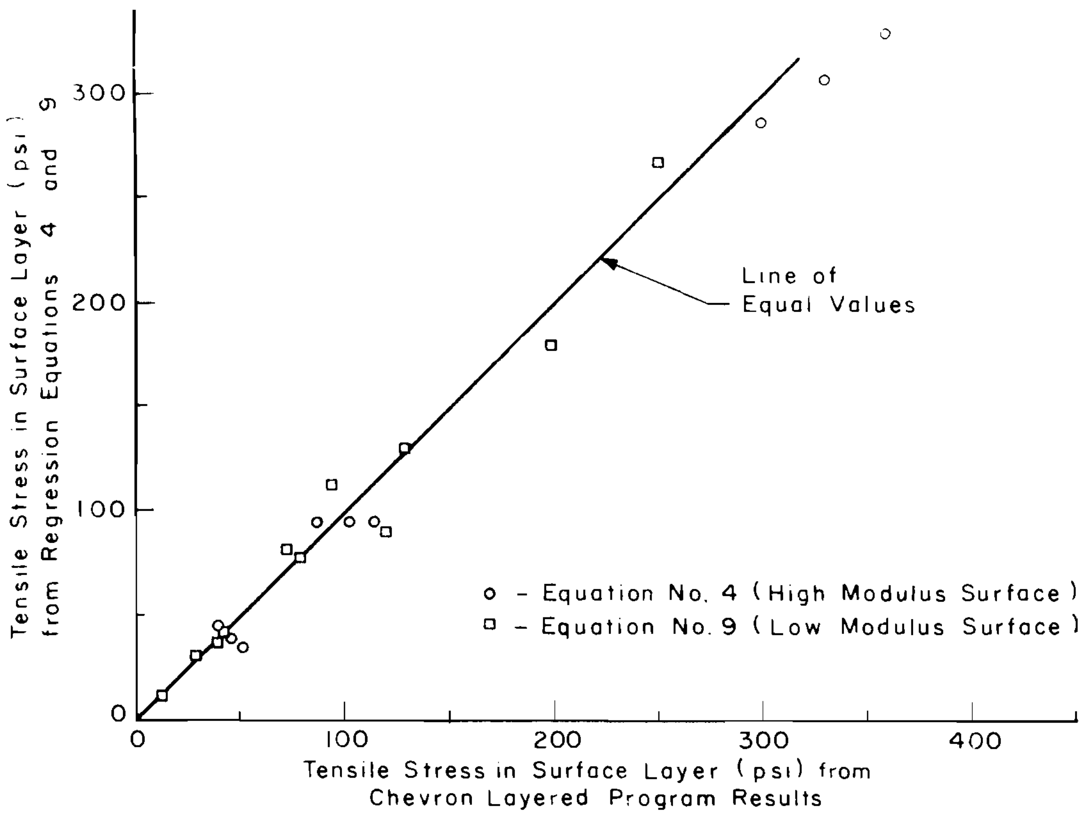


Fig 3.12. A comparison of tensile stress in the surface layer: design equations versus layered theory equations.

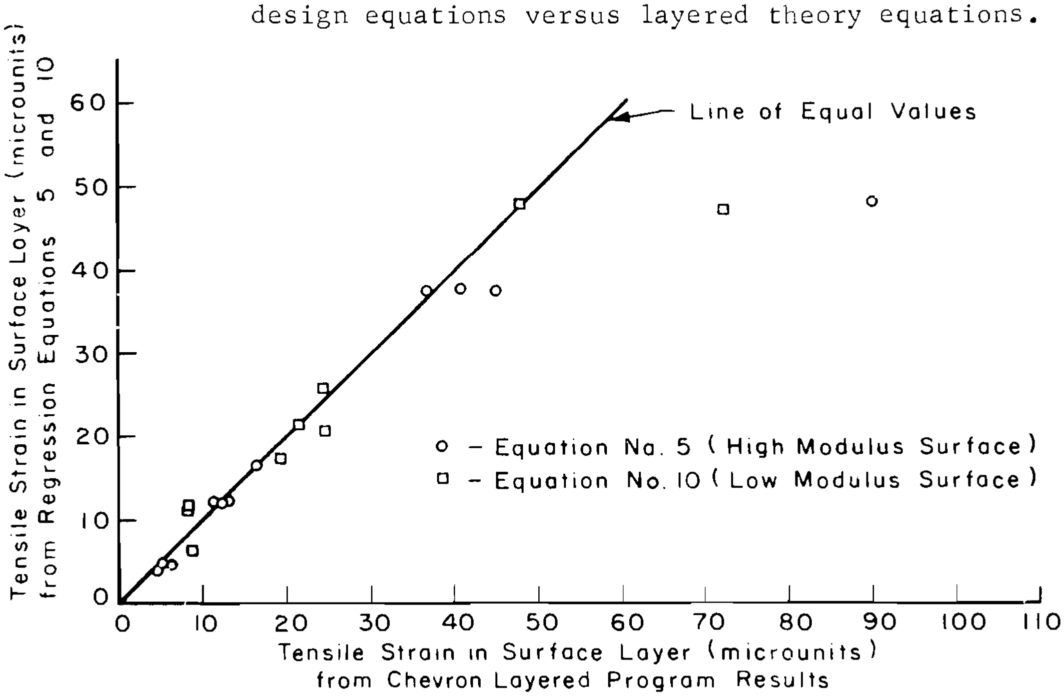


Fig 3.13. A comparison of tensile strain in the surface layer: design equations versus layered theory equations.

from these solutions would then be the corresponding subbase design thickness. However, the equations can also be used to obtain the design thickness of the surface layer as well as critical design tensile stress or strain for the upper two layers if proper estimates of the other variables are provided as inputs for the equations.

A cost function for the different materials could be included in the analysis of the equation, thereby providing the capability for using optimization techniques to select the most economical design sections. The cost functions would have to be based on previous cost data and would have to be updated periodically. As a part of the analysis, the equations could be solved for a number of surface types and thicknesses, subbase layer types, and subgrade modulus of elasticity, and the results could be provided in tabular form along with the base thickness design and the cost of the total design section. The selection of the appropriate design section among those of similar costs could be made by the proper design authority.

Since computer facilities are not readily available to all designers, there is a need for a practical method of solving the design equations. Nomographs fulfilling this need are included in Appendices 3 and 4 for design Eqs 1 through 5 and 6 through 10, respectively. An example problem is included in each appendix to illustrate the procedures necessary for use of the nomographs.

Thickness Selection Procedure

The procedure for selecting a subbase thickness is illustrated in Fig 3.14 for a constant surface thickness and given material properties. The process is broken down into five separate designs. The first two design thicknesses are based on allowable tensile stress or strain in the subbase layer. The third design is based on compressive strain in the subgrade and is provided to insure that lateral movement of the subgrade will not occur and that the integrity of the pavement system is maintained. The final two design thicknesses are obtained by checking to insure that the tensile stresses and strains produced in the surface layer do not exceed the allowable values for the surface layer materials.

All five subbase thicknesses are compared in order to select a critical design thickness that will satisfy all conditions. A typical design analysis

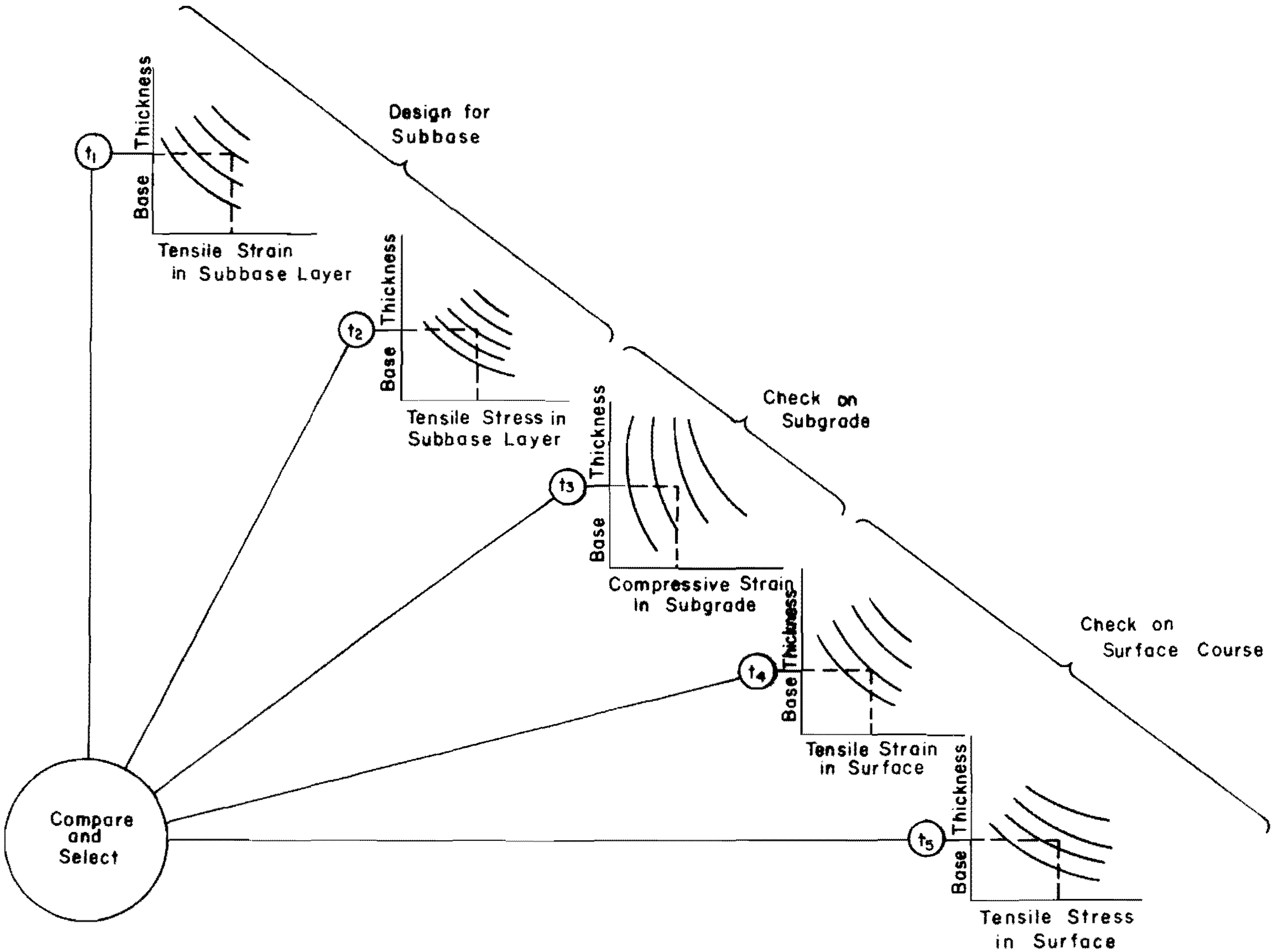


Fig 3.14. Process for selecting final base or subbase thickness.

would involve a number of iterative computations since changes in material types as well as different combinations of surface and base thicknesses can be evaluated in the process of selecting the most economical design section.

This design procedure could also be used to select the thickness of the surface course as well as to consider the effect of changes in the material properties on thickness requirements. In either case, the design would involve an iterative process of selecting a minimum subbase thickness, which, in turn, would affect the thickness of the surface course.

The equations presented in this chapter are based on a pavement structure which includes a subbase layer with a modulus of elasticity in the range from $.1 \times 10^6$ to 1×10^6 psi and cannot be used to evaluate the situation of a surface layer lying directly on the subgrade. Therefore, the fact that a subbase is not required for a given design stress or strain, i.e., $T_b = 0.0$, does not mean that a subbase is not required, but rather indicates that a minimum thickness of the subbase material is adequate or that a lower quality subbase material, i.e., a subbase material with a lower tensile strength, may be used for the particular design criteria.

SUMMARY

In this chapter a formalized design system, the basis of which is the prevention of tensile failures in pavement layers, has been presented for use in the structural design of stabilized pavement layers. Layered theory was selected as the basic design theory and was used in the development of a series of design equations relating tensile stresses and strains at selected locations in the pavement layers to a number of the more important design variables. Applications of the design equations to the structural design of stabilized subbases were also presented, including definite procedures for the selection of a critical subbase design thickness. Since these design equations are based on linear elastic theory, the materials which form the layers in the hypothetical pavement are assumed to be homogeneous, isotropic, and elastic in nature. It is, therefore, necessary to characterize the pavement materials by the two independent elastic constants: modulus of elasticity and Poisson's ratio. It is equally important that estimates of design stresses and strains be obtained in order to insure the proper selection of a critical design thickness. The next chapter is concerned with the development of the techniques for characterizing the various highway materials which will have direct application with the design equations of this chapter.

CHAPTER 4. CHARACTERIZATION OF MATERIAL PROPERTIES FOR DESIGN APPLICATIONS

The design of a pavement structure must include an evaluation of a wide variety of factors which can affect the short-term behavior as well as the long-term performance of the structure. Layered theory can be used effectively to evaluate the behavior of a pavement structure under a given load through proper selection of material properties; however, the theory cannot be used directly to evaluate the performance of a pavement because the effects of environmental variables as well as repetitive loads are not inherently included in the theory. In addition, layered theory does not include provisions for the effects of time and temperature on the properties of the stabilized materials used in the various pavement layers.

This chapter presents recommendations concerning characterization of the various stabilized materials and includes methods for considering (1) repeated loading effects for all stabilized materials and (2) the effects of loading rate and temperature on the properties of asphalt-treated materials.

BASIC MATERIAL CHARACTERIZATION

One of the more important aspects in the use of a theoretical design approach involves the estimation of the fundamental properties of the materials comprising the different stabilized pavement layers. Consequently the method of obtaining estimates of these properties is then an important link in the total design system. Ideally the method of characterization would provide unbiased estimates of all the required properties and would be independent of test equipment or method used.

Recent developments in the use of the indirect tensile test have included a technique for estimating fundamental properties of modulus of elasticity, Poisson's ratio, tensile strength, and tensile failure strains (Ref 3.2) for different stabilized materials. This technique appears to be the most practical method available for obtaining estimates of fundamental material properties of cohesive highway materials.

The Indirect Tensile Test

The test involves the loading of a right circular cylindrical specimen with compressive line loads acting along two opposite generators (Fig 4.1). The compressive loads are applied through a curved stainless steel load strip in order to distribute the load and to maintain a constant loading area. This loading configuration produces a uniform tensile stress along the vertical diametral plane perpendicular to the direction of the applied load. The specimen fails by splitting or rupturing along the vertical diameter.

The relationships and procedures used to estimate these properties are based upon theoretical equations for the stresses and strains in the indirect tensile test specimen which were developed by Hondros (Ref 4.1). Since it is easier and more economical to measure total specimen deformations than to measure strains in the specimen, these theoretical equations were extended and modified to include the use of total deformations. At the same time, equipment for measuring these deformations during testing was developed (Ref 4.3). A step-by-step procedure developed by Hadley et al for estimating each of the properties of tensile strength, Poisson's ratio, modulus of elasticity, and elastic tensile strains is included in Refs 3.1 and 4.2.

Application of the Indirect Tensile Test to a Variety of Materials

The indirect tensile test has been used to evaluate a wide variety of materials, including portland cement concrete (Refs 4.1 and 4.4 through 4.11), cement-treated materials (Refs 4.12 and 4.13), asphaltic materials (Refs 3.1, 4.3 and 4.14 through 4.20), lime-treated materials (Refs 4.21 through 4.23), and untreated cohesive soils (Refs 4.24 and 4.25).

The theory of the indirect tensile test was derived from linear elasticity; however, it has recently been shown (Ref 4.26) that an identical equation for tensile strength can also be derived from the theory of perfect plasticity. Thus the test is apparently applicable for the evaluation of plastic as well as elastic materials. In addition, the indirect tensile test configuration has been shown to be applicable for the fatigue study of stabilized materials subjected to repeated tensile stresses (Refs 4.27 and 4.28).

The selection of a single technique for characterizing the properties of a variety of materials requires that the applicability of the test configuration to these materials be investigated or considered. This is especially

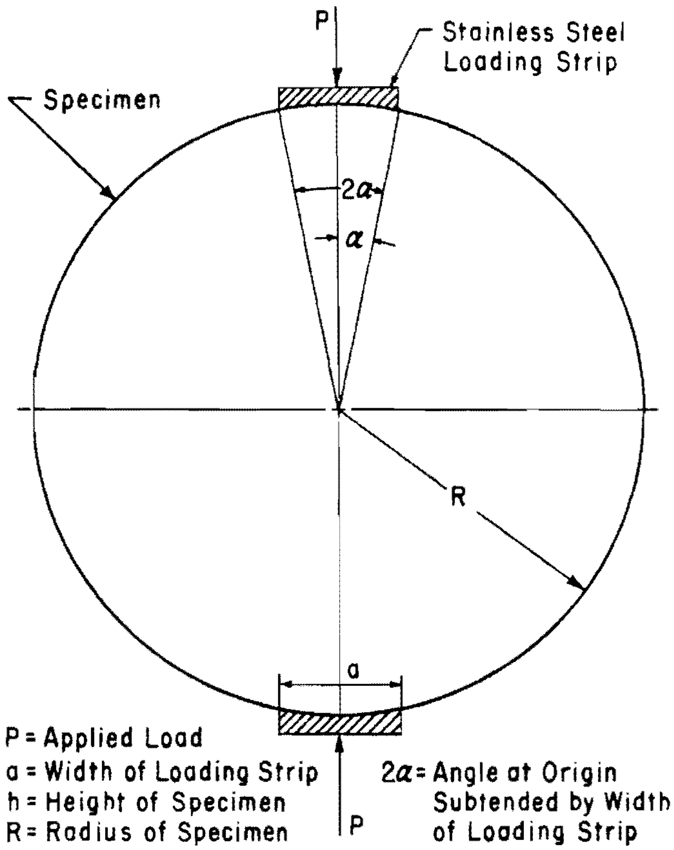


Fig 4.1. Indirect tensile test.

true when the technique is being considered for a diverse variety of highway materials ranging from a brittle portland cement concrete to a viscoelastic asphalt-treated material.

Experimental work was, therefore, conducted to investigate the applicability of the indirect tensile test for estimating modulus of elasticity, Poisson's ratio, and failure strains of various highway materials. The testing program used in that study, outlined in Appendix 5, involved a comparison of tensile strains, modulus of elasticity, and Poisson's ratio calculated from the total deformation relationships developed by Hadley et al (Ref 4.3) with measured strains and modulus of elasticity and Poisson's ratio obtained from Hondros' theoretical equations (Ref 4.1) using measured strain data.

In this study the theoretical equations (Ref 2.25) for estimating material properties from total deformation data were verified by tests on thin aluminum and plexiglas discs. The modulus of elasticity, Poisson's ratio, and tensile strains were in excellent agreement with those values obtained from center strain data using Hondros' equations (Ref 4.1). Based on the test data presented in Appendix 5 the technique using total deformation data can also be used to adequately estimate the tensile properties of asphalt-treated, lime-treated, and cement-treated materials. Therefore, the indirect tensile test is recommended for characterizing the various stabilized pavement materials, since estimates of all the required properties, i.e., modulus of elasticity, tensile strength, and tensile strain, can be obtained from this test. The indirect tensile test is also recommended for use in characterizing portland cement concrete materials.

Although the test has been shown to be applicable on a limited basis to the evaluation of clay materials, the properties of the subgrade required for the design subsystem (see Fig 3.1) can be obtained from plate load tests, modulus of resilience tests, or any other technique which provides an estimate of the subgrade modulus of elasticity. Further work, however, is required concerning a method of characterizing subgrade materials, including the permissible compressive strains for a variety of subgrade materials.

The data presented in Appendix 5 also allow a direct comparison of design criteria for the three stabilized materials. The cement-treated materials, as expected, exhibited the highest modulus of elasticity (approximately 2.0×10^6 psi) and tensile strength (approximately 300 to 350 psi) but the lowest tensile strain at failure (approximately 150 to 250 microunits). The asphalt-treated materials exhibited the lowest modulus of elasticity of the stabilized materials (approximately 1.5×10^5 psi), a tensile strength of approximately 130 psi, and the highest tensile strain at failure (3500 to 7000 microunits). Although the modulus of elasticity of lime-treated materials (approximately 8.0×10^5 psi) fell between those for cement- and asphalt-treated materials, the tensile strength values (approximately 35 psi) were much lower than either of the other two stabilized materials. The tensile failure strains for lime-treated materials ranged from approximately 250 to 750 microunits and were, therefore, slightly higher than those for cement-treated materials. From this limited information, it can be seen that the tensile strengths and failure strains are quite different for the three stabilized materials and that a design for a specific stabilized material must be based upon both critical strength and strain criteria.

REPEATED LOADING CONSIDERATIONS

Since pavement failures have been attributed in some cases to fatigue of the pavement layers, the behavior of stabilized materials subjected to repeated applications of tensile stresses and strains is important in the design of the various pavement layers. In this design system (see Fig 3.1), the fatigue or repeated loading behavior of the various stabilized materials will be useful in establishing the design stresses and strains required in conjunction with the design equations of Chapter 3.

It is obvious that the stresses and strains which cause failure in a particular mix under static test conditions cannot be used as criteria for design of stabilized pavement layers, because one load application of this stress would cause failure in the pavement layer. Consequently the design stresses and strains must be of some magnitude which will insure that failure would not occur in the pavement layer for the desired pavement life. Although fatigue studies of the various highway materials are still in their infancy, especially for a wide variety of types, magnitudes, frequencies, and patterns of loadings, the results of the available studies can still be used to provide an estimate of design stresses and strains necessary to insure a longer fatigue life and by inference a longer pavement life.

Fatigue Results - Tensile Stresses

For this design system the fatigue strength information obtained from various fatigue studies will be used to relate the results of laboratory tests to necessary design criteria, i.e., tensile stresses which will provide for longer lasting pavements. For instance, the tensile strengths of the materials to be used in the surface and base layers would be obtained from indirect tensile tests, and then a fatigue strength ratio* would be multiplied by these limiting material properties to obtain the critical design values. An appropriate design thickness for a pavement structure with known material properties could subsequently be obtained from the design equations presented in Chapter 3 which satisfy these critical design values.

Regression analysis techniques are normally used in fatigue studies to obtain an equation relating repeatedly applied stress to the logarithm of the number of applications, and the fatigue strength is defined by this equation at a selected number of load applications or fatigue life. Since it is defined in this manner, the fatigue strength approximates the average applied stress at a particular fatigue life, i.e., some selected number of load applications. This means (1) that there are probably specimens with the same fatigue life which were subjected to a lower applied stress and (2) that approximately one-half of the specimens tested at the applied stress defined as the fatigue strength would fail prior to the selected fatigue life.

A slightly different technique is used in this design approach to obtain the fatigue strength ratio for a number of highway materials, including portland cement concrete as well as various stabilized highway materials. In this technique a line which forms a lower bound on all the test data for a particular study was used to establish the fatigue strength ratio for that material. An example of the technique is presented in Fig 4.2. This fatigue strength ratio is, therefore, one for which no failures occurred, at least through one million load applications. Fatigue strength ratios were developed for a variety of highway materials from available fatigue studies and are presented in Table 4.1.

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*Fatigue strength ratio of a material is defined here as the ratio of the fatigue strength of the material at 10^7 load applications to the ultimate strength of the material.

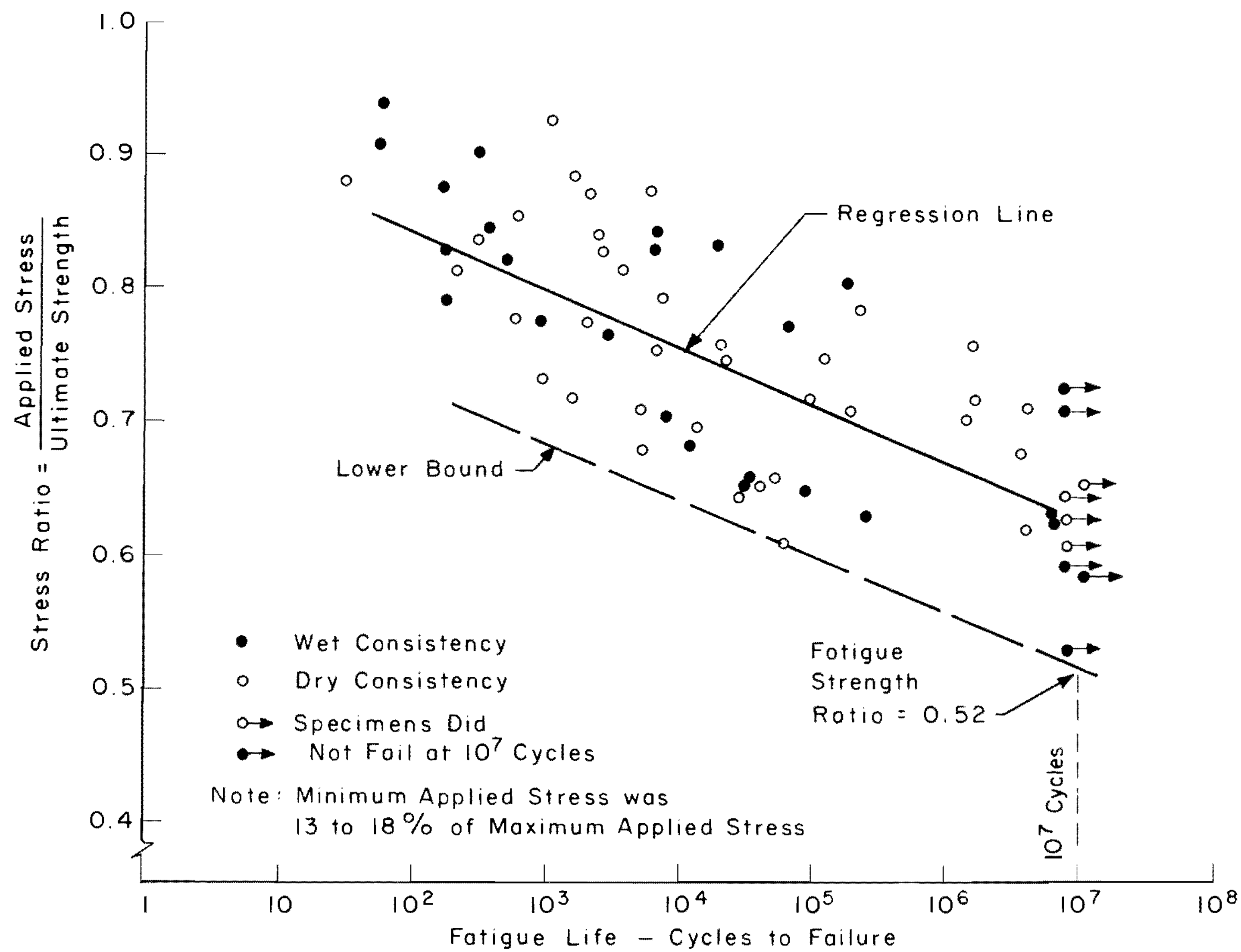

Fig 4.2. Typical fatigue results of a portland cement (Ref 4.29).

TABLE 4.1. RECOMMENDED LOWER BOUND FATIGUE STRENGTH RATIOS FOR DIFFERENT HIGHWAY MATERIALS (ONE MILLION LOAD APPLICATIONS)

Portland cement concrete	.52
Soil cement-cement treated materials	.35
Lime-treated materials	.35
Asphalt-treated materials	.125

TABLE 4.2. RECOMMENDED ALLOWABLE TENSILE STRAINS FOR DIFFERENT HIGHWAY MATERIALS

Material Types	Allowable Tensile Strains (microunits)
Portland cement concrete	20
Cement-treated materials	20
Lime-treated materials	20
Asphalt-treated materials	50

Information concerning the effect of temperature on fatigue strength ratio of asphalt-treated materials is not yet available; therefore, the fatigue strength ratio is assumed to be the same (0.125) regardless of the temperature of the material, i.e., the fatigue strength ratio is independent of temperature. Further fatigue research studies are needed to determine the validity of this assumption.

Fatigue Results - Tensile Strains

Most fatigue studies have been concerned primarily with an evaluation of fatigue strength; therefore, there is a definite lack of information concerning fatigue strain ratios, i.e., ratio of repeated applied strain to ultimate failure strain at some preselected number of load applications. In fact there is very little information available about the effects of repeatedly applied tensile strains on the behavior of the various pavement materials. Although there is no information about fatigue strain ratios there are, however, fatigue data available which can be used to recommend allowable tensile strains.

Hilsdorf and Kesler (Ref 4.29) found from fatigue tests on portland cement concrete that the tensile strain at failure was independent of fatigue life at least for tensile strains ranging from 20 to 30 microunits. Based upon this data a limiting tensile strain under repeated loading must be less than 21 microunits. As a result a minimum allowable tensile strain of 20 microunits is recommended for portland cement concrete. Moore and Kennedy (Refs 4.27 and 4.28) found in a fatigue study of asphalt-treated materials that an estimated initial tensile strain of approximately 50 microunits corresponded to a fatigue life of one million load applications. These two studies form the basis for the recommended design strains outlined in Table 4.2. Although there are no fatigue-strain data available for lime-treated and cement-treated materials, their behavior is assumed to be similar to that of portland cement concrete and the same design strain of 20 microunits is tentatively recommended for these two materials.

Compressive Strain in Subgrade

Information concerning the allowable compressive strain for subgrade materials is limited to that suggested by Dormon and Metcalf (Ref 2.10).

Based on their recommendations, a critical design compressive strain of 420 microunits, which corresponds to ten million load applications, is accepted for use in this design subsystem; however, more research is required in this area to substantiate the validity of this design criteria.

EFFECTS OF TEMPERATURE AND RATE OF APPLICATION OF LOAD ON PROPERTIES OF ASPHALTIC MATERIALS

The use of asphalt-stabilized pavement layers creates a special problem for the design of a pavement section since material properties such as modulus of elasticity, Poission's ratio, tensile strength, and tensile strain at failure are a function of both the rate of application of load and the temperature of the stabilized layer.

Because layered theory was selected as the basic design theory for this design approach, the effects of temperature and rate of loading must be considered when selecting a modulus of elasticity which is representative of the in-service asphalt-stabilized layer. The selection process should be of such general nature that limiting material properties such as tensile strength and tensile strain at failure which are representative of existing conditions can be selected in light of applicable estimates of temperature and rate of loading.

Therefore, another important part of this design approach is a requirement for a technique with which to evaluate the effects of temperature and rate of loading on the properties of asphalt stabilized mixtures. Based on a previous study by Hudson and Kennedy (Ref 4.3) a set of curves (Figs 4.3 through 4.5) were developed depicting the relationship between material properties and temperature and rate of loading for use with asphalt stabilized materials. The procedures and data as well as equations used in the development of these figures are included in Appendix 6. These curves can be used to estimate changes in material properties for two different design conditions. Curve A should be used in the design of pavements for most highways, while curve B should be used in the design of low-speed facilities in which frequent stops or delays are expected, e.g., some city streets and parking areas.

The ordinate scale of the figures represents index numbers for the various material properties. These index numbers can be used to obtain

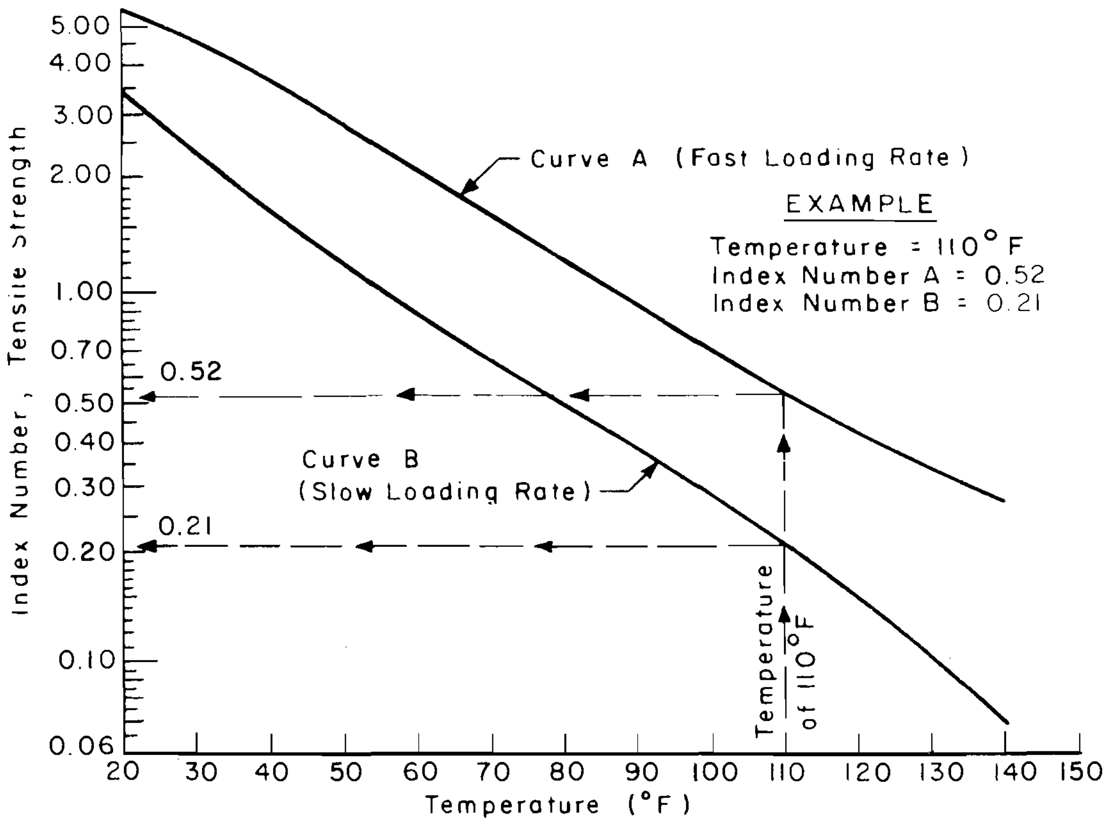

Fig 4.3. Tensile strength index numbers for various temperatures and loading rates.

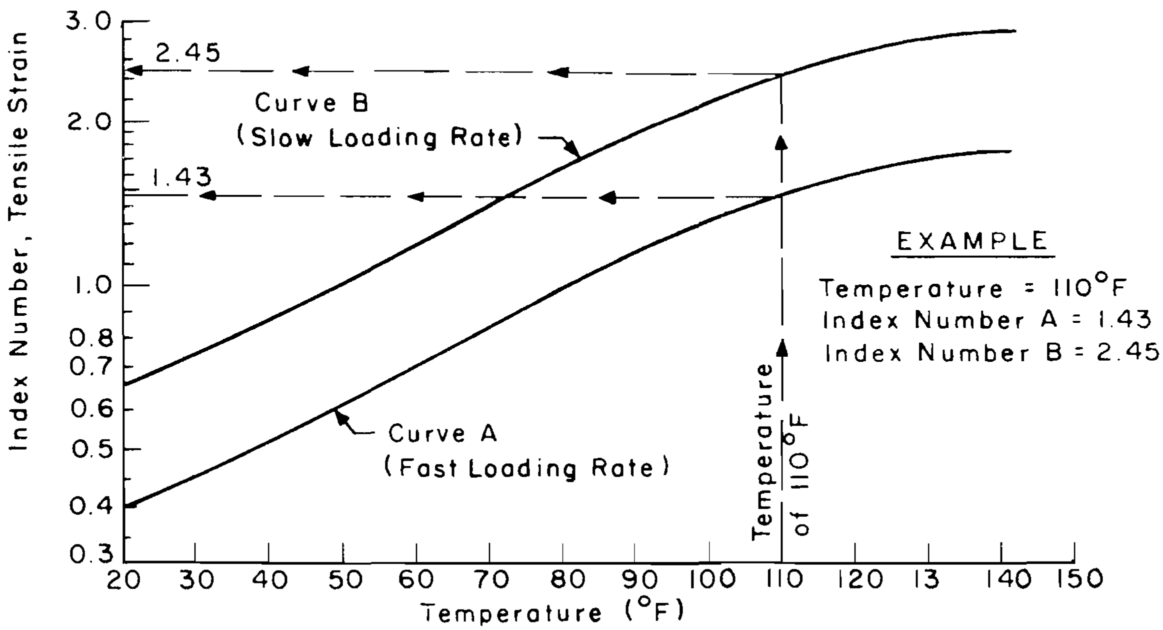

Fig 4.4. Tensile strain index numbers for various temperatures and loading rates.

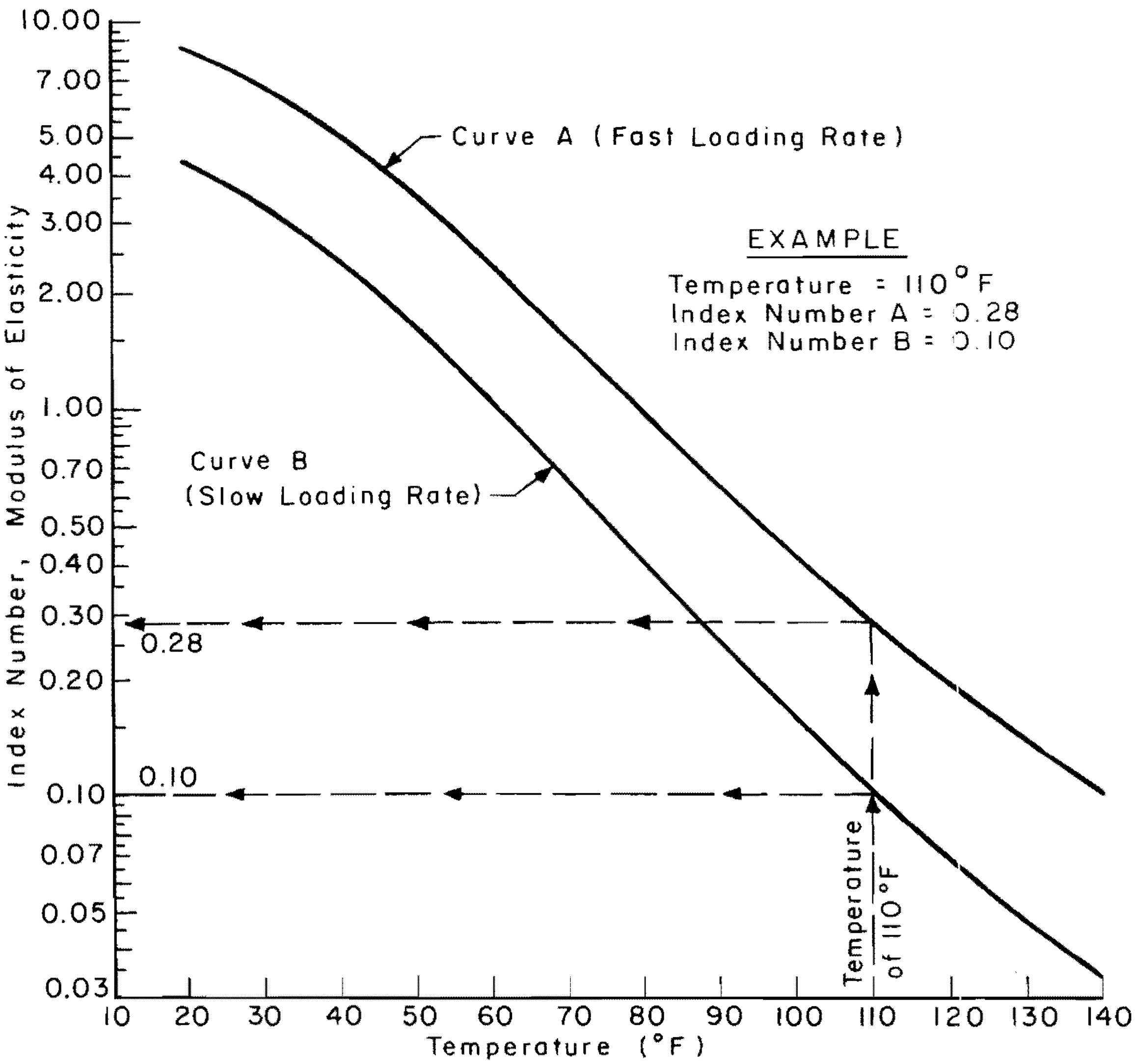

Fig 4.5. Modulus of elasticity index numbers for various temperatures and loading rates.

estimates of the different material properties by multiplying the numbers times the properties obtained from the indirect tensile test at standard test conditions.* The curves are used by entering with an estimate of the temperature of the asphalt layer and projecting a line vertically until it intersects with either curve A or B. An index number is obtained by projecting a line horizontally from this intersection to the ordinate scale.

The procedure is illustrated in an example problem. Indirect tensile tests conducted at standard conditions produced the material properties presented in column 1 of Table 4.3. Estimates of these properties are desired for an asphaltic layer at a temperature of 110^{o} F. Each of the index numbers for the three properties is obtained from Figs 4.3 through 4.5 and included in columns 2 and 3 of Table 4.3 for curves A and B respectively. The resulting estimates at 110^{o} F are obtained from the product of the original material properties and index numbers and are presented in columns 4 and 5 of Table 4.3.

The curves presented in these figures can be used to obtain estimates of material properties provided adequate design temperature information is available. Under actual conditions the temperature of an asphaltic layer varies not only on an hourly, daily, monthly, and seasonal basis, but also with the location of the asphaltic layer in the pavement structure. Estimates of the temperature of an asphaltic layer in a flexible type pavement can be obtained from theory (Refs 4.30 through 4.32) and actual test results (Refs 4.32 through 4.35). However, similar estimates for composite pavements, i.e., portland cement concrete with a stabilized subbase, cannot at present be made because no technique is available for estimating the temperature in the various layers of the pavement structure.

Because of this situation a simplified technique is recommended for use in this design system. The recommended approach is to use two different design temperatures: one representative of fall and winter conditions, and the other of summer conditions. It is further recommended that the average ambient temperature for these two periods be used in estimating the design temperature. These temperatures are expected to approximate those attained in the base or subbase layer of the pavement structure during the two design periods.

*Standard test conditions of indirect tensile test are a test temperature of 75^{o} F and approximate loading rate of 2.0 inches/minute.

TABLE 4.3. EXAMPLE PROBLEM ILLUSTRATING THE PROCEDURE FOR ESTIMATING PROPERTIES OF ASPHALTIC MATERIALS

Material Property	Results of Indirect Tensile Test	Index Numbers* from Curve		Estimated Properties at 110° F for Curve	
		A	B	A	B
Modulus of elasticity, 10^5 psi	2.5	0.10	0.28	0.25	0.70
Tensile strength, psi	100	0.52	0.21	52	21
Tensile strain, microunits	400	1.43	2.45	572	980

*Dimensionless numbers.

Application of Index Numbers to Thickness Design of Asphaltic Stabilized Layers

The tensile strength index numbers for a given pavement design temperature can be used in conjunction with the recommended fatigue strength ratio for asphalt stabilized materials listed in Table 4.1 to obtain the design stresses for use with the design equations of Chapter 3. For example the design stresses for the hypothetical problem presented in Table 4.3 would be 6.5 psi (100 psi $\times$ 0.52 $\times$ .125 = 6.5 psi) for a Type A facility and 2.6 psi for a type B facility. As previously indicated a minimum design strain of 50 micro-units is tentatively recommended for design of all asphalt stabilized materials (see Table 4.2). The tensile strain index curves cannot at present be used because of the lack of a fatigue strain ratio. In addition, the modulus of elasticity index numbers for the pavement design temperatures can also be used to obtain modulus of elasticity of asphaltic materials for use in the design equations of Chapter 3.

SUMMARY

This chapter was concerned with the development of techniques for characterizing highway materials for direct application with the design equations of Chapter 3. Laboratory results indicated that the indirect tensile test can be used to estimate the tensile properties of a variety of stabilized highway materials. The results of fatigue studies were used as a basis for establishing minimum design strains and fatigue strength ratios which are useful in estimating the design stress criteria. In addition, curves are presented which allow estimates of the properties of asphalt-treated materials under various temperature design conditions.

The material characterization techniques presented in this chapter fulfill the requirements for the first two phases of the design system (see Fig 3.1). The techniques provide the necessary information for use of the system in the structural design of a subbase.

The next chapter includes example problems which illustrate the use of the characterization techniques and the design equations (1 through 12) in the structural design of various stabilized subbase layers.

CHAPTER 5. APPLICATION OF DESIGN TECHNIQUE

INTRODUCTION

Three design examples are presented in this chapter to illustrate the overall approach necessary in the structural design of a subbase.

(1) The first example includes a detailed structural design of an asphalt-stabilized subbase layer under a portland cement concrete surface layer and involves an evaluation of two hypothetical portland cement concrete mix designs and two surface thicknesses.

(2) The second example involves the structural design of a cement-stabilized subbase layer for a rigid pavement structure and includes an evaluation of subbase thickness requirements for two surface layer thicknesses as well as two hypothetical portland cement concrete mix designs.

(3) The final example problem illustrates the application of this approach to the design of asphalt-stabilized base layers in flexible pavement types and includes thickness requirements for five surface layer thicknesses.

PROBLEM NO. 1 - DESIGN OF AN ASPHALT-STABILIZED SUBBASE LAYER FOR A RIGID PAVEMENT STRUCTURE

This example problem illustrates the steps necessary in the design of an asphalt-stabilized subbase layer for a rigid pavement structure. The total design analysis included an evaluation of asphalt-stabilized subbase thickness requirements for summer and winter conditions as well as design considerations for two surface thicknesses and two portland cement concrete mixes. This example is not meant to provide a complete analysis of the factors in the design equations which can affect subbase requirements but to provide an indication of the relative effects of two levels of the factors included in this example problem. A comprehensive design analysis would include a larger number of mix designs for the surface and base layers as well as a variety of surface thicknesses in order to allow selection of a final structural pavement design based upon such decision criteria as availability of funds, safety, and cost of construction. The different mix designs would be characterized by varying material properties and would probably require different subbase thicknesses.

In this particular example, the surface thickness was varied to provide an estimate of the effect of changes in surface thickness on subbase thickness and two surface layer mix designs were included in the analysis to provide an indication of the effect of changes in mix design on the required subbase thickness. Structural designs were obtained for both the expected summer (mean ambient temperature of 85° F) and winter temperature conditions (mean ambient temperature of 65° F).

The first step in the design process involves characterization of the materials used in the various pavement layers. The properties assumed for the portland cement concrete mixes and the asphalt-treated material are presented in Table 5.1 and are representative of values obtained from indirect tensile tests conducted at The University of Texas at Austin. The modulus of elasticity of the subgrade is assumed to be 8000 psi and average ambient summer and winter temperatures are expected to be 85° F and 65° F respectively. These two design temperatures are used in conjunction with Figs 4.3 and 4.5 to obtain estimates of modulus of elasticity and tensile strength for asphalt-stabilized materials which are representative of the two design periods. For instance, an index number for tensile strength of 1.075 is obtained from curve A of Fig 4.3 for a temperature of 85° F. A tensile strength of 100 psi is then obtained from the product of the tensile strength of 93 psi and an index number of 1.075. The same approach is also used to estimate modulus of elasticity values for the two design periods. The resulting estimates of material properties for the two design periods are outlined in Table 5.2.

The second step involves determination of the design stress criteria for the various pavement layers. The design stress criteria are obtained from the product of the design tensile strength (Tables 5.1 and 5.2) and the recommended fatigue strength ratios (Table 4.1) for the various pavement materials. The results of the procedure for obtaining the design stresses are presented in Table 5.3. For this example, the design stresses for the surface layer were 160 psi and 140 psi respectively for portland cement concrete mixes 1 and 2, and were 12.5 psi and 22.5 psi respectively for the asphalt-stabilized subbase for the summer and winter design conditions. The design strain criteria used are those recommended previously in Table 4.2.

The third step involves substitution of the various material properties, design criteria, and surface layer thickness in the design equations of Chapter 3 and solving for the subbase thicknesses which satisfy each of the five

TABLE 5.1. MATERIAL PROPERTIES OF PORTLAND CEMENT CONCRETE AND ASPHALT-TREATED MATERIAL - PROBLEM NO. 1

Portland Cement Concrete	
Mix No. 1	
Modulus of elasticity	4.75×10^6 psi
Tensile strength	310 psi
Mix No. 2	
Modulus of elasticity	3.50×10^6 psi
Tensile strength	270 psi
Asphalt-Treated Material*	
Modulus of elasticity, 75^o F	1.850×10^5 psi
Tensile strength, 75^o F	93 psi
Subgrade Material	
Modulus of elasticity	8.00×10^3 psi
Average summer temperature	85^o F
Average winter temperature	65^o F

*Results from indirect tensile test at standard conditions.

TABLE 5.2. DESIGN MODULUS OF ELASTICITY AND TENSILE STRENGTHS FOR ASPHALT-TREATED MATERIALS - PROBLEM NO. 1

	Design Conditions and Temperatures	
	Summer 85° F	Winter 65° F
Tensile strength, 75° F, psi	93	93
Index number for tensile strength (1)	1.075	1.95
Design tensile strength, psi	100	180
Modulus of elasticity, 75° F, 10^5 psi	1.85	1.85
Index number for modulus of elasticity (2)	0.81	1.89
Design modulus of elasticity, 10^5 psi	1.50	3.50

(1) From Fig 4.3.

(2) From Fig 4.5.

TABLE 5.3. DETERMINATION OF DESIGN CRITERIA FOR USE IN DESIGN EQUATIONS - PROBLEM NO. 1

Material	Design Tensile Strength, psi	Fatigue Strength Ratio (1)	Design Stress, psi (2)	Design Strain, (3) Microunits
Portland cement concrete				
Mix No. 1	310	0.52	160	20
Mix No. 2	270	0.52	140	20
Asphalt-treated				
Summer conditions	100	0.125	12.5	50
Winter conditions	180	0.125	22.5	50

(1) See Table 4.1.

(2) Design stress = (fatigue strength ratio) × (tensile strength).

(3) See Table 4.2.

design criteria. The solutions to each of the eight individual designs evaluated in this example are presented in Table 5.4.

The final step in the design process includes a comparison of the different design thicknesses and with the aid of a set of decision criteria the selection of a final subbase design thickness. For this example, only the eight different critical design thicknesses are compared. After the decision criteria are established the final design could be selected from these eight critical subbase designs.

The subbase requirements for a rigid pavement structure with 7-1/2 inches of portland cement concrete mix number 1 ($E_s = 4.75 \times 10^6$ psi) ranged from 4.3 inches during the winter design period to 7.1 inches during the summer design period, and the subbase requirements for the same thickness of surface design mix number 2 ($E = 3.5 \times 10^6$ psi) ranged from 4.8 inches during winter to 7.1 inches during summer. Therefore, a critical subbase thickness of 7.1 inches was required for both surface layer mix designs.

On the other hand, subbase thickness requirements for an 8-1/2-inch surface-layer thickness ranged from approximately 1.8 inches during the winter to 3.4 inches during summer for surface mix design number 1 ($E = 4.75 \times 10^6$ psi). Similarly for surface mix design number 2 ($E = 3.50 \times 10^6$ psi) the subbase design thickness ranged from 2.7 inches to 3.4 inches for winter and summer design conditions, respectively. Based on these results (Table 5.4) a critical subbase design thickness of 3.4 inches is required with an 8-1/2 inch surface thickness for both design mixes.

The critical subbase thicknesses, i.e., the greatest thickness required to satisfy the five design criteria, for the eight alternate designs are presented in Table 5.5. From these results it can be seen that for this particular example problem

(1) an increase in surface layer thickness reduced the required subbase thickness, and

(2) the change in surface layer mix designs had very little effect on subbase requirements.

The results of the eight different designs presented in Table 5.5 can also provide information concerning the possible existence of a single controlling design criterion, i.e., the criterion which always requires thicker subbases. If one criterion produced the critical design in each of the eight cases there would be some evidence that only that particular criterion need be

TABLE 5.4. SUBBASE THICKNESS REQUIREMENTS FOR A NUMBER OF DESIGN CONDITIONS - PROBLEM NO. 1

Surface Layer Thickness	Mix Design	Modulus of Elasticity: Surface (10^6 psi)	Subbase (10^5 psi)	Subgrade (10^3 psi)	Subbase Thickness for Design Criteria of: σ_b	ϵ_b	ϵ_c	σ_s	ϵ_s
7.5	1	4.75	3.50 (w)*	8.0	0	0	0	3.0	4.3
7.5	1	4.75	1.5 (s)	8.0	0	0	0	4.0	7.1
8.5	1	4.75	3.5 (w)	8.0	0	0	0	0	1.8
8.5	1	4.75	1.5 (s)	8.0	0	0	0	0	3.4
7.5	2	3.5	3.5 (w)	8.0	1.8	0	0	4.8	4.3
7.5	2	3.5	1.5 (s)	8.0	0	0	0	6.8	7.1
8.5	2	3.5	3.5 (w)	8.0	0	0	0	2.7	1.8
8.5	2	3.5	1.5 (s)	8.0	0	0	0	2.8	3.4

*The letter in parentheses following the modulus of elasticity of the subbase indicates the design temperature for the asphalt-stabilized layer, i.e., s is the average summer temperature, 85° F, and w the average winter temperature, 65° F.

TABLE 5.5. A SUMMARY OF CRITICAL DESIGNS - PROBLEM NO. 1

Mix Design No.	Portland Cement Concrete Modulus of Elasticity, (10^6 psi)	Surface Thickness	Design Information Subbase Thickness	Design Information Controlling Criteria
1	4.75	7.5	4.3 (w)*	ϵ_s
1	4.75	7.5	7.1 (s)	ϵ_s
1	4.75	8.5	1.8 (w)	ϵ_s
1	4.75	8.5	3.4 (s)	ϵ_s
2	3.50	7.5	4.8 (w)	σ_s
2	3.50	7.5	7.1 (s)	ϵ_s
2	3.50	8.5	2.7 (w)	σ_s
2	3.50	8.5	3.4 (s)	ϵ_s

*The letter in parentheses following the subbase thickness indicates the design period, i.e., s is for the summer design period and w is for the winter design period.

evaluated, thereby simplifying the design process. This possibility was not substantiated by the results. For example, the tensile stress and strain criteria in the surface layer were the controlling criteria for each of the four designs with an 8-1/2-inch surface layer. However, tensile strain in the surface layer was the controlling criterion for the four alternate designs with a 7-1/2-inch surface layer. With one exception, there were no thickness requirements for the subbase layer based on tensile stress or strain in the subbase and the compressive strain in the subgrade. In the case of the design criteria for the subbase layer, i.e., tensile stress or strain in the subbase, the fact that no subbase thickness is required does not necessarily mean that a subbase is not required, but rather indicates either that a minimum thickness of that material is adequate or that a lower quality stabilized subbase material, i.e., a material with lower tensile strength, may be used in this particular design analysis.

PROBLEM NO. 2 - DESIGN OF A CEMENT-STABILIZED SUBBASE FOR A RIGID PAVEMENT

This example illustrates the procedure for design of cement-stabilized subbases and provides an indication of changes in subbase thickness requirements for two different surface thicknesses of the two hypothetical portland cement concrete mixes used in the first problem. In addition, the results of this example allow for a limited comparison between thickness requirements for cement-stabilized and asphalt-stabilized materials for similar surface thicknesses and mix designs.

The material properties assumed for the two portland cement concrete mixes and the cement-stabilized mixture are presented in Table 5.6 and are representative of those obtained from indirect tensile tests conducted at The University of Texas at Austin. The modulus of elasticity of the subgrade is assumed to be 8000 psi. The design stresses for the various materials are also included in Table 5.6 and were obtained from the product of the design tensile strength and the recommended fatigue strength ratios (Table 4.1). For example, the design stress of 87.5 psi for the cement-treated subbase material was obtained by multiplying the tensile strength of 250 psi times a fatigue strength ratio of 0.35 (250 psi x 0.35 = 87.5 psi). The design strain criteria are also included in the table and are those recommended previously (Table 4.2).

TABLE 5.6. MATERIAL PROPERTIES FOR PORTLAND CEMENT CONCRETE AND CEMENT-STABILIZED MIXTURES: CEMENT-STABILIZED SUBBASE FOR RIGID PAVEMENT DESIGN - PROBLEM NO. 2

	Material Type		
	Portland Cement Concrete		Cement-Stabilized Material
	Mix No. 1	Mix No. 2	
Modulus of elasticity (10^6 psi)	4.75	3.50	1.00
Tensile strength, psi	310	270	250
Fatigue strength ratio (1)	0.52	0.52	0.35
Design tensile stress, psi (2)	160	140	87.5
Design tensile strain, microunits (3)	20	20	20

(1) See Table 4.1.

(2) Design stress = (fatigue strength ratio) x (tensile strength)

(3) See Table 4.2.

The subbase design thicknesses for the four design conditions were obtained by substituting the various material properties, surface thickness, and design criteria in the appropriate design equation and by solving for the subbase thicknesses which satisfy each of the five design criteria. The solutions to each of the four individual designs are presented in Table 5.7.

The design thicknesses for the cement-treated layer ranged from 5.9 to 9.0 inches. The tensile strain criteria for the subbase layer ϵ_b provided the critical design thickness in all four cases. From Table 5.7 it can be seen that neither the tensile stress criteria for the subbase layer σ_b nor the compressive strain criteria for the subgrade ϵ_c produced any requirements for a subbase. However, a thin subbase layer (less than 3.0 inches) was necessary based upon tensile stress and tensile strain in the surface layer.

The results in Table 5.7 show that an increase in the surface layer from 7.5 inches to 8.5 inches for either mix resulted in an approximate 1-1/2-inch decrease in subbase thickness. On the other hand, changes in the portland cement concrete mix design from mix number 1 ($E_s = 4.75 \times 10^6$ psi and S_T = 310 psi) to mix number 2 ($E_s = 3.50 \times 10^6$ psi and S_T = 270 psi) resulted in approximately a 1-1/2-inch increase in subbase thickness. Therefore, in this example the change in mix design produced approximately the same change in subbase thickness as a 1-inch change in thickness of the surface layer. As expected the thicker pavement surface of the higher quality mix (mix number 1) required the thinnest subbase thickness.

A comparison limited to the hypothetical materials assumed in the first two problems can be made between thicknesses of asphalt-treated and cement-treated subbase layers from the results presented in Table 5.8. For a 7-1/2-inch-thick surface layer, approximately the same subbase thickness is required for the two stabilized material types (difference in thickness of 0.6 and 1.9 inches); however, for the thicker pavement surface (T_s = 8.5 inches) the subbase requirements for the asphalt-treated material are approximately one-half of the requirements for the cement-treated material.

PROBLEM NO. 3 - DESIGN OF AN ASPHALT-STABILIZED BASE FOR A FLEXIBLE PAVEMENT

This final problem is presented to illustrate the applicability of the design approach to flexible pavements. The hypothetical pavement section

TABLE 5.7. SUBBASE THICKNESS REQUIREMENTS FOR VARIOUS DESIGN CRITERIA: CEMENT-STABILIZED SUBBASE FOR RIGID PAVEMENT DESIGN - PROBLEM NO. 2

Surface Thickness, inches	Mix Design No.	Modulus of Elasticity			Subbase Thickness for Design Criteria, inches				
		Surface (10^6 psi)	Subbase (10^5 psi)	Subgrade (10^3 psi)	σ_b	ϵ_b	ϵ_c	σ_s	ϵ_s
7.5	1	4.75	10.0	8.0	0	7.7*	0	2.0	1.0
7.5	2	3.5	10.0	8.0	0	9.0*	0	2.8	1.0
8.5	1	4.75	10.0	8.0	0	5.9*	0	1.5	0.6
8.5	2	3.5	10.0	8.0	0	7.4*	0	2.7	0.6

*Critical design thickness.

TABLE 5.8. A COMPARISON OF SUBBASE THICKNESS REQUIREMENTS

Mix Design No.	Surface Layer: Modulus of Elasticity (10^6 psi)	Surface Layer: Thickness, inches	Subbase Thickness Requirements, inches, for Asphalt-treated Material (1)	Subbase Thickness Requirements, inches, for Cement-treated Material (2)
1	4.75	7.5	7.1	7.7
1	4.75	8.5	3.4	5.9
2	3.5	7.5	7.1	9.0
2	3.5	8.5	3.4	7.4

(1) Results of problem no. 1.

(2) Results of problem no. 2.

includes a hot mix asphaltic concrete (HMAC) surface and an asphalt-stabilized base layer.

The material properties assumed for the two pavement layers are presented in Table 5.9 and are typical of those obtained from laboratory evaluation of various asphalt-treated materials (Refs 3.1 and 3.2). The modulus of elasticity of the subgrade is assumed to be 12,000 psi. The design criteria used in this design problem are also presented in Table 5.9. The design stresses were obtained from the product of recommended fatigue strength ratios (see Table 4.1) for asphaltic materials (0.125) and the tensile strengths. The design tensile strain criteria are those recommended previously (see Table 4.2). For ease of analysis, only a design for winter temperature conditions was provided.

Base design thicknesses were obtained for five different surface thicknesses of HMAC by substituting the various properties, surface thickness, and design criteria into Eqs 6 through 10 and solving for the subbase thicknesses which satisfy each of the five design criteria. The solutions to each of the five individual designs are presented in Table 5.10. From the results in this table it can be seen that the tensile strain criterion for the base layer was the controlling design criterion for the pavement sections with surface thicknesses less than approximately 10.0 inches while the tensile strain criterion for the surface layer was the controlling criterion for the pavement section with a surface thickness of 12 inches.

The results of this example are presented graphically in Fig 5.1 to indicate that the relationship between surface thickness and the corresponding subbase design thickness can be evaluated in this design approach. As expected, the subbase thickness requirements are reduced as the surface layer thickness is increased; however, there is a nonlinear trend between these two effects, as indicated in Fig 5.1. It is interesting to note that increases in surface layer thickness above approximately 10-1/2 inches requires an increase rather than a decrease in subbase requirements. This corresponds to the point at which the tensile strain criterion in the surface layer controls the selection of the critical design thickness (see Table 5.10). The decision as to which of the five design sections to use could therefore be based upon the most economical design obtained with the aid of Fig 5.1 and suitable decision criteria.

TABLE 5.9. MATERIAL PROPERTIES FOR ASPHALTIC CONCRETE AND ASPHALT-STABILIZED MIXTURES: FLEXIBLE PAVEMENT DESIGN - PROBLEM NO. 3

	Material Type	
	Surface Layer Hot Mix Asphaltic Concrete	Base Layer Asphalt-treated Material
Modulus of elasticity	5.00×10^5 psi	2.900×10^5 psi
Tensile strength, psi	265	180
Fatigue strength ratio (1)	0.125	0.125
Design tensile stress, psi (2)	33.1	22.5
Design tensile strain, microunits (3)	50	50

(1) See Table 4.1.

(2) Design stress = (fatigue strength ratio) x (tensile strength).

(3) See Table 4.2.

TABLE 5.10. BASE THICKNESS REQUIREMENTS FOR VARIOUS DESIGN CRITERIA: FLEXIBLE PAVEMENT DESIGN - PROBLEM NO. 3

Surface Thickness, inches	Base Thickness, inches, for Design Criteria of					Total Design Thickness, inches
	σ_b	ϵ_b	ϵ_c	σ_s	ϵ_s	
4	14.0	14.2*	1.4	4.1	0	18.2
6	12.2	12.5*	0	5.4	0	18.5
8	9.7	9.9*	0	5.9	1.8	17.9
10	5.7	5.8*	0	5.0	3.6	15.8
12	0	0	0	0	5.5*	17.5

*Critical base design thickness.

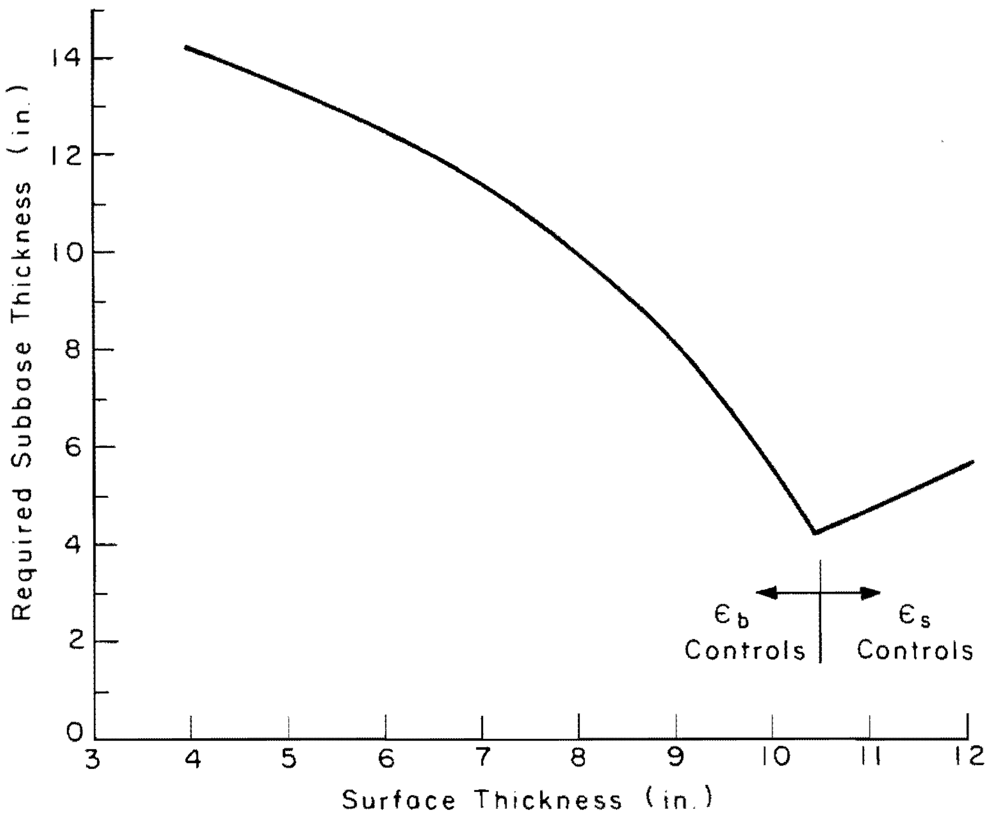

Fig 5.1. Subbase thickness requirements for various surface thicknesses - Example Problem No. 3.

A simple design analysis is required in the example presented here; however, in actual use the design process would probably be expanded to include a comprehensive evaluation of a variety of mix designs, including different aggregate types, gradations, and asphalt contents, and would subsequently provide data necessary for a systematic evaluation to determine the most economical design section. This design approach, then, provides a technique based upon structural requirements for selecting the necessary mix design and at the same time a design asphalt content. In some cases a design mix with less than an optimum asphalt content (based upon strength, fatigue, etc.) could provide an adequate and less expensive design section. The use of a more economical design section could release funds which could be used for other purposes such as safety, beautification, and construction of additional highway lanes.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

This report presents a design system which can be used for the structural design of stabilized pavement layers. A summary of the development of the design system and recommendations for future improvements to the system are stated below. The thickness requirements provided by this system are not intended to supersede established requirements, such as those resulting from expected depth of frost penetration, which may require a thicker layer.

SUMMARY

The basis for the design system is the prevention of tensile failures in the surface and subbase layers of a pavement structure involving one or more layers of stabilized materials. The design system is composed of a series of design equations as well as techniques for characterizing the properties of the materials proposed for use in the various pavement layers. Layered theory was used in the development of design equations for

(1) tensile stress in the surface layer,
(2) tensile strain in the surface layer,
(3) tensile stress in the subbase layer,
(4) tensile strain in the subbase layer, and
(5) compressive strain in the subgrade layer.

Separate equations were developed for the design of high modulus portland cement concrete rigid pavements (the modulus of elasticity of surface layer exceeds 3.5×10^6 psi) and for the design of flexible pavements and low modulus portland cement concrete pavements (the modulus of elasticity of surface layer less than 3.5×10^6 psi). Procedures for proper application of these design equations were developed, including a method for selection of a critical design thickness and practical solutions of the design equations through the use of nomographs.

Characterization techniques were also developed to provide necessary estimates of material properties as well as limiting design criteria for the materials proposed for the various pavement layers. In addition, the indirect tensile test is recommended as the principal method of characterizing the highway materials in the laboratory. A special characterization technique was developed to allow for the design of asphaltic materials for summer and winter temperature conditions.

The application of the total design system to the structural design of various types of stabilized subbase layers is illustrated in three example problems.

The design system presented here is based on a practical interpretation of layered theory which emphasizes the contribution of each individual layer to the behavior of the total pavement structure. The new design system because of its dependence on layered theory requires verification through trial use and field observation. This theoretical design system, however, offers the basis for correcting and updating by comparing designs based on the theoretical equations against observed pavement performance.

RECOMMENDATIONS

Several recommendations concerning the design system are presented in the form of immediate and future research needs.

Immediate Research Needs

Certain assumptions were made in the development of the design system which should be verified in the near future by research studies. One of the major research items involves further development of limiting tensile-strain criteria for all pavement materials.

Other immediate research needs include development of compressive-strain criteria for a variety of subgrade types, additional studies to establish definite fatigue-strength-ratio criteria for different stabilized pavement-materials, and an evaluation of the effects of temperature on the fatigue strength and fatigue strain ratios for a wide variety of asphaltic materials, including hot-mix asphaltic concrete.

The time-temperature relationships for a variety of asphaltic materials should also be investigated to determine the effects of such variables as asphalt content, aggregate type, and asphalt cement type. In conjunction with this requirement there is a need for development of a temperature distribution theory to allow for estimation of temperatures in the various layers of a pavement.

Future Research Needs

The system presented here should be augmented in the future by including some of the following items.

(1) A systematic technique is required for estimating the stresses produced by the effects of temperature so that these stresses can be superposed on the load stresses predicted by layered theory. Furthermore, a method of integrating the two systems should also be developed since temperature stresses occur over a relatively long period of time while stresses due to vehicle loads occur rapidly.

(2) Dynamic loading effects should be added to the design system with the ultimate aim of incorporating the effects of random loadings and dynamic loadings through research work in vehicle dynamics.

(3) The validity of the design approach should be evaluated by long-term observations of pavements designed in accordance with this design method and any of the other accepted base or subbase thickness requirements. Provisions should also be made in conjunction with this continuing pavement evaluation for procedures by which the system could be updated on the basis of field data.

(4) There is a definite need to investigate the cumulative damage of highway materials or the effects produced when materials or pavements are subjected to random loadings, including different stress levels and numbers of load applications. A cumulative design concept is required which will provide estimates of life of a particular highway material based on its material properties and some random loading sequence.

(5) Additional material evaluation studies are needed for a wide variety of highway materials, including a wide range of asphaltic materials, to include the use of lower quality materials in the design process, thereby allowing for a greater number of alternate designs from which a final design can be chosen.

(6) A systematic technique for estimating the effects of environmental variables on the design criteria, i.e., stresses and strains, should also be developed. The effects of such factors as freezing, aging, and moisture on the material as well as fatigue properties should also be included. For example, during aging some highway materials increase in strength and stiffness but have a corresponding decrease in allowable tensile strains. In this case, the same vehicle load could produce different stresses in the pavement structure as the pavement material ages.

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APPENDIX 1

EFFECT OF CHANGES IN POISSON'S RATIO ON STRESSES AND STRAINS IN PAVEMENT LAYERS

APPENDIX 1. EFFECT OF CHANGES IN POISSON'S RATIO ON STRESSES AND STRAINS IN PAVEMENT LAYERS

In the studies reported herein the Poisson's ratio values for the different layers were assumed for each of the pavement sections to facilitate the development of the design equations. This assumption was based on the fact that the stresses and strains were less affected by changes in Poisson's ratio values than by changes in moduli of elasticity and layer thicknesses.

Since Poisson's ratio does have an effect, it was felt that the magnitude of the effect should be evaluated. Linear elastic layered analyses were conducted on the six separate design sections indicated in Table A1.1. Both thin and thick pavement sections were evaluated. The load configuration presented in Fig 3.3 was used in the analysis. For each design section all possible combinations of Poisson's ratios for surface and base layers indicated in Fig A1.1 were analyzed. Each of the stresses and strains obtained for the individual runs was normalized by the values for the standard design section; i.e., that design section with Poisson's ratio of surface and base course both equal 0.25. An example of the technique is included in Fig A1.1 for tensile stress in subbase layer from design number 4 of Table A1.1. These normalized values can therefore be used as correction factors to alter the basic design stresses and strains for changes in Poisson's ratio of the surface and base layers.

The results of the analyses are presented in Figs A1.2 through A1.5. From the figures it can be seen that changes in Poisson's ratio for the upper two layers can effect changes in all stresses and strains; however, changes in Poisson's ratio values for a particular layer have a greater effect on the tensile stress in that layer than on the stresses and strains in the other layers. In addition, the normalized strain values were less affected than the normalized stress values by changes in Poisson's ratios of the two layers. There was also good agreement between the results for the thin and the thicker pavement sections.

From Figs A1.2 through A1.5 it can be seen that extreme values of Poisson's ratio in base and surface layers, i.e., 0.0 and 0.50, create large changes in the theoretical stresses and strains. For example, from Fig A1.4

TABLE A1.1. DIFFERENT DESIGN SECTIONS USED IN INVESTIGATION OF EFFECTS ON POISSON'S RATIO

Variable	Design Number 1	2	3	4	5	6
Modulus of elasticity surface layer, 10^6 psi	1.5	1.5	3.5	3.5	6.5	6.5
Thickness of surface layer, inches	3.0	9.0	3.0	9.0	3.0	9.0
Modulus of elasticity subbase layer, 10^5 psi	1.0	1.0	5.0	5.0	15.0	15.0
Thickness of subbase layer, inches	3.0	9.0	3.0	9.0	3.0	9.0
Modulus of elasticity subgrade, 10^3 psi	5.5	5.5	15.5	15.5	15.5	15.5

Poisson's Ratio Surface Layer \ Poisson's Ratio Subbase Layer	0	.125	.25	.375	.50
0	12.94 .855	14.07 .930	15.42 1.019	17.08 1.129	19.25 1.272
.125	12.91 .853	14.03 .927	15.37 1.016	17.02 1.125	19.18 1.268
.25	12.72 .841	13.82 .913	15.13 1.000	16.75 1.107	18.87 1.247
.375	12.36 .817	13.41 .886	14.67 .970	16.24 1.073	17.53 1.159
.50	11.76 .777	12.75 .843	13.93 .921	15.41 1.019	17.35 1.147

← Tensile Stress, psi *
← Normalized Stress, psi

Standard Design Section (Poisson's ratio .25 surface layer, .25 subbase layer)

* Tensile stress in subbase layer design section no. 4 of Table A1.1. The normalized stresses were obtained by dividing each of the stresses by the stress for the standard design section.

Fig A1.1. Factorial arrangement of different combinations of Poisson's ratio values investigated.

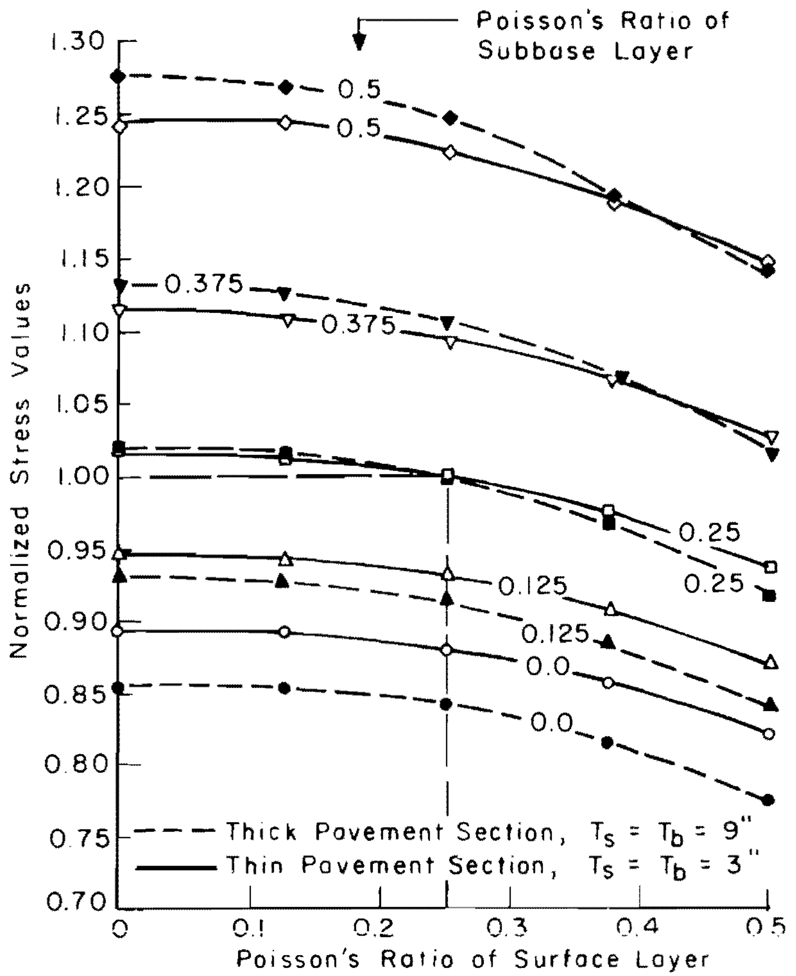


Fig A1.2. Effect of changes in Poisson's ratio of surface and subbase layers on tensile stress in subbase layer.

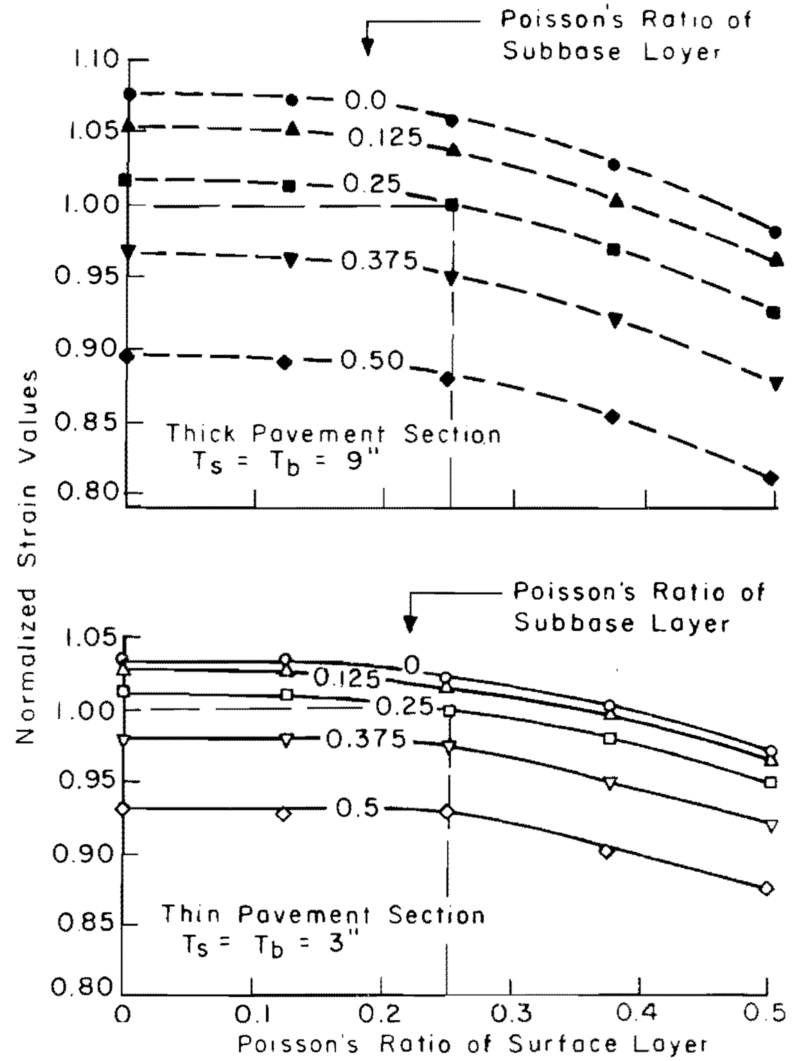


Fig A.13. Effect of changes in Poisson's ratio of surface and subbase layers on tensile strain in subbase layer and compressive strain in subgrade.

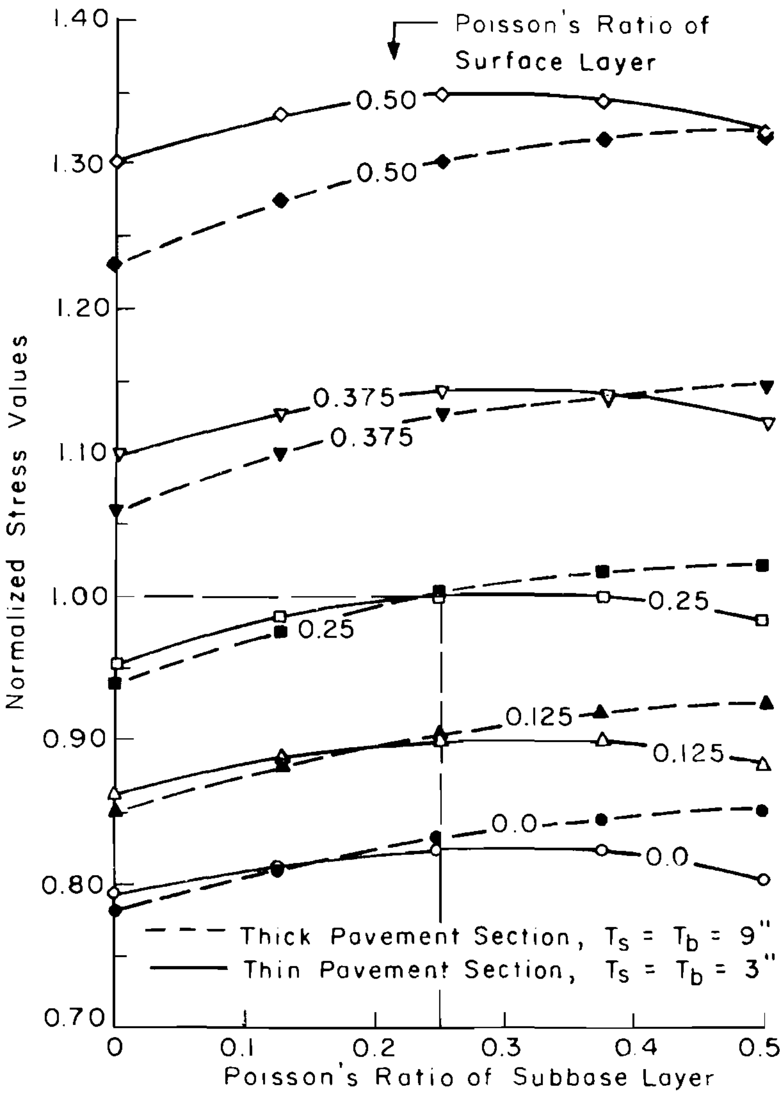


Fig A1.4. Effect of changes in Poisson's ratio of surface and subbase layers on tensile stress in surface layer.

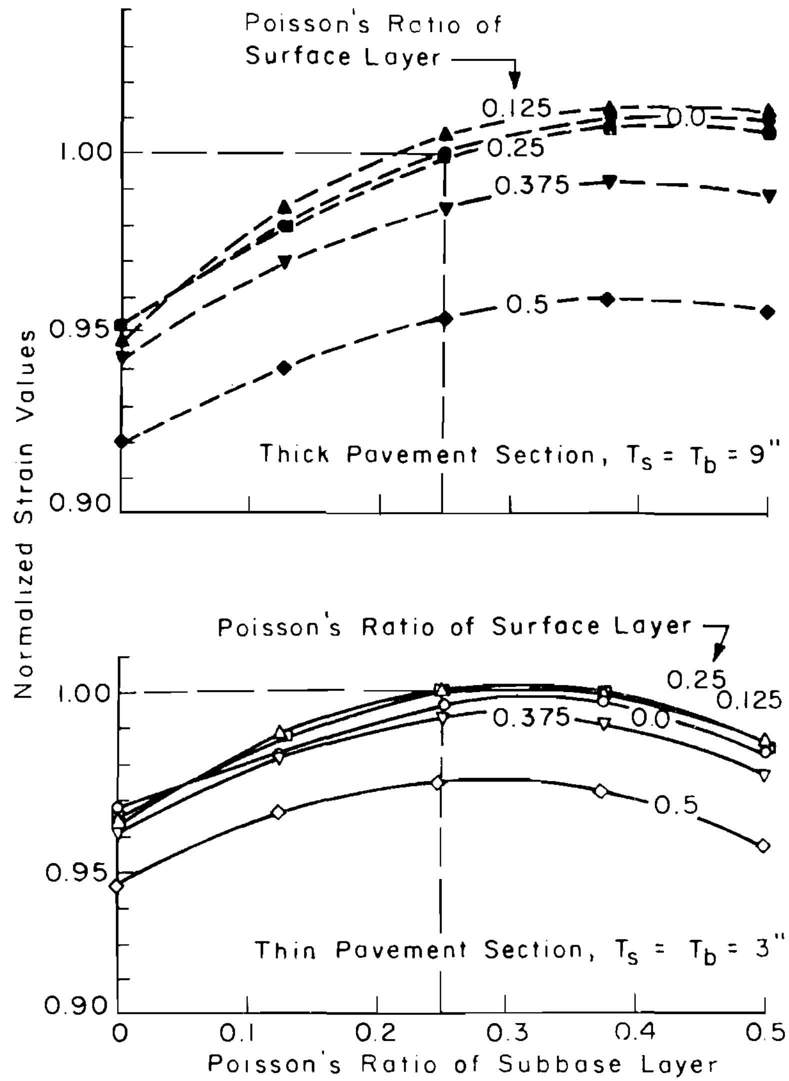


Fig A1.5. Effect of changes in Poisson's ratio of surface and subbase layers on tensile strain in surface layer.

a Poisson's ratio of 0.5 for the surface layer produces up to a 35 percent increase in the theoretical tensile stress values and up to 19 percent decrease in the theoretical strain in the surface layer, while a Poisson's ratio of 0.0 in the surface layer creates up to a 20 percent decrease and an 8 percent increase in the theoretical stress and strain values, respectively. On the other hand, for a more realistic range of Poisson's ratio in the two layers of 0.125 to 0.375, maximum changes of 15 percent and 8 percent were produced in the theoretical stress and strain values, respectively.

Therefore, from a theoretical standpoint a change in Poisson's ratio of the particular highway material used in the pavement can create changes in stress and strains developed in the pavement layers. The effect in general is not as great as that produced by other properties such as modulus of elasticity and thicknesses of the layers. This is evident from comparison of the design curves in Appendices 3 and 4 with the results presented in Figs A1.2 through A1.5. Nevertheless, consideration should be given to the effects of Poisson's ratio on theoretical stresses and strains, and Figs A1.2 through A1.5 can be useful in estimating these changes.

APPENDIX 2

EFFECT OF CHANGES IN MAGNITUDE OF LOAD AND CONTACT PRESSURE ON STRESSES AND STRAINS IN PAVEMENT LAYERS

APPENDIX 2. EFFECT OF CHANGES IN MAGNITUDE OF LOAD AND CONTACT PRESSURE ON STRESSES AND STRAINS IN PAVEMENT LAYERS

The recoverable or elastic stresses and strains induced in the pavement layers by moving traffic loads are dependent not only upon the properties of the layers of the pavement system but also upon the magnitude of the load applied and the contact pressure of the load with the pavement surface. Since the load and contact pressure vary with vehicle type, wheel load, and other variables such as pavement roughness and vehicle dynamics, a comprehensive structural design system should provide the flexibility to evaluate a variety of pavement loadings. In addition, the system must be broad enough to consider the design of a variety of pavements ranging from lightly traveled farm-to-market roads to heavily traveled interstate highways and to allow for future design load requirements, especially increases in the legal load limit. Therefore, a method of estimating the effects of a variety of load magnitudes and contact pressures on theoretical stresses and strains should be included in the design system.

Layered analyses were completed on the nine different design sections indicated in Table A2.1. Dual wheel load results were obtained by superposition of two equal single wheel loads located 12 inches center to center. Three different thicknesses were evaluated: a thin (6 inches), a medium (12 inches), and a thick section (18 inches).

For each design section all possible combinations of load and contact pressure indicated in Fig A2.1 were analyzed. The stresses and strains for the individual sections were normalized by those values obtained for the standard design section, i.e., that design section with two 4500-pound wheel loads and 80-psi contact pressure. An example of the technique is included in Fig A2.1 for tensile stress in base layer from design number 5 of Table A2.1. These normalized values then relate changes in stresses and strains in the various pavement layers to a variety of contact pressures and loads and can be used as correction factors to alter the basic design stresses and strains.

The results are presented in Figs A2.2 through A2.4 where the normalized values are related to load, contact pressure, and radius of applied load.

TABLE A2.1. DIFFERENT DESIGN SECTIONS USED IN INVESTIGATION OF EFFECTS OF MAGNITUDE OF LOAD AND CONTACT PRESSURE

Variable	Design Number								
	1	2	3	4	5	6	7	8	9
Modulus of elasticity surface layer, 10^6 psi	1.5	1.5	1.5	3.5	3.5	3.5	6.5	6.5	6.5
Thickness of surface layer, inches	3.0	6.0	9.0	3.0	6.0	9.0	3.0	6.0	9.0
Modulus of elasticity subbase layer, 10^5 psi	1.0	1.0	1.0	5.0	5.0	5.0	15.0	15.0	15.0
Thickness of subbase layer, inches	3.0	6.0	9.0	3.0	6.0	9.0	3.0	6.0	9.0
Modulus of elasticity subgrade, 10^3 psi	5.5	5.5	5.5	15.5	15.5	15.5	15.5	15.5	15.5

NOTE: Poisson's ratio of surface = 0.25
Poisson's ratio of subbase = 0.25
Poisson's ratio of subgrade = 0.50

Dual Wheel Load (pound) \ Contact Pressure (psi)		40	60	80	100	120
3000	Tensile Stress (psi)*	10.74	10.84	10.89	10.92	10.94
	Normalized Stress	0.338	0.341	0.343	0.343	0.344
5000	Tensile Stress (psi)*	17.58	17.85	17.98	18.07	18.12
	Normalized Stress	0.553	0.561	0.566	0.568	0.570
7000	Tensile Stress (psi)*	24.18	24.69	24.95	25.11	25.22
	Normalized Stress	0.761	0.777	0.785	0.790	0.793
9000	Tensile Stress (psi)*	30.54	31.37	31.79 (Standard Design Section)	32.05	32.22
	Normalized Stress	0.961	0.987	1.000 (Standard Design Section)	1.008	1.014
11,000	Tensile Stress (psi)*	37.03	37.89	38.50	38.89	39.15
	Normalized Stress	1.165	1.192	1.211	1.223	1.231

* Tensile stress in base layer for design section no. 5 of Table A2.1. The normalized stresses were obtained by dividing each of the stresses by the stress for the standard design section.

Fig A2.1. Factorial arrangement of different combinations of load and contact pressure.

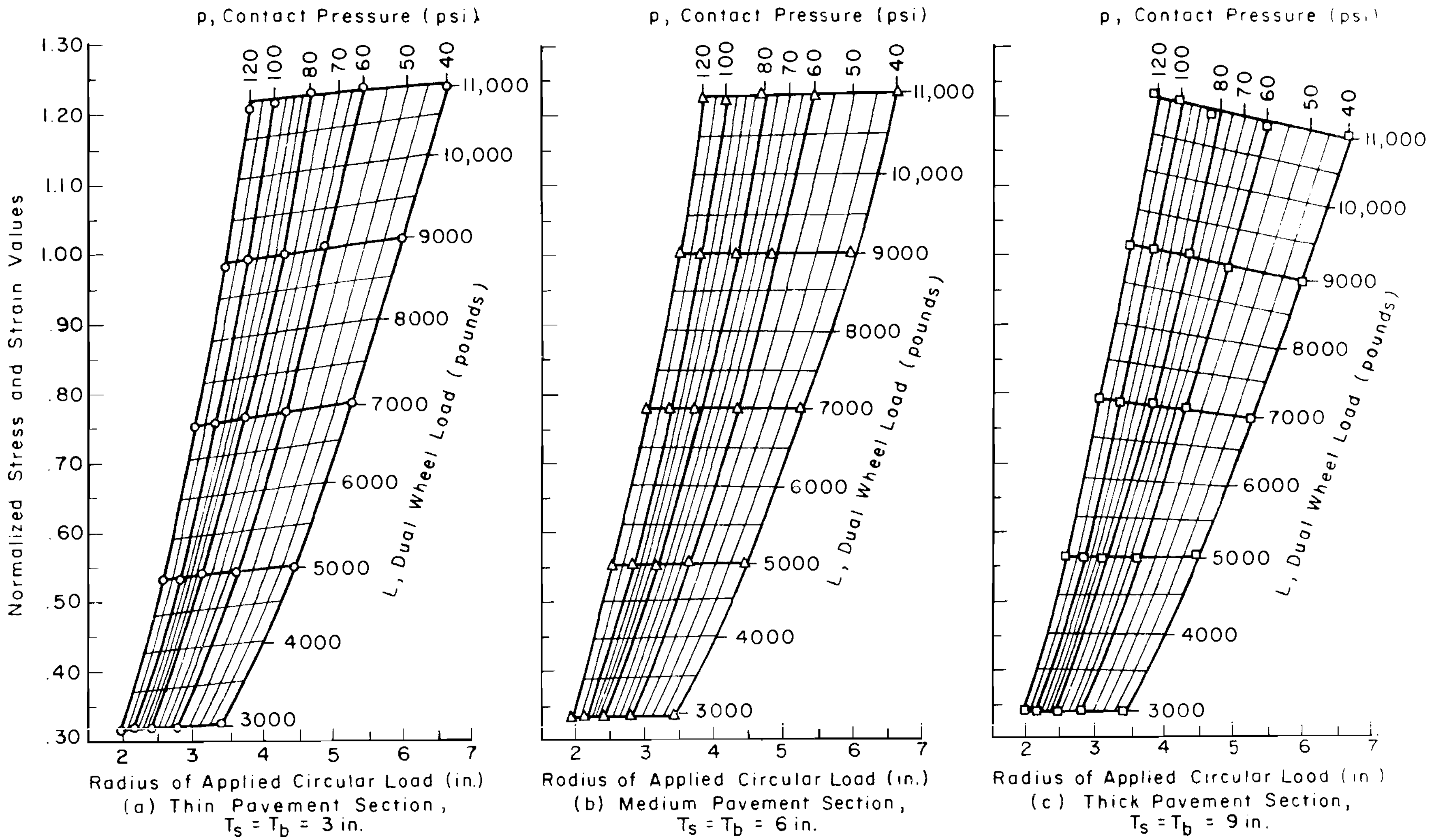


Fig A2.2. Effects of changes in magnitude of load and contact pressure on tensile stresses and strains in subbase layer and compressive strains in subgrade.

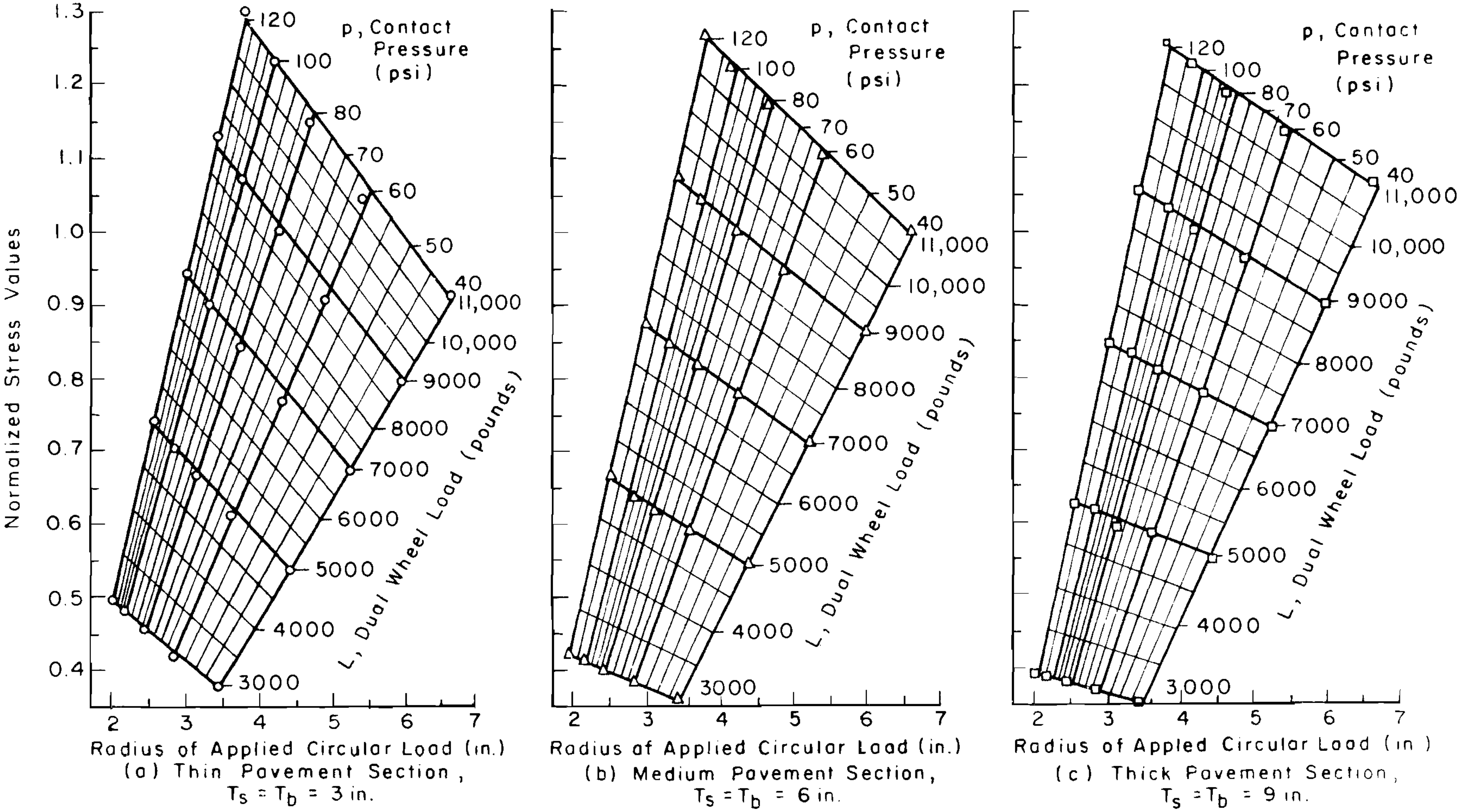
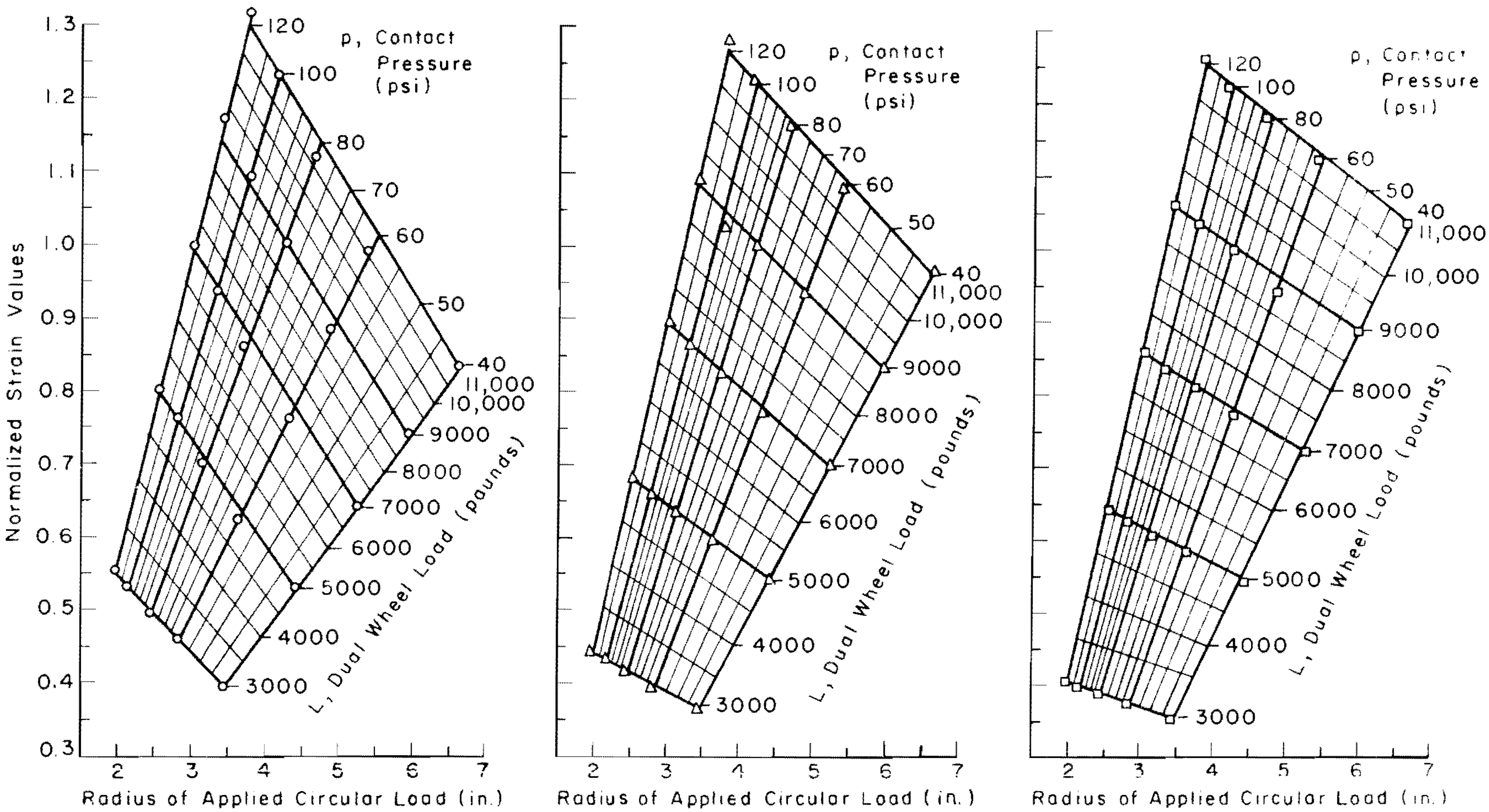


Fig A2.3. Effects of changes in magnitude of load and contact pressure on tensile stress in surface layer.



(a) Thin Pavement Section, $T_s = T_b = 3$ in.

(b) Medium Pavement Section, $T_s = T_b = 6$ in.

(c) Thick Pavement Section, $T_s = T_b = 9$ in.

Fig A2.4. Effects of changes in magnitude of load and contact pressure on tensile strain in surface layer.

The heavy lines represent the actual values obtained from layered analyses while the lighter lines represent interpolated values. Similar relationships were found for tensile stress and strain in the subbase layer and compressive strain in the subgrade (Fig A2.2) while slightly different relationships were obtained for tensile stress in the surface layer (Fig A2.3) and tensile strain in the surface layer (Fig A2.4).

From Fig A2.2 it can be seen that changes in contact pressure have only a slight effect on normalized tensile stress and strain values in subbase layer and compressive strain in subgrade for all three pavement thicknesses. Increases in magnitude of load, as expected, had great effects on the stress and strain values, and these increases are linearly related to load increases. In general, changes in contact pressure have little or no effect on tensile stress or strain in the subbase layer or compressive strain in the subgrade, while changes in the magnitude of load produce corresponding linear changes in stress and strain values.

Similar relationships exist for both tensile stress and tensile strain in the surface layer, as indicated in Figs A2.3 and A2.4, respectively, where increases in contact pressure and magnitude of load produce higher stresses and strains. The effect of both contact pressure and load are dependent upon the thickness of pavement section. The thinner section is affected less by load and more by contact pressure.

Although the curves presented in Figs A2.2 through A2.4 were not directly used in the examples presented in this study they can be used in conjunction with the design equations of Chapter 3 or the design curves presented in Appendices 3 and 4 to provide estimates of stresses and strains in the layers of a pavement structure subjected to loads and contact pressures other than those adopted for this design system. Additionally, the curves in Figs A1.2 through A1.5 can also be used to provide estimates of the stresses and strains for different combinations of Poisson's ratios in the surface and subbase layers. The combination of all these curves then provides the flexibility required in a structural design system for the design of a variety of highway pavements subjected to various traffic loads.

APPENDIX 3

DESIGN CURVES FOR HIGH MODULUS RIGID PAVEMENTS

(MODULUS OF ELASTICITY OF SURFACE LAYER

BETWEEN 3.5×10^6 AND 6.5×10^6 PSI)

APPENDIX 3. DESIGN CURVES FOR HIGH MODULUS RIGID PAVEMENTS (MODULUS OF ELASTICITY OF SURFACE LAYER BETWEEN 3.5×10^6 AND 6.5×10^6 PSI)

Introduction

The design equations presented in Chapter 3 can best be solved in a computer because of the number of terms involved. The equations could be solved for any one of the six variables as long as estimates of the other five are available. However, since computer facilities are still not universally available to all designers, there is a need for a practical method of solving the design equations. Nomographs fulfilling this need for design equations 1 through 5 are included in this appendix along with an example explaining their use. The example problem is identical to one of the designs included as example problem 2 of Chapter 5.

Application of Nomographs

A set of nomographs is presented here which can be used to graphically solve equations 1 through 5 of Chapter 3. For these equations iterative solutions of the curves are required in order to obtain a final design thickness. The procedures for the nomographs are presented in the following paragraphs with an example problem as a guide. A detailed description of the required procedure is provided for one set of nomographs to insure proper understanding while brief descriptions are provided for the other four nomograph sets. Subbase design thicknesses can be obtained for each of the five different nomograph sets; therefore, final design thickness would be obtained from a comparison of the individual design thicknesses.

Estimates of the material properties which are required in the initial design stage for each set of nomographs are included in Table A3.1.

Subbase Thickness Design Based Upon Tensile Stress in Subbase Layer σ_b

Step 1 - Obtain the required material characterization data for the surface, subbase, and subgrade layer (see Table A3.1).

TABLE A3.1. MATERIAL PROPERTIES REQUIRED FOR SUBBASE DESIGN

REQUIRED PROPERTIES	Assumed for Example Problem
For the Surface Layer	
(1) modulus of elasticity	4.75×10^6 psi
(2) thickness	8.5 inches
(3) design tensile stress	160 psi
(4) design tensile strain	20 microunits
For the Subbase Layer	
(1) modulus of elasticity	10×10^5 psi
(2) thickness	Required
(3) design tensile stress	87.5 psi
(4) design tensile strain	20 microunits
For the Subgrade	
(1) modulus of elasticity	8.00×10^3 psi
(2) design compressive strain	420 microunits

Step 2 - Enter Fig A3.1a with the given surface thickness T_s = 8.5 inches on the abscissa scale and project a line vertically until it intersects the curve for modulus of elasticity of the subbase layer $E_b = 10.0 \times 10^5$ psi. From this point project a line horizontally to the ordinate scale and read off a correction term A of 0.80.

Step 3 - Enter Fig A3.1b with an estimate of the subgrade modulus of elasticity E_g = 8000 psi on the abscissa scale and project a line vertically until it intersects the curve for the modulus of elasticity of the surface layer $E_s = 4.75 \times 10^6$ psi. From this intersection project a line horizontally to the ordinate scale and read off a correction term B of 0.90.

Step 4 - Enter Fig A3.1c with the surface thickness T_s = 8.5 inches on the abscissa scale and project a line vertically until it intersects a curve for a preliminary estimate of the subbase thickness T_b = 7.5 inches. From this intersection project a line horizontally to the ordinate scale and read off a preliminary estimate of correction term C of 1.00.

Step 5 - Determine a critical design stress $\sigma_b{*}$ from the division of design tensile stress, σ_b, by correction terms A, B, and C, i.e., $\sigma_b{*} = \frac{\sigma_b}{A \times B \times C}$.

For the example problem with σ_b = 87.5 psi, A = 0.80, B = 0.90, and C = 1.00, a critical design stress of 121.2 psi is obtained.

Step 6 - Enter Fig A3.1d with modulus of elasticity of the subbase layer $E_b = 10 \times 10^5$ psi on the abscissa scale and project a vertical line upwards. Also enter the figure with the critical design stress of 121.2 psi on the ordinate scale and project a line horizontally to the right. At the intersection of these two projected lines a preliminary subbase thickness of 0.0 is obtained.

Step 7 - Using the estimate of subbase thickness from Step 6, repeat Steps 4 through 6 to obtain new values of correction term C, critical design stress, and subbase thickness design. Compare the subbase design thickness of the second iteration with the preliminary thickness determined in Step 6. If the difference is greater than 0.1 inches, complete additional iterative solutions of Steps 4 through 6 until consecutive solutions agree within 0.1 inches.

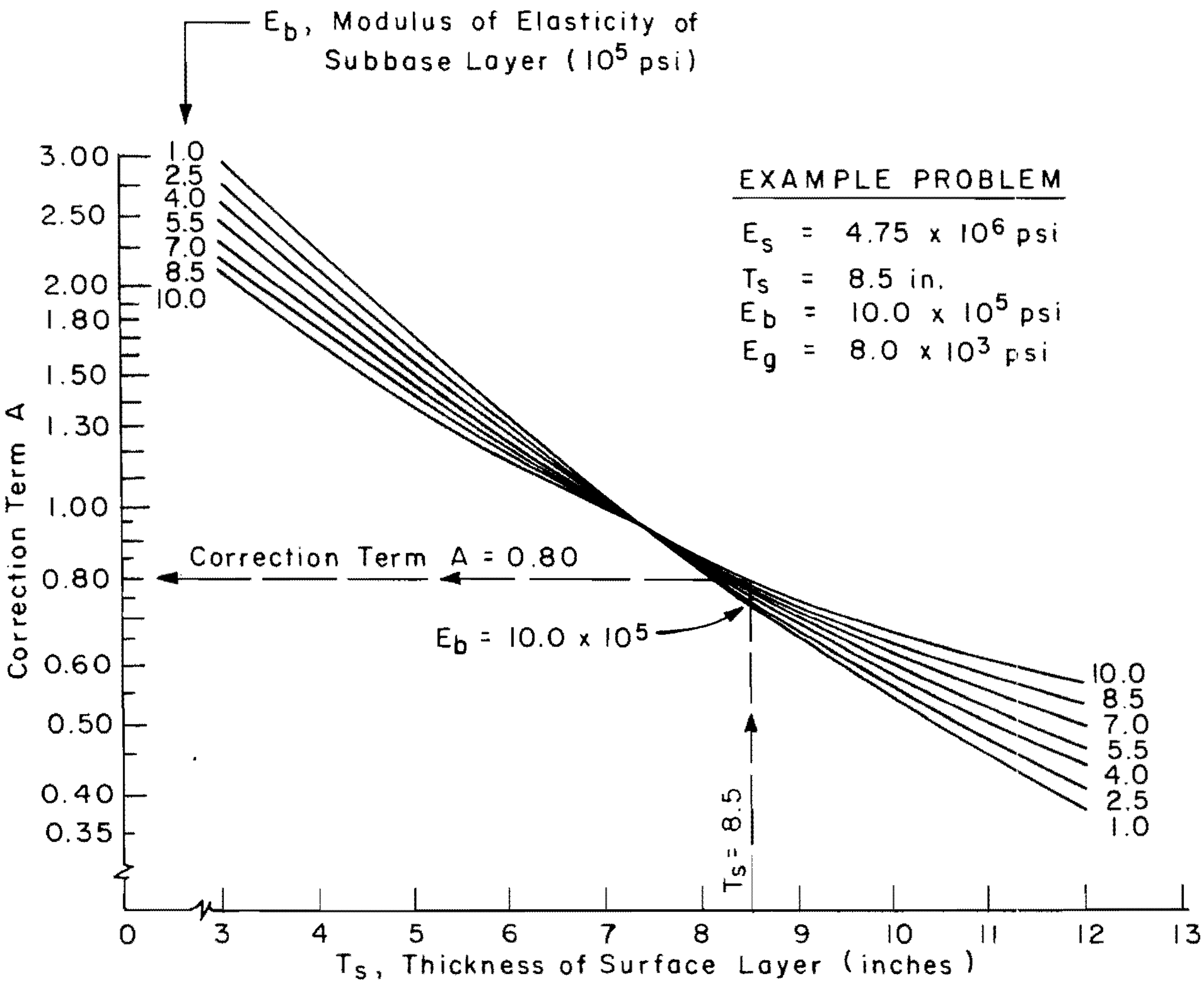


Fig A3.1a. Correction curve A for tensile stress in subbase layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

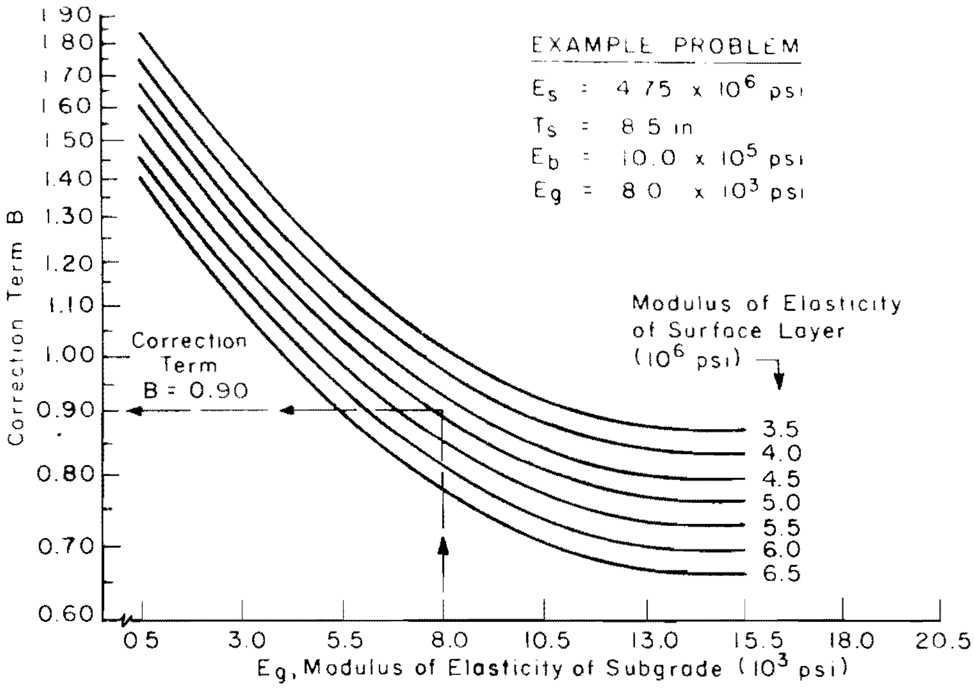


Fig A3.1b. Correction curve B for tensile stress in subbase layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

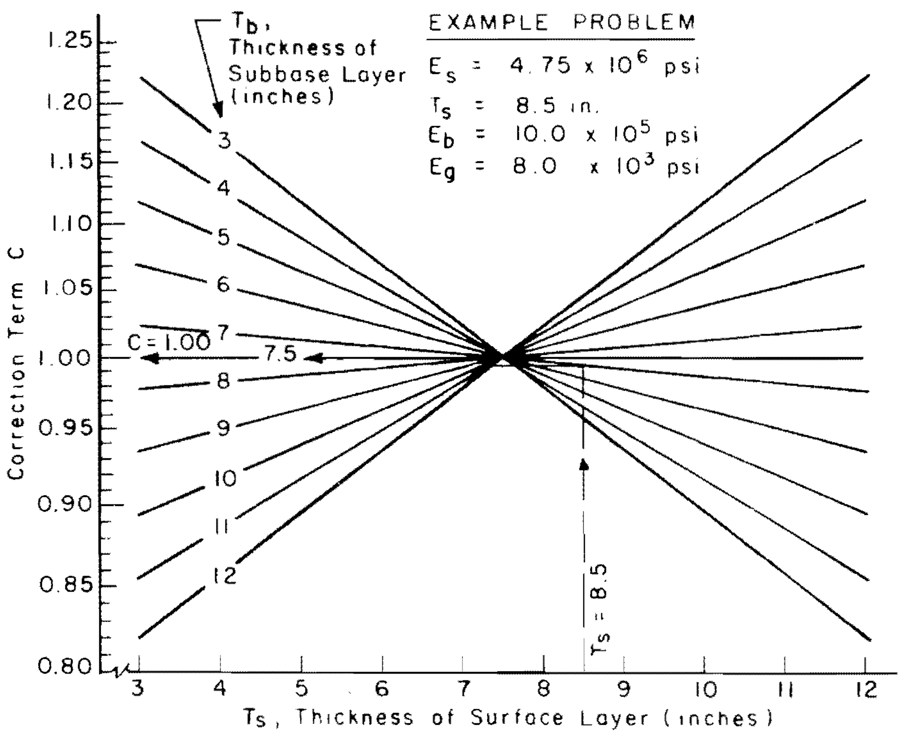


Fig A3.1c. Correction curve C for tensile stress in subbase layer: modulus of elasticity of surface layer between 3.5×10^6 and 6.5×10^6 psi.

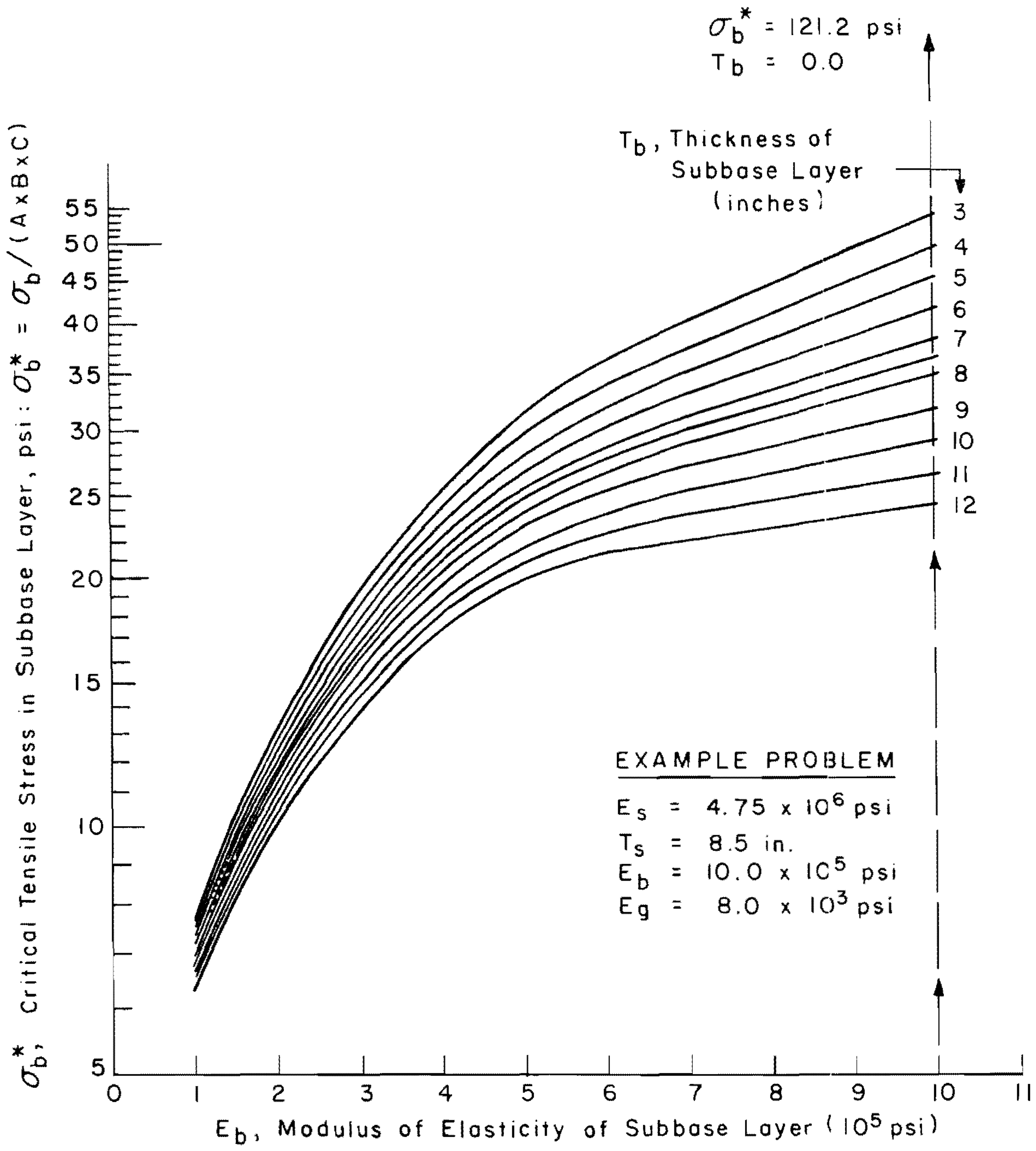


Fig A3.1d. Basic design curve for tensile stress in bottom of subbase layer: modulus of elasticity of surface layer between 3.5 x 10^6 and 6.5 x 10^6 psi.

The results of two iterative solutions to the example problem are presented in Table A3.2. Based upon these results no subbase is required for this design criteria.

<u>Subbase Thickness Design Based Upon Tensile Strain in Base Layers ϵ_b</u>

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A3.1).

Step 2 - Enter Fig A3.2a with surface thickness T_s = 8.5 inches and modulus of elasticity of the subbase layer $E_b = 10 \times 10^5$ psi to obtain a correction term A of 0.82.

Step 3 - Enter Fig A3.2b with surface layer modulus of elasticity $E_s = 4.75 \times 10^6$ psi and subgrade modulus of elasticity E_g = 8000 psi and determine a correction term B of 0.90.

Step 4 - Enter Fig A3.2c with surface thickness T_s = 8.5 inches and a preliminary estimate of subbase thickness T_b = 7.5 inches and determine a correction term C of 1.00.

Step 5 - Estimate a critical design strain ϵ_b* from the division of the design strain ϵ_b = 20 microunits by correction terms A, B, and C, i.e.,

$$\epsilon_b{}^* = \frac{\epsilon_b}{A \times B \times C} \quad . \quad \epsilon_b{}^* = \frac{20.0}{(0.82)(.90)(1.00)} = 27.0 \text{ microunits.}$$

Step 6 - Enter Fig A3.2d with critical design strain ϵ_b* = 27 microunits and modulus of elasticity of subbase layer $E_b = 10 \times 10^5$ psi to estimate a subbase design thickness of 6.2 inches.

Step 7 - Using the estimate of subbase thickness from Step 6 repeat Steps 4 through 6 to obtain new values of correction term C, critical design strain, and subbase thickness design. Compare the latter subbase thickness with the preliminary thickness determined in Step 6. If the difference is greater than 0.1 inch, complete additional iterative solutions of Steps 4 through 6 until consecutive solutions agree with 0.1 inch.

The results of two iterative solutions to the example problem are presented in Table A3.3. Based upon these results a subbase thickness of 6.1 inches is required for tensile strain criteria.

TABLE A3.2. ITERATIVE SOLUTIONS FOR SUBBASE DESIGN BASED UPON TENSILE STRESS IN SUBBASE LAYER, σ_b

	Iteration Number 1	Iteration Number 2	
Correction term A	0.80	0.80	
Correction term B	0.90	0.90	
Correction term C	1.00	0.90	
Design stress, psi	87.5	87.5	
Critical design stress, psi	121.2	135.2	
Subbase design thickness, inches	0.0	0.0	← Design thickness

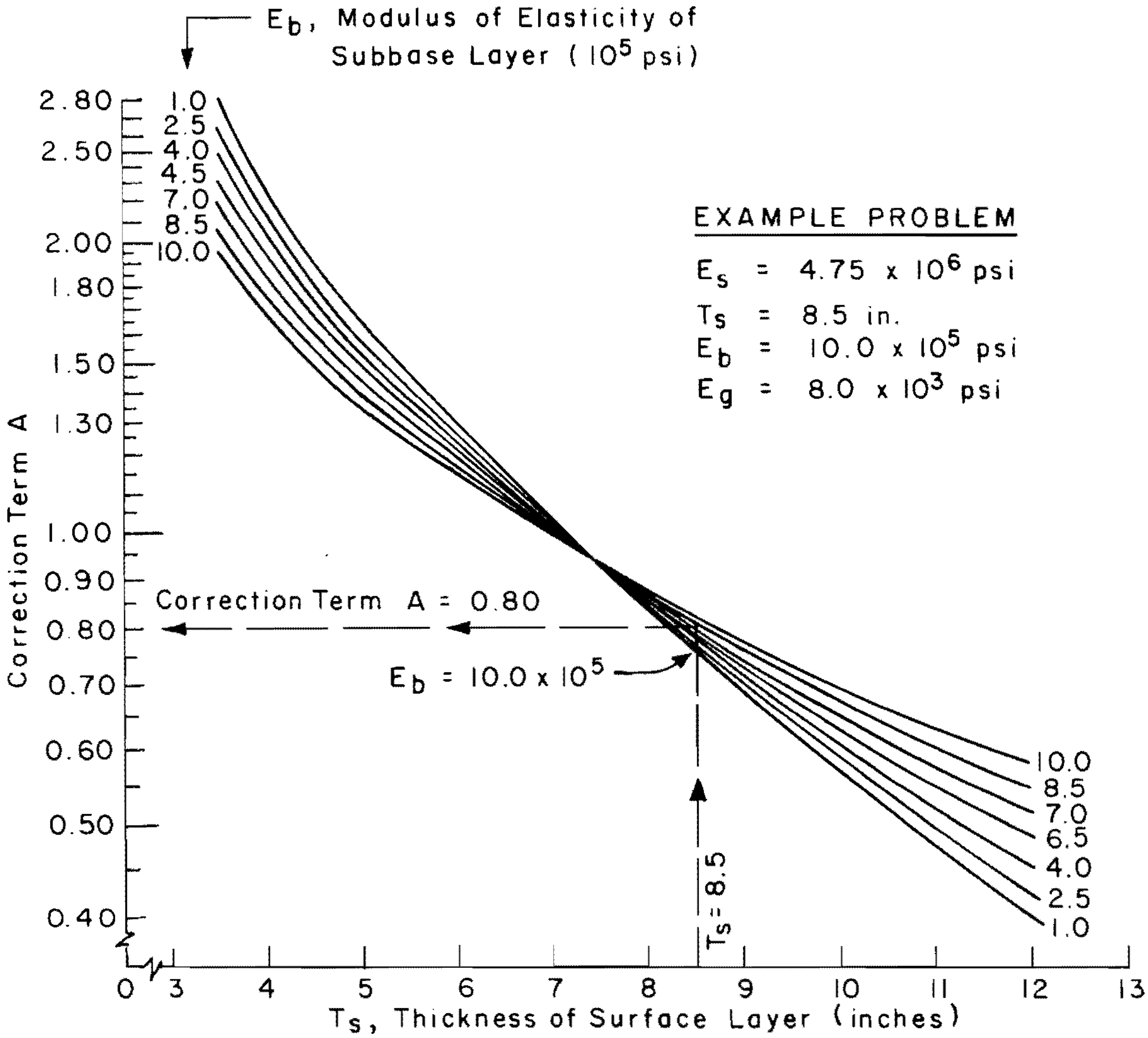


Fig A3.2a. Correction curve A for tensile strain in subbase layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

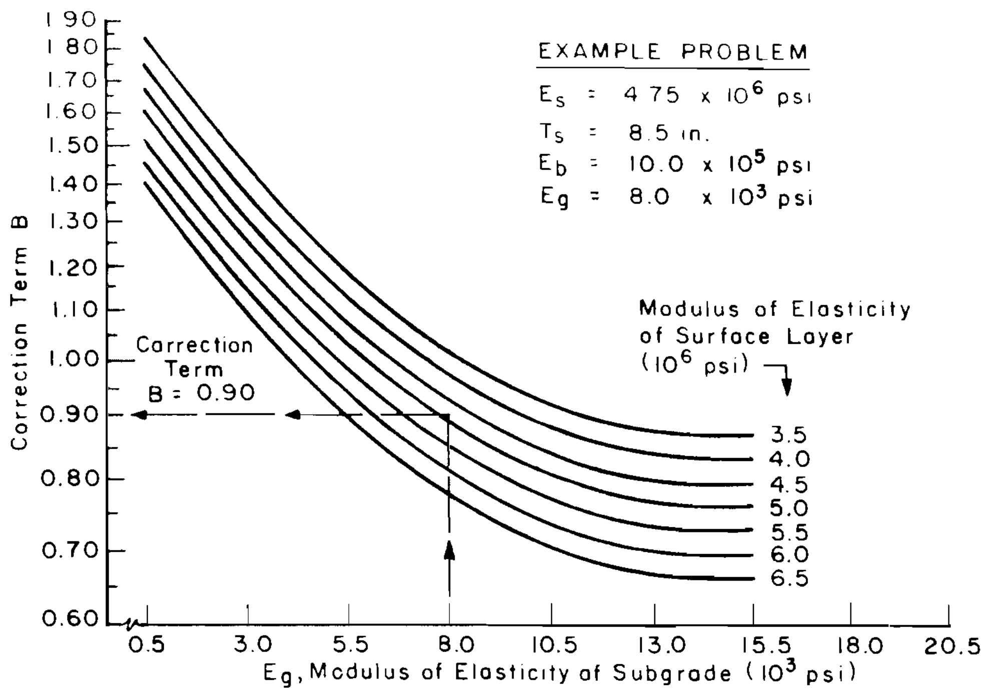


Fig A3.2b. Correction curve B for tensile strain in subbase layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

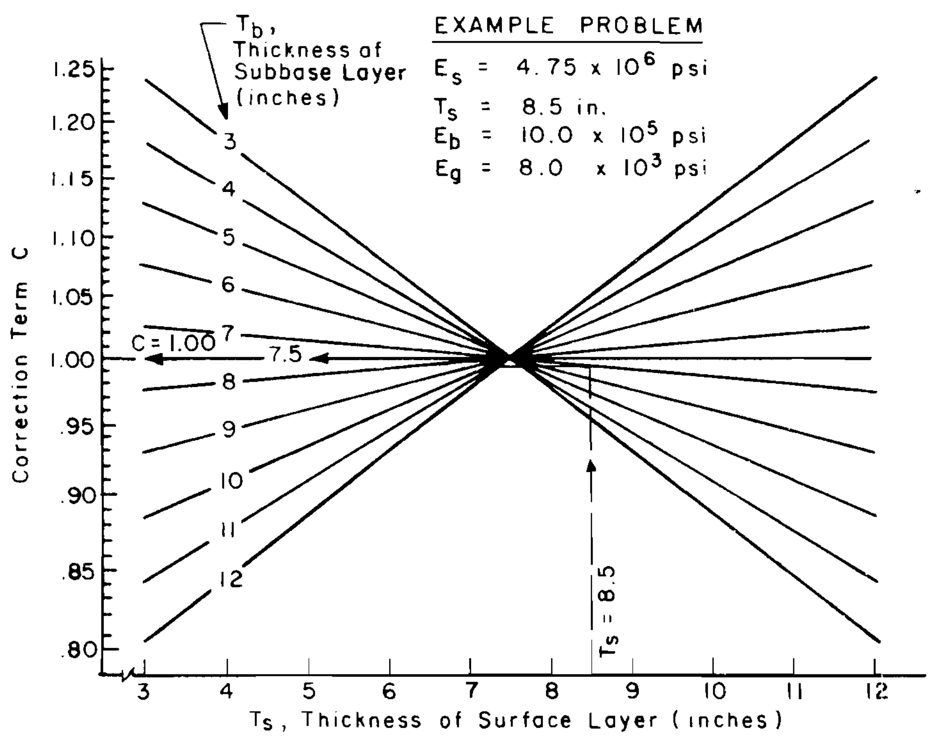


Fig A3.2c. Correction curve C for tensile strain in subbase layer: modulus of elasticity of surface layer between 3.5×10^6 and 6.5×10^6 psi.

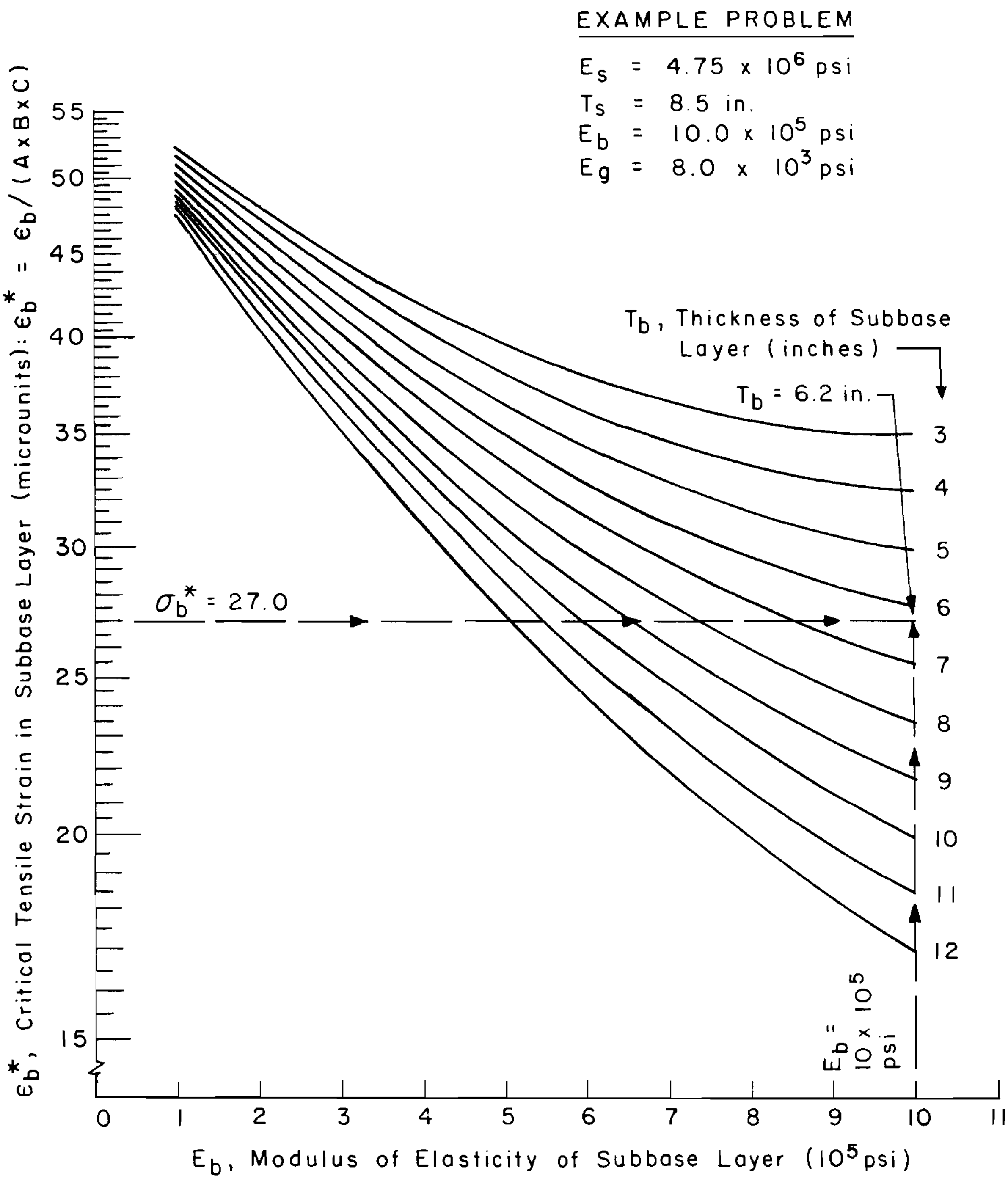


Fig A3.2d. Basic design curve for tensile strain in bottom of subbase layer: modulus of elasticity of surface layer between 3.5 x 10^6 and 6.5 x 10^6 psi.

TABLE A3.3. ITERATIVE SOLUTIONS FOR SUBBASE DESIGN BASED UPON TENSILE STRAIN IN SUBBASE LAYER, ε_b

	Iteration Number 1	2	
Correction term A	.82	.82	
Correction term B	.90	.90	
Correction term C	1.00	.99	
Design strain, microunits	20.0	20.0	
Critical design strain, microunits	27.0	27.4	
Subbase design thickness, inches	6.2	6.1	← Design thickness

Subbase Thickness Design Based Upon Compressive Strain in Subgrade ϵ_c

Step 1 - Obtain the required material characterization data for surface, subbase, and subgrade layers (see Table A3.1).

Step 2 - Enter Fig A3.3a with thickness T_s = 8.5 inches and modulus of elasticity $E_s = 4.75 \times 10^6$ psi of the surface layer and determine a correction term A of 1.025.

Step 3 - Enter Fig A3.3b with modulus of elasticity of subgrade E_g = 8000 psi and determine a correction term B of 0.88.

Step 4 - Enter Fig A3.3c with thickness of surface layer T_s = 8.5 inches and modulus of elasticity of subbase layer E_b - 10×10^5 psi and determine a correction term C of 1.03.

Step 5 - Enter Fig A3.3d with thickness of surface layer T_s = 8.5 inches and a preliminary estimate of subbase thickness T_b = 7.5 inches and determine a correction term D of 0.77.

Step 6 - Estimate a critical design strain ϵ_c* by dividing the design strain ϵ_c by correction terms A, B, C, and D, i.e., $\epsilon_c* = \frac{\epsilon_c}{A \times B \times C \times D}$.

$$\epsilon_c* = \frac{420 \text{ microunits}}{(1.025)(.88)(1.03)(.77)} = 581 \text{ microunits.}$$

Step 7 - Enter Fig A3.3e with critical design strain $\epsilon_c* = 581$ microunits and modulus of elasticity of subbase layer $E_b = 10 \times 10^5$ psi; and estimate subbase thickness requirements.

Since ϵ_c* greatly exceeds numbers on abscissa scale no preliminary subbase thickness is required.

Step 8 - Using the estimate of subbase thickness from Step 7 repeat Steps 5 through 7 to obtain new values of correction term D, critical design strains and subbase thickness design. Compare the latter subbase thickness with the preliminary thickness determined in Step 7. If the difference is greater than 0.1 inch, complete additional iterative solutions of Steps 5 through 7 until consecutive solutions agree within 0.1 inch.

The results of two iterative solutions to the example problem are presented in Table A3.4. Based upon these results no subbase is required for this design criteria.

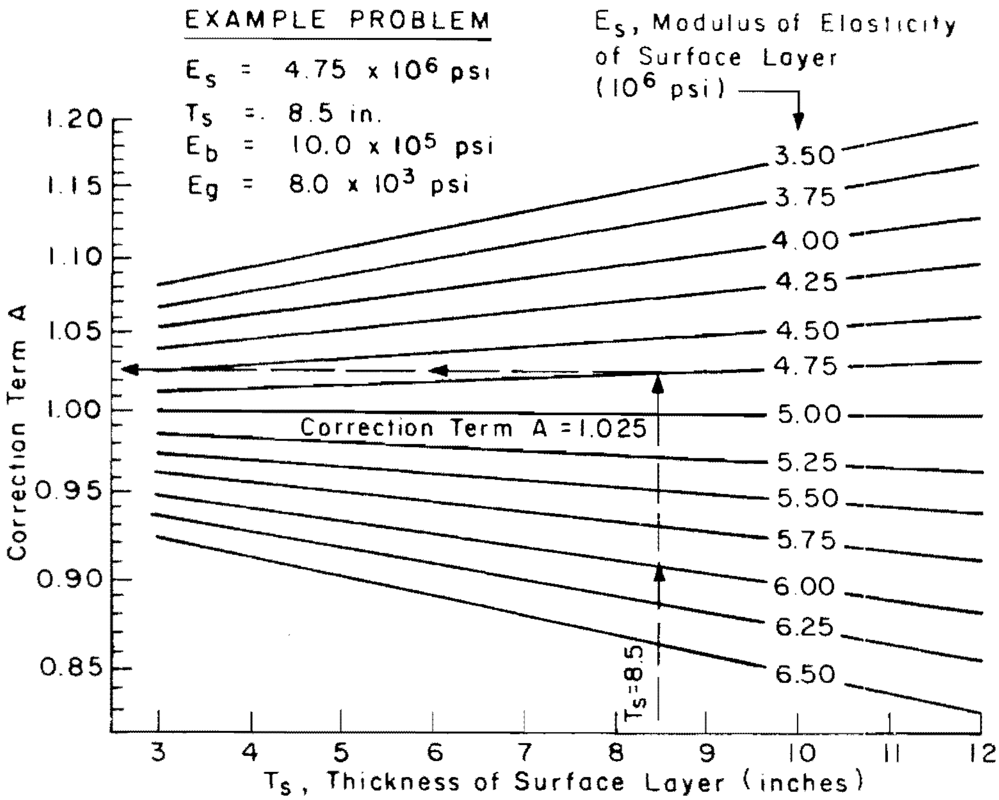


Fig A3.3a. Correction curve A for compressive strain in subgrade: E_s between 3.5×10^6 and 6.5×10^6 psi.

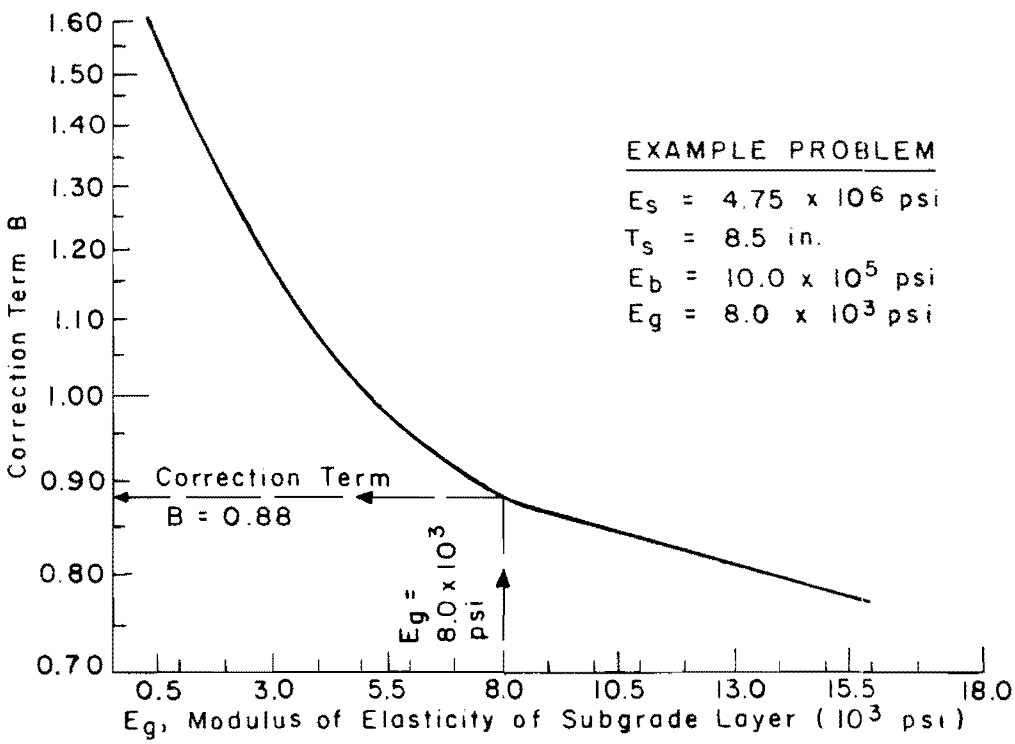


Fig A3.3b. Correction curve B for compressive strain in subgrade: E_s between 3.5×10^6 and 6.5×10^6 psi.

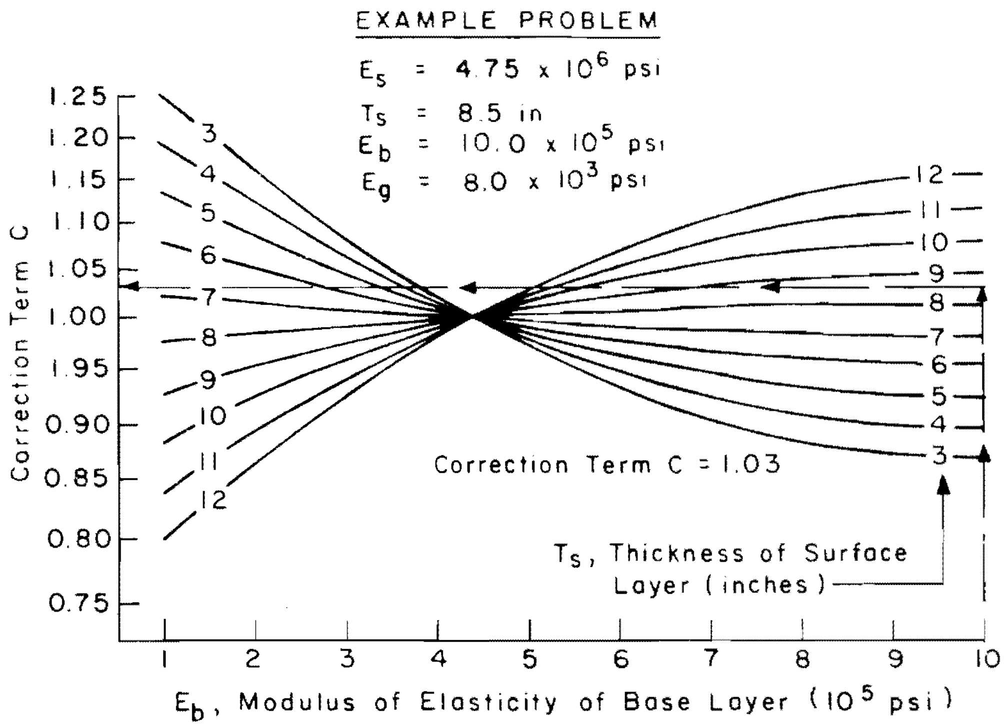


Fig A3.3c. Correction curve C for compressive strain in subgrade: E_s between 3.5×10^6 and 6.5×10^6 psi.

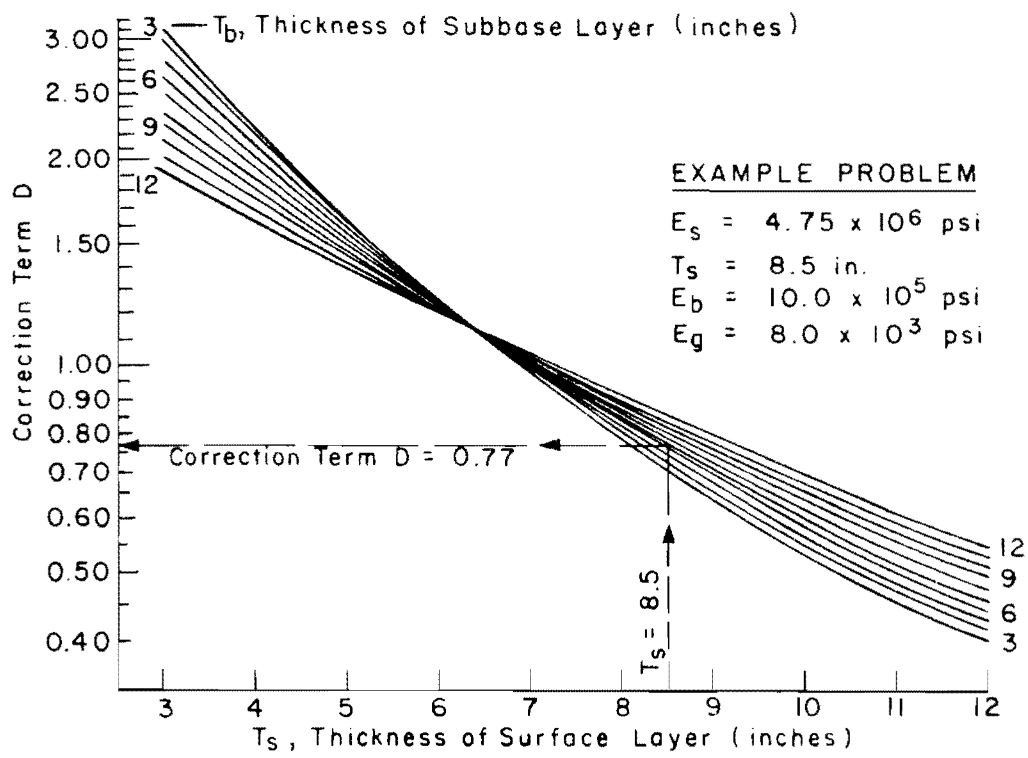


Fig A3.3d. Correction curve D for compressive strain in subgrade: E_s between 3.5×10^6 and 6.5×10^6 psi.

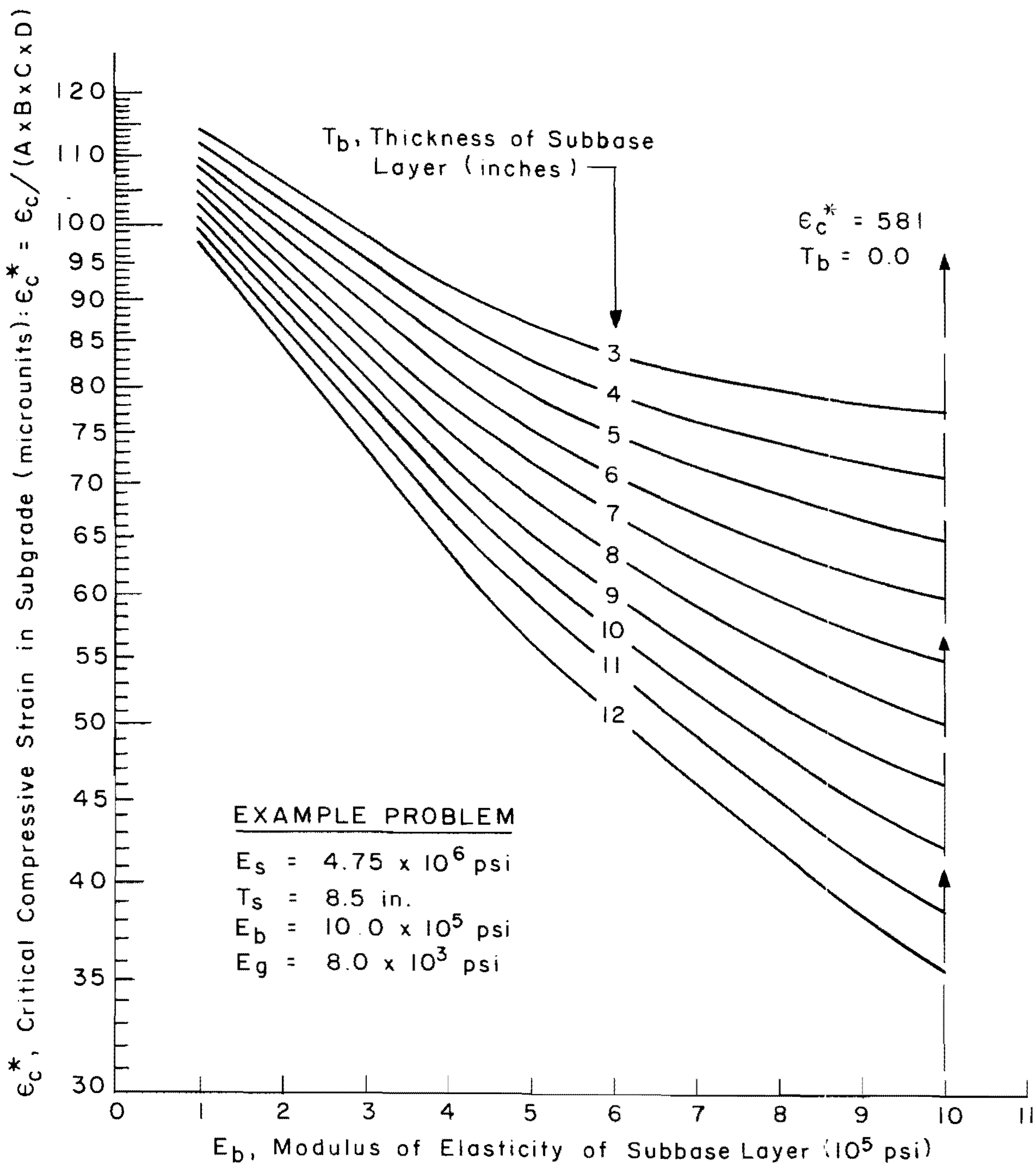


Fig A3.3e. Basic design curve for compressive strain in subgrade: E_s between 3.5×10^6 and 6.5×10^6 psi.

TABLE A3.4. ITERATIVE SOLUTIONS FOR SUBBASE THICKNESS DESIGN BASED UPON COMPRESSIVE STRAIN IN SUBGRADE, ε_c

	Iteration Number	
	1	2
Correction term A	1.025	1.025
Correction term B	.88	.88
Correction term C	1.03	1.03
Correction term D	0.77	0.67
Design strain, microunits	420	420
Critical design strain, microunits	581	675
Subbase thickness	0.0	0.0 ← Design thickness

Subbase Thickness Design Based Upon Tensile Stress in Surface Layer σ_s

Step 1 - Obtain proper information concerning material characterization for surface, subbase, and subgrade layers (see Table A3.1).

Step 2 - Enter Fig A3.4a with modulus of elasticity of subgrade E_g = 8000 psi and determine a correction term A of 1.00.

Step 3 - Enter Fig A3.4b with thickness of surface layer T_s = 8.5 inches and modulus of elasticity of surface layer $E_s = 4.75 \times 10^6$ psi and determine a correction term B of 1.007.

Step 4 - Enter Fig A3.4c with thickness of surface layer T_s = 8.5 inches and modulus of elasticity of subbase layer $E_b = 10 \times 10^5$ psi and determine a correction term C of 1.18.

Step 5 - Enter Fig A3.4d with thickness of surface layer T_s = 8.5 inches and a preliminary estimate of subbase thickness T_b = 7.5 inches and determine a correction term D of 1.00.

Step 6 - Estimate a critical design stress σ_s^* from division of the design stress σ_s plus 26.4 by correction terms A, B, C, and D, i.e.,

$$\sigma_s^* = \frac{\sigma_s + 26.4}{A \times B \times C \times D} = \frac{160 + 26.4}{(1.0)(1.007)(1.18)(1.0)} = 157 \text{ psi.}$$

Step 7 - Enter Fig A3.4e with critical design stress σ_s^* = 157 psi and modulus of elasticity of subbase layer $E_b = 10 \times 10^5$ psi and estimate a required subbase thickness T_b of 2.2 inches.

Step 8 - Using the estimate of subbase thickness of Step 7, repeat Steps 5 through 7 to obtain new values of correction factor D, critical design stress, and subbase thickness. Compare the latter subbase thickness with the preliminary thickness determined in Step 7. If the difference is greater than 0.1 inch, complete additional iterative solutions of Steps 5 through 7 until consecutive solutions agree within 0.1 inch.

The results of three iterative solutions to the example problem are presented in Table A3.5. Based upon these results a subbase thickness of approximately 1.6 inches is required.

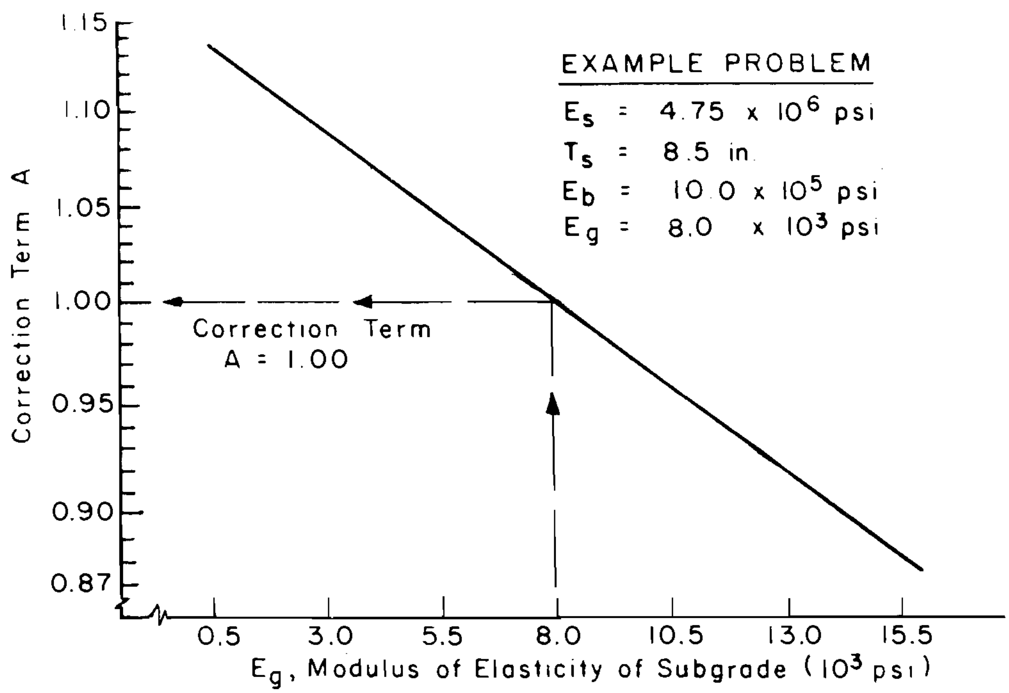


Fig A3.4a. Correction curve A for tensile stress for surface layer: E_s between 3.5 × 10^6 and 6.5 × 10^6 psi.

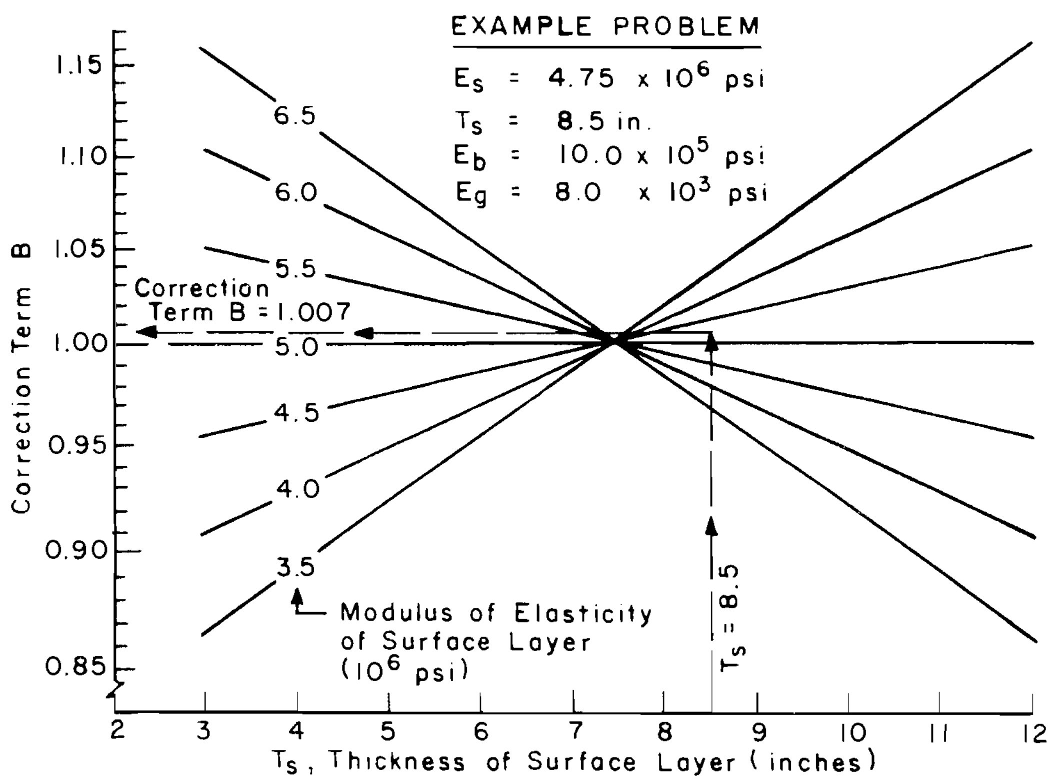


Fig A3.4b. Correction curve B for tensile stress function for surface layer: E_s between 3.5 × 10^6 and 6.5 × 10^6 psi.

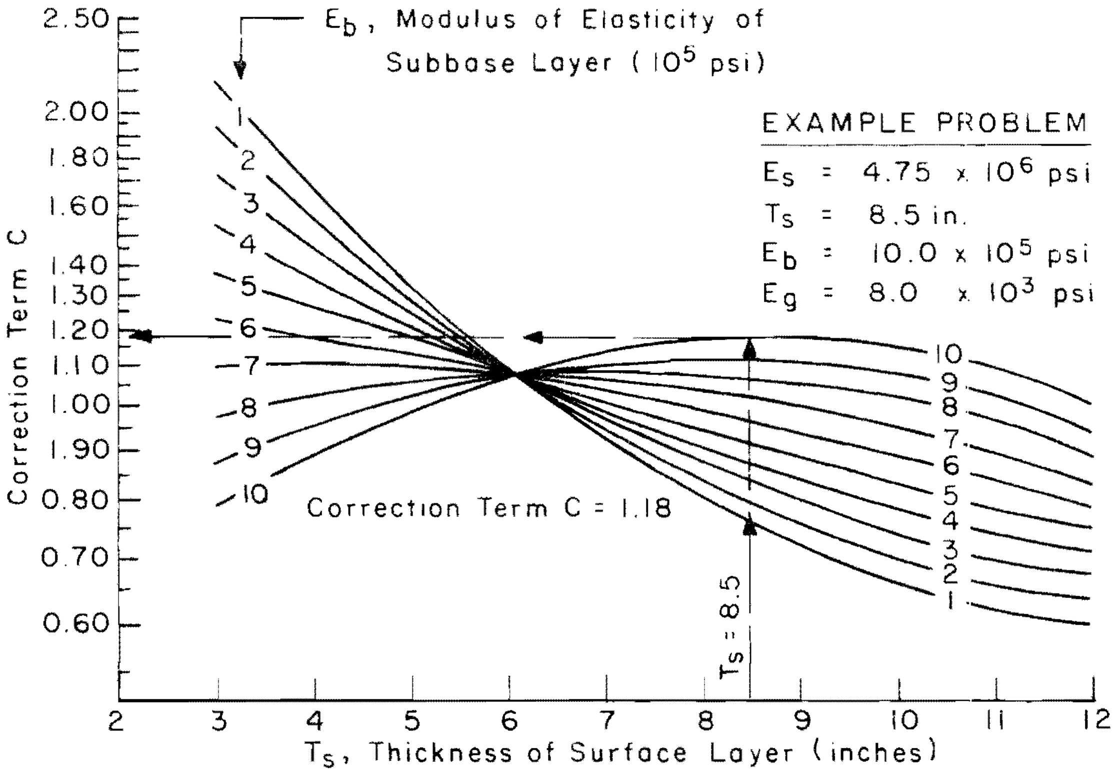


Fig A3.4c. Correction curve C for tensile stress function for surface layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

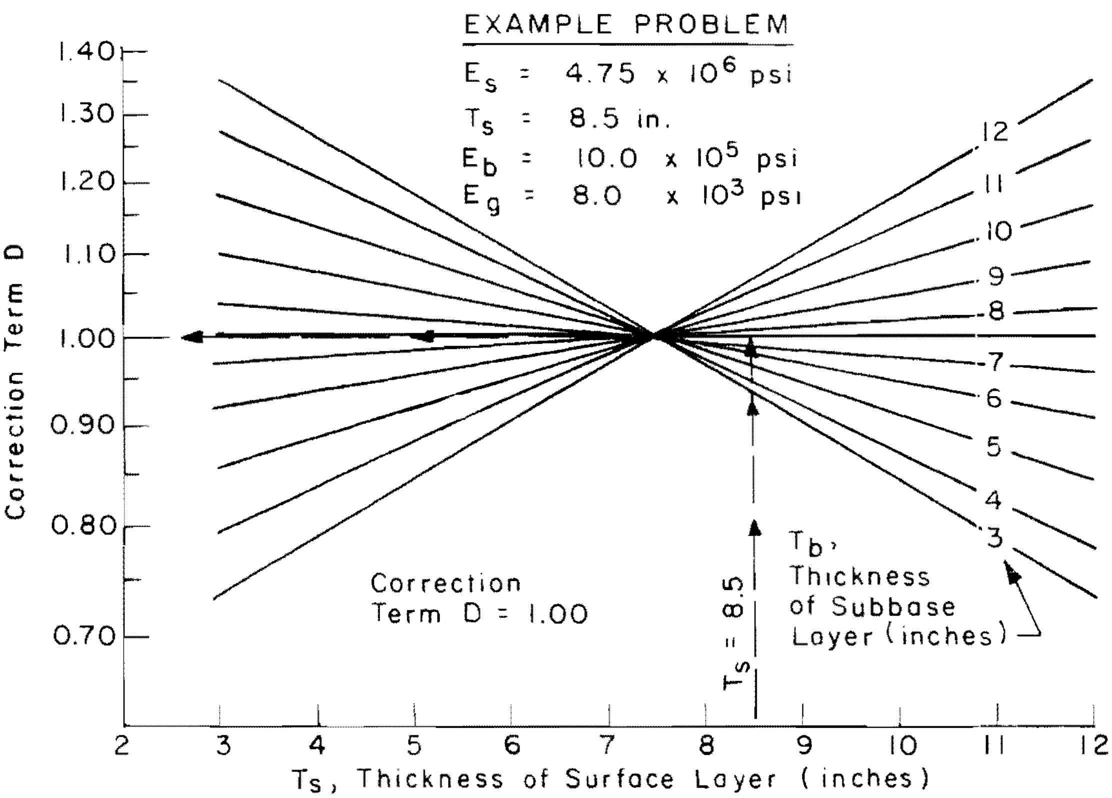


Fig A3.4d. Correction curve D for tensile stress function for surface layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

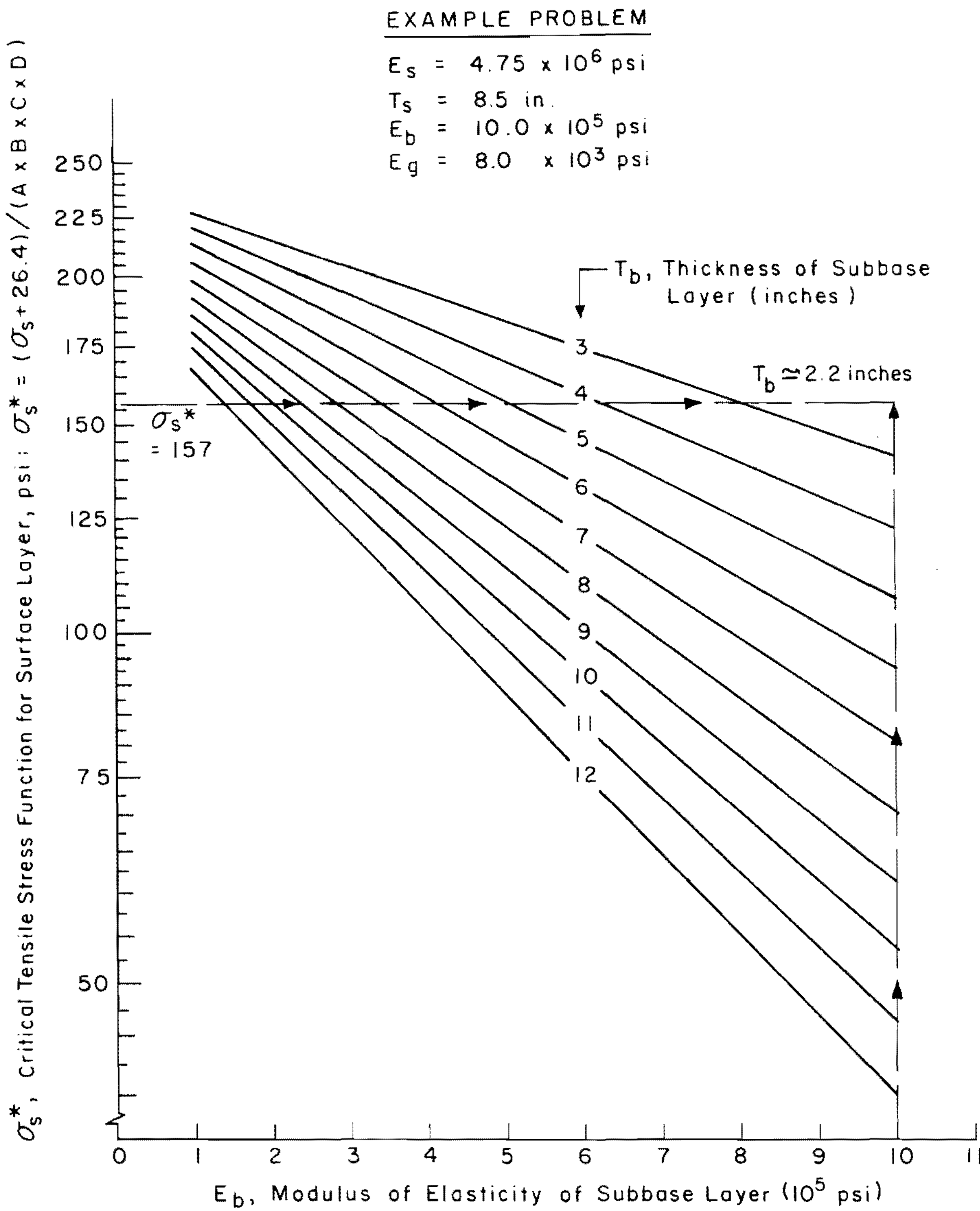


Fig A3.4e. Basic design curve for tensile stress in bottom of surface layer: modulus of elasticity of surface layer between 3.5×10^6 and 6.5×10^6 psi.

TABLE A3.5. ITERATIVE SOLUTIONS FOR SUBBASE THICKNESS DESIGN BASED UPON TENSILE STRESS IN SURFACE LAYER σ_s

	Iteration Number		
	1	2	3
Correction term A	1.00	1.00	1.00
Correction term B	1.007	1.007	1.007
Correction term C	1.18	1.18	1.18
Correction term D	1.00	.92	.915
Design stress, psi	160	160	160
Critical design stress, psi	157	170	172
Subbase thickness, inches	2.2	1.6	1.5 ← Design thickness

Subbase Thickness Design Based Upon Tensile Strain in Surface Layer ϵ_s

Step 1 - Obtain proper information concerning material characterization for surface, subbase, and subgrade layers (see Table A3.1).

Step 2 - Enter Fig A3.5a with modulus of elasticity of subgrade E_g = 8000 psi and determine a correction term A of 1.00.

Step 3 - Enter Fig A3.5b with thickness of surface layer T_s = 8.5 inches and modulus of elasticity of subbase layer $E_b = 10 \times 10^5$ psi and determine a correction term B of 1.034.

Step 4 - Enter Fig 3.5c with thickness of surface layer T_s = 8.5 inches and a preliminary estimate of subbase thickness T_b = 7.5 inches, and estimate a correction term C of 1.00.

Step 5 - Estimate a critical design strain ϵ_s* by adding 5.15 to the design strain and dividing by correction terms A, B, and C, i.e.,

$$\epsilon_s^* = \frac{\epsilon_s + 5.15}{A \times B \times C} = \frac{20 + 5.15}{(1.0)(1.034)(1.0)} = 24.3 \text{ microunits.}$$

Step 6 - Enter Fig A3.5d with critical design strain ϵ_s^* = 24.3 microunits and modulus of elasticity of the subbase layer $E_b = 10 \times 10^5$ psi and determine a required subbase thickness of approximately 1.3 inches.

Step 7 - Using the estimate of subbase thickness of Step 6, repeat Steps 4 through 6 to obtain new values of correction term C, critical design strain, and subbase thickness. Compare the latter subbase thickness with the preliminary thickness determined in Step 6. If the difference is greater than 0.1 inch, complete additional iterative solutions of Steps 4 through 6 until consecutive solutions agree within 0.1 inch.

The results of three iterative solutions to the example problem are presented in Table A3.6. Based upon these results a subbase thickness of approximately 0.5 inch is required.

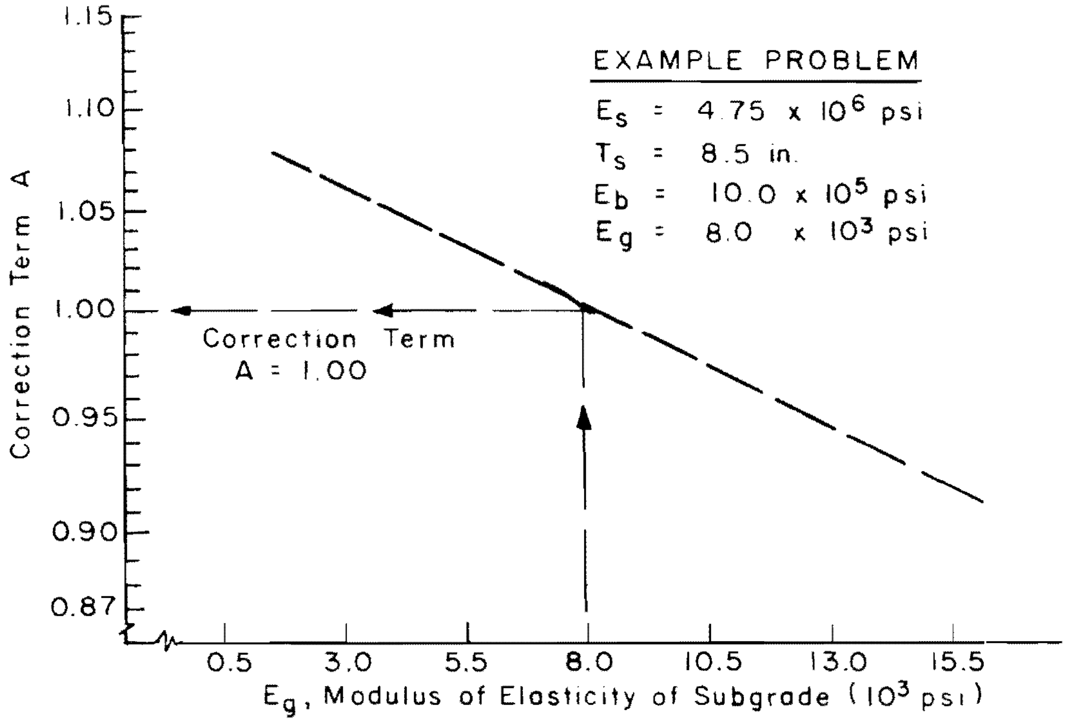


Fig A3.5a. Correction curve A for tensile strain function for surface layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

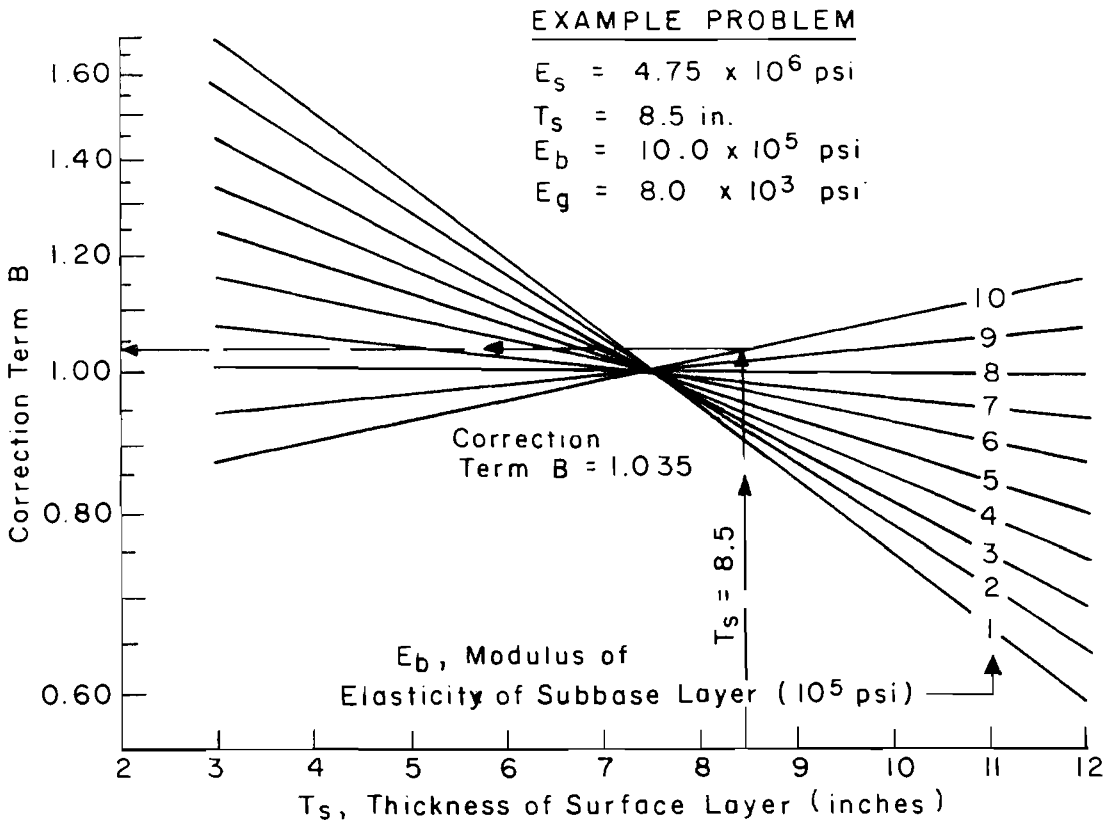


Fig A3.5b. Correction curve B for tensile strain function for surface layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

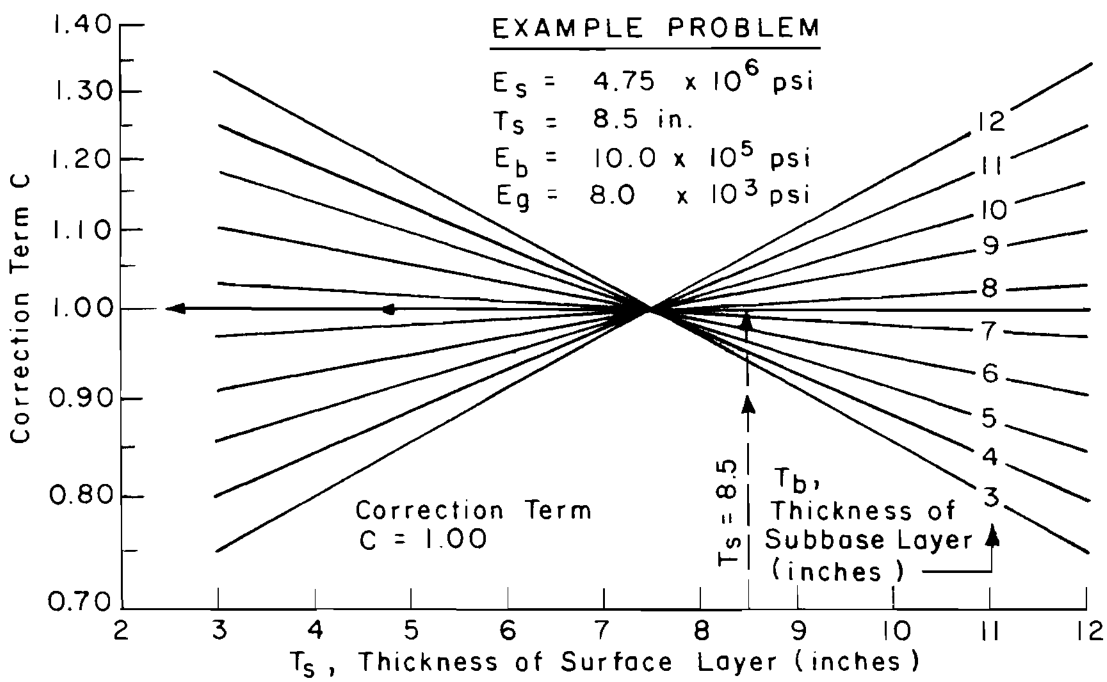


Fig A3.5c. Correction curve C for tensile strain function for surface layer: E_s between 3.5×10^6 and 6.5×10^6 psi.

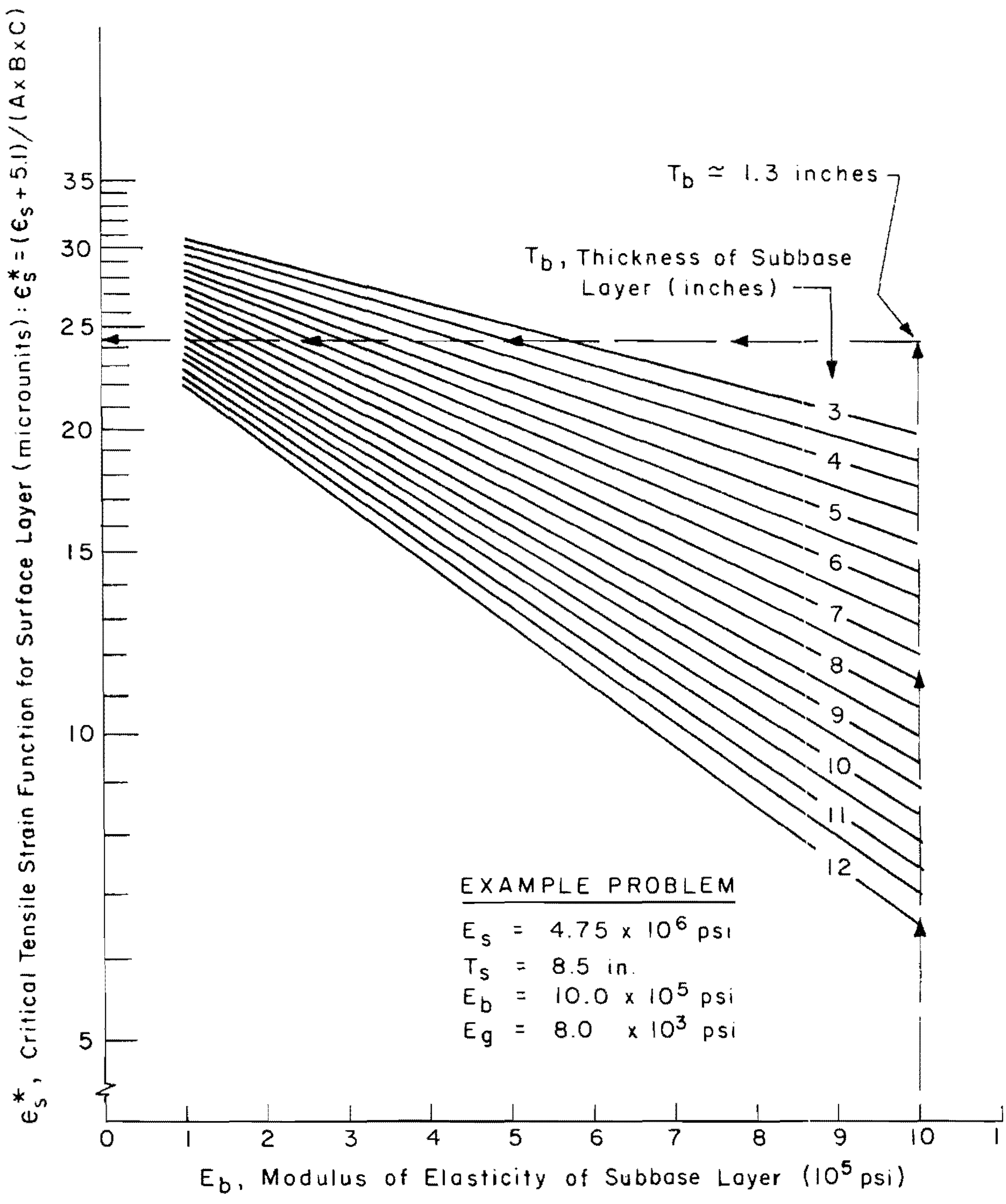


Fig A3.5d. Basic design curve for tensile strain function for surface layer: modulus of elasticity of surface layer between 3.5×10^6 and 6.5×10^6 psi.

TABLE A3.6. ITERATIVE SOLUTIONS FOR SUBBASE THICKNESS DESIGN BASED UPON TENSILE STRAIN IN SURFACE LAYER ϵ_s

	Iteration Number			
	1	2	3	
Correction term A	1.00	1.00	1.00	
Correction term B	1.034	1.034	1.034	
Correction term C	1.00	.92	.91	
Design strain, microunits	20.0	20.0	20.0	
Critical design strain, microunits	24.3	26.5	26.8	
Subbase thickness, inches	≃1.3	≃0.6	≃0.5	← Design thickness

APPENDIX 4

DESIGN CURVES FOR LOW MODULUS RIGID AND FLEXIBLE PAVEMENT TYPES

(MODULUS OF ELASTICITY OF SURFACE LAYER BETWEEN 0.5×10^6 AND 3.5×10^6 PSI)

APPENDIX 4. DESIGN CURVES FOR LOW MODULUS RIGID AND FLEXIBLE PAVEMENT TYPES (MODULUS OF ELASTICITY OF SURFACE LAYER BETWEEN 0.5×10^6 AND 3.5×10^6 PSI)

Introduction

The design equations presented in Chapter 3 can best be solved in a computer because of the number of terms involved. The equations could be solved for any one of the six variables as long as estimates of the other five are available. However, since computer facilities are still not universally available to all designers, there is a need for a practical method of solving the design equations. Nomographs fulfilling this need for design equations 6 through 10 are included in this appendix along with an example explaining their use. The example problem is identical to one of the designs included as example problem 3 of Chapter 5.

Application of Nomographs

A set of nomographs are presented in this appendix which can be used to graphically solve equations 6 through 10 of Chapter 3. The nomographs presented here provide solutions for the five equations for low modulus surface layer pavements. The procedures for using the nomographs are presented in the following paragraphs, with an example problem as a guide. A detailed description of the required procedures is provided for one set of nomographs to insure proper understanding of the approach while brief descriptions are provided for the other four nomograph sets. A subbase design thickness is obtained for the five different nomograph sets; therefore, the final design thickness would be obtained from a comparison of the individual design thicknesses.

The material properties which are required for the initial design stage for each set of nomographs include the data in Table A4.1. The values assumed for the example problem are also included in the same table.

TABLE A4.1. MATERIAL PROPERTIES REQUIRED FOR SUBBASE DESIGN

REQUIRED PROPERTIES	ASSUMED VALUES FOR EXAMPLE PROBLEM
Surface Layer	
(1) modulus of elasticity	0.5×10^6 psi
(2) thickness	8.0 inches
(3) design tensile stress	30.0 psi
(4) design tensile strain	50 microunits
Subbase Layer	
(1) modulus of elasticity	2.90×10^5 psi
(2) thickness	A design requirement
(3) design tensile stress	22.5 psi
(4) design tensile strain	50 microunits
Subgrade	
(1) modulus of elasticity	12.00×10^3 psi
(2) design compressive strain	420 microunits

Subbase Thickness Design Based Upon Tensile Stress in Subbase Layer σ_b

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A4.1).

Step 2 - Enter Fig A4.1a with a modulus of elasticity of subgrade $E_g = 12000$ psi on the abscissa scale and project a line vertically until it intersects the curved line. From this point project a horizontal line to the ordinate scale and read off the value for correction term A of 0.875.

Step 3 - Enter Fig A4.1b with thickness of surface layer $T_s = 8.0$ inches on the abscissa scale and project a line vertically until it intersects the modulus of elasticity of the surface layer $E_s = 0.5 \times 10^6$ psi. From this intersection, project a line horizontally to the ordinate scale and read off the value for correction term B of 1.38.

Step 4 - Enter Fig A4.1c with a modulus of elasticity of the subbase layer $E_b = 2.90 \times 10^5$ psi on the abscissa scale and project a line vertically until it intersects the curve for the surface thickness $T_s = 8.0$ inches. From this point project a line horizontally to the ordinate scale and read off the value for correction term C of 0.700.

Step 5 - Estimate a critical design stress $\sigma_b{*}$ by dividing the design stress σ_b by correction terms A, B, and C, i.e., $\sigma_b{*} = \dfrac{\sigma_b}{A \times B \times C}$.

$$\sigma_b{*} = \frac{22.5}{(.875)(1.38)(0.70)} = 26.6 \text{ psi.}$$

Step 6 - Enter Fig A4.1d with (1) a critical design stress $\sigma_b{*} = 26.6$ psi on the ordinate scale and project a line horizontally to the right and (2) surface thickness $T_s = 8.0$ inches on the abscissa scale and project a line vertically upwards. A subbase design thickness of 9.7 inches is then obtained from the location of the intersection of these construction lines with respect to the design thickness curves.

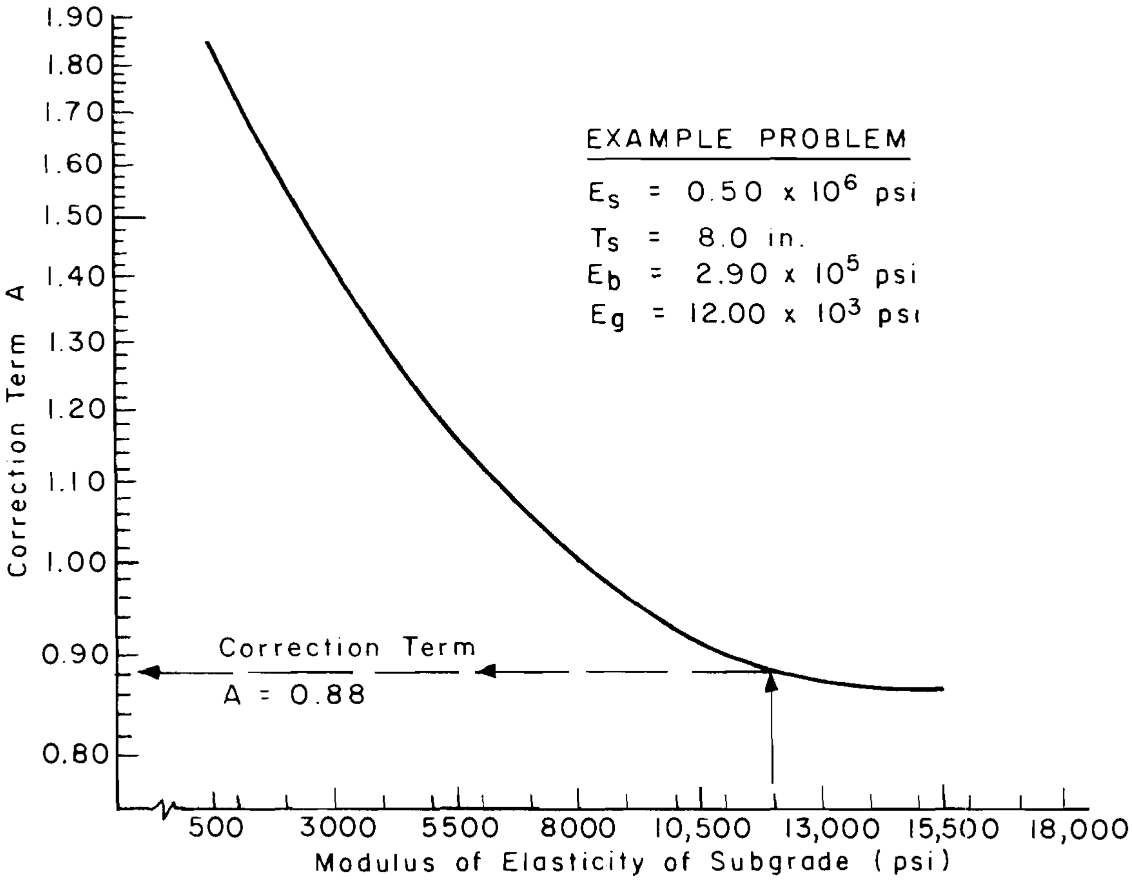


Fig A4.1a. Correction curve A for tensile stress in subbase layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

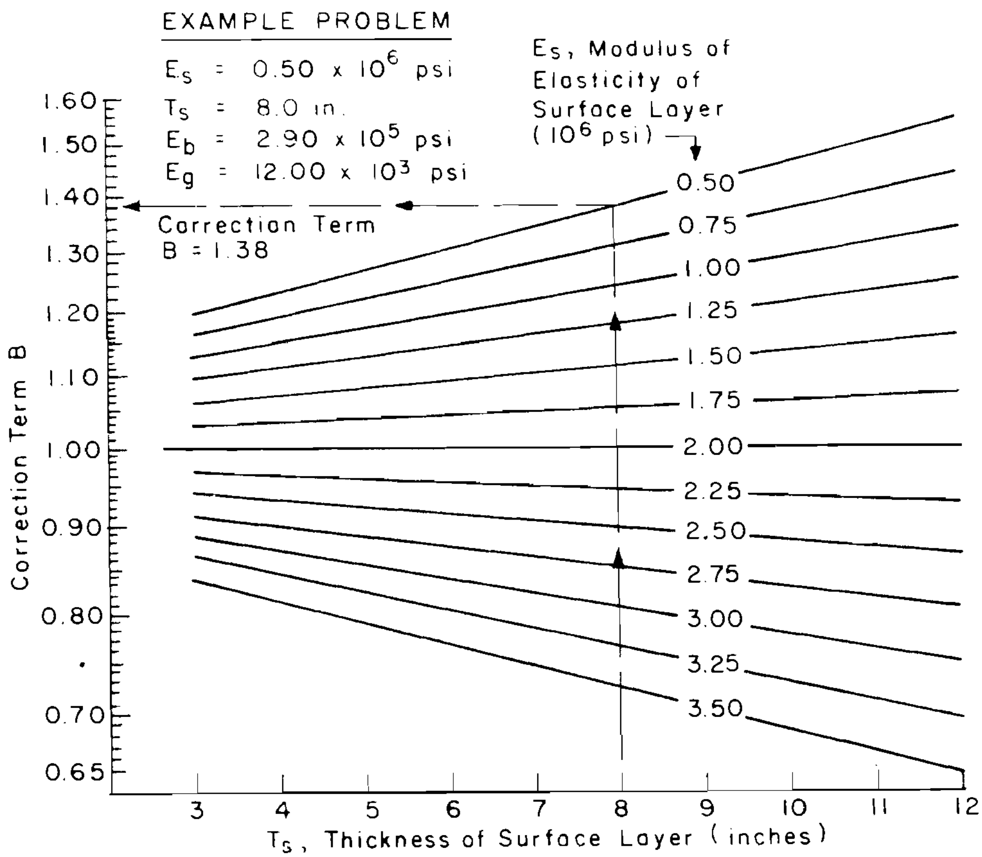


Fig A4.1b. Correction curve B for tensile strain in subbase layer E_s between 0.5×10^6 and 3.5×10^6 psi.

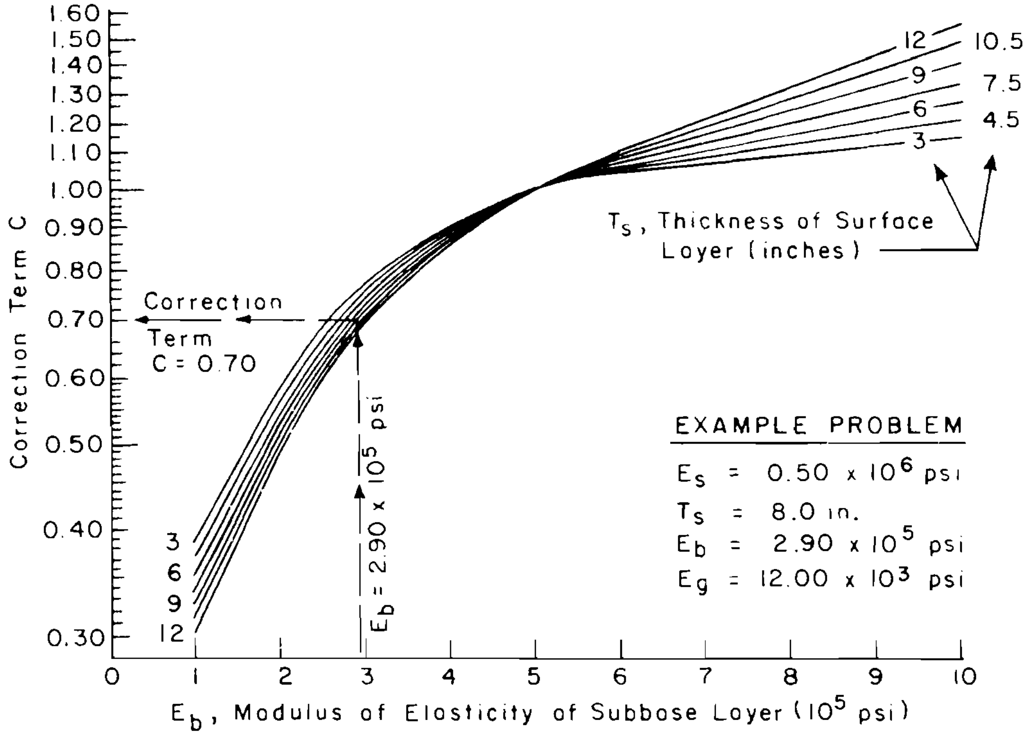


Fig A4.1c. Correction curve C for tensile stress in subbase layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

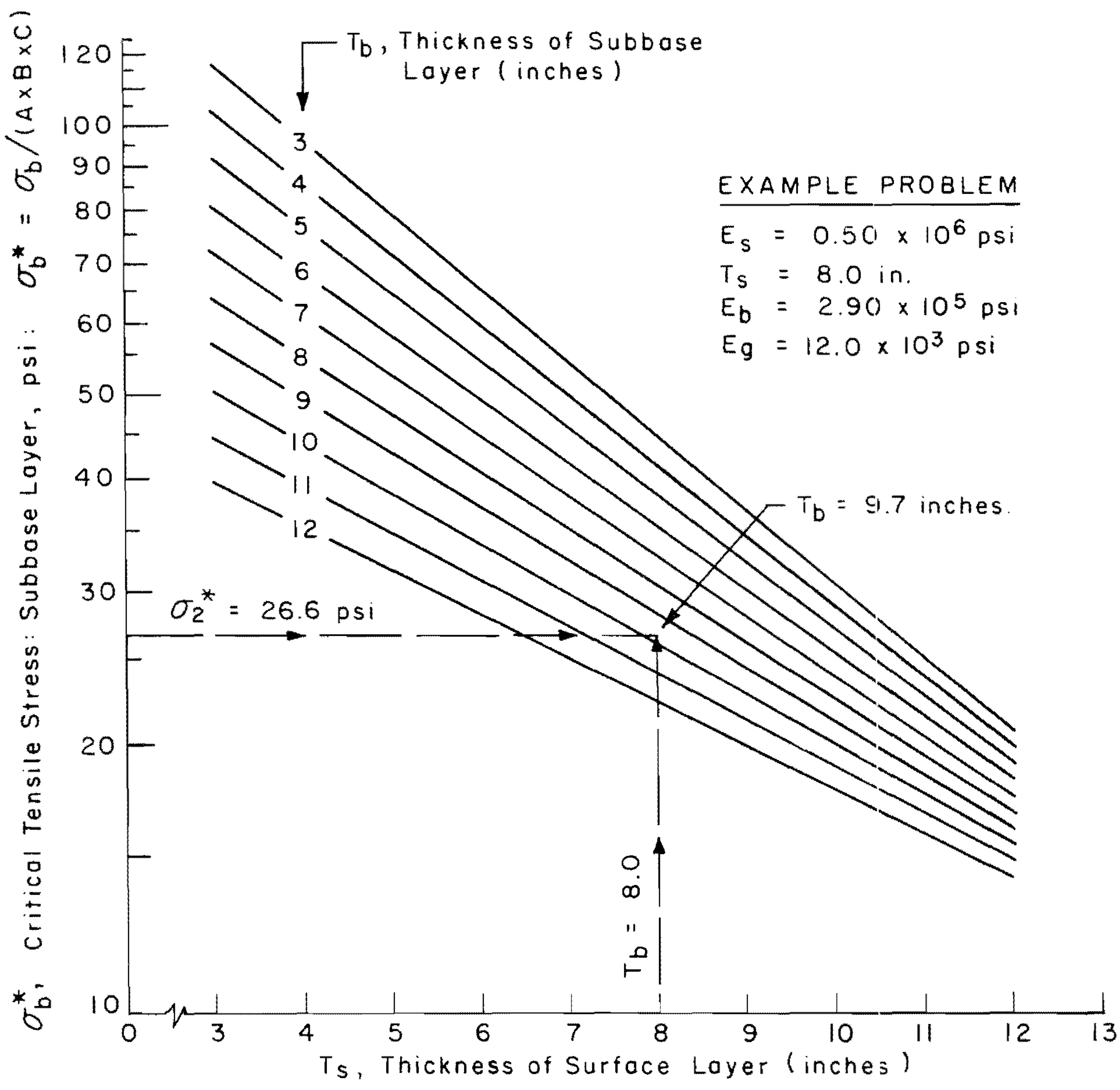


Fig A4.1d. Basic design curve for tensile stress in subbase layer: E_s between 0.5 x 10^6 and 3.5 x 10^6 psi.

Subbase Thickness Design Based Upon Tensile Strain in Subbase Layer ϵ_b

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A4.1).

Step 2 - Enter Fig A4.2a with modulus of elasticity of subgrade E_g = 12000 psi and determine correction term A of 0.87.

Step 3 - Enter Fig A4.2b with thickness T_s = 8.0 inches and modulus of elasticity $E_s = 0.5 \times 10^6$ psi of the surface layer and determine a correction term B of 1.35.

Step 4 - Enter Fig A4.2c with thickness of surface layer T_s = 8.0 inches and modulus of elasticity of the base layer $E_b = 2.90 \times 10^5$ psi and determine a correction term C of 1.30.

Step 5 - Estimate a critical design strain ϵ_b* by dividing the design strain ϵ_b of 50 microunits by correction terms A, B, and C, i.e., $\epsilon_b^* = \frac{\epsilon_b}{A \times B \times C}$.

For the example problem, an estimate of the critical design strain ϵ_b*, of 32.8 microunits is obtained.

Step 6 - Enter Fig A4.2d with a critical design strain ϵ_b = 32.8 microunits and thickness of surface layer T_s = 8.0 inches and determine a subbase design thickness T_b of 9.9 inches.

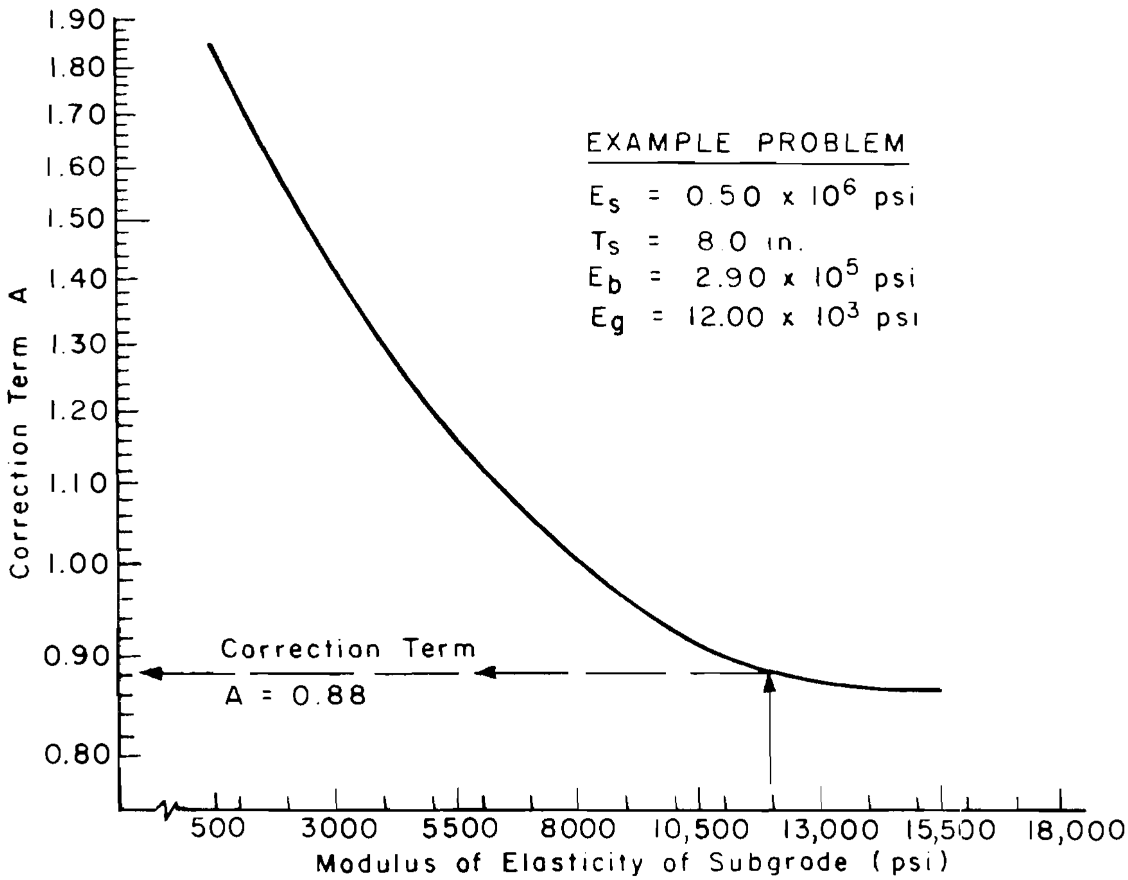


Fig A4.2a. Correction curve A for tensile strain in subbase layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

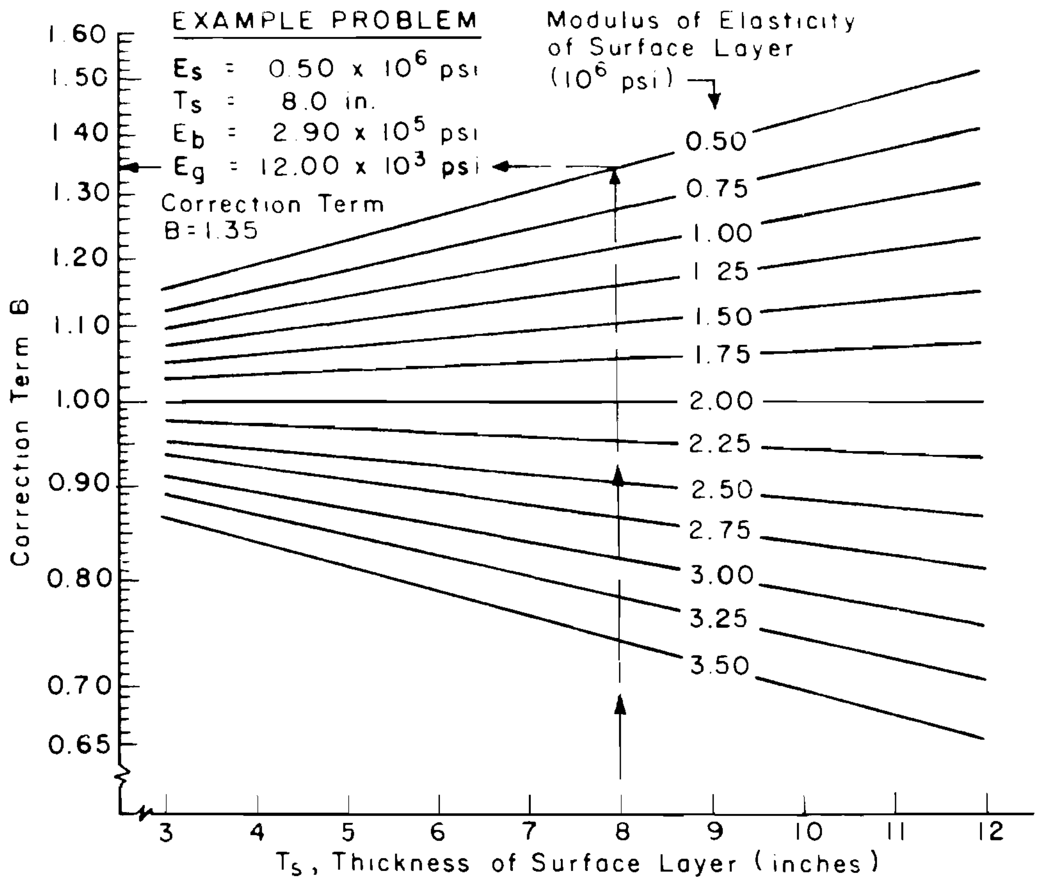


Fig A4.2b. Correction curve B for tensile strain in subbase layer: E_s between 0.5 × 10^6 and 3.5 × 10^6 psi.

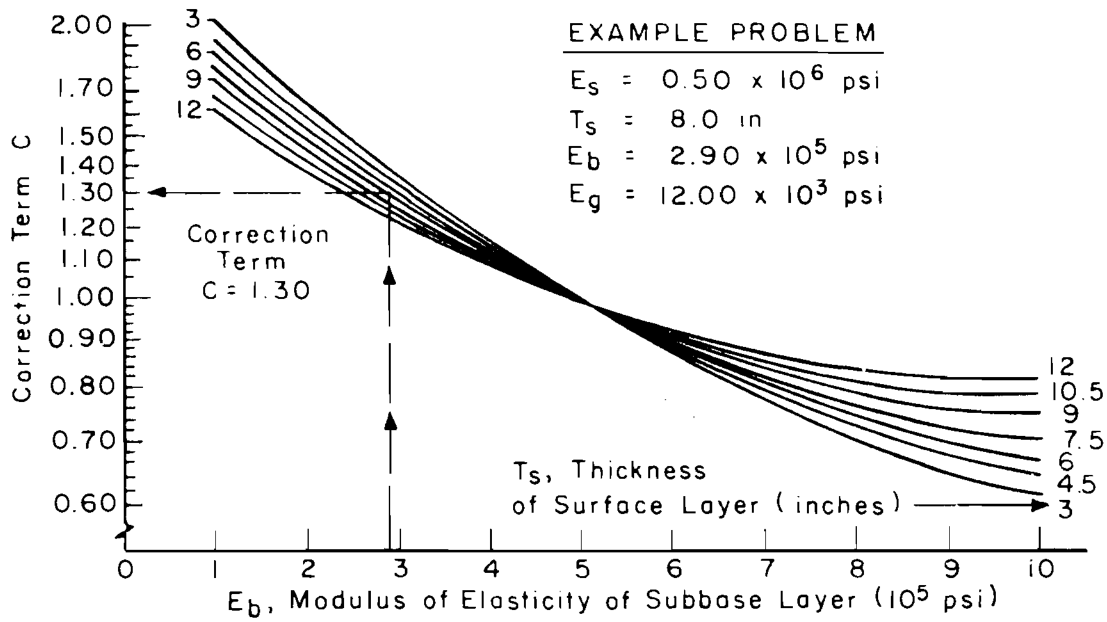


Fig A4.2c. Correction curve C for tensile strain in subbase layer: E_s between 0.5 × 10^6 and 3.5 × 10^6 psi.

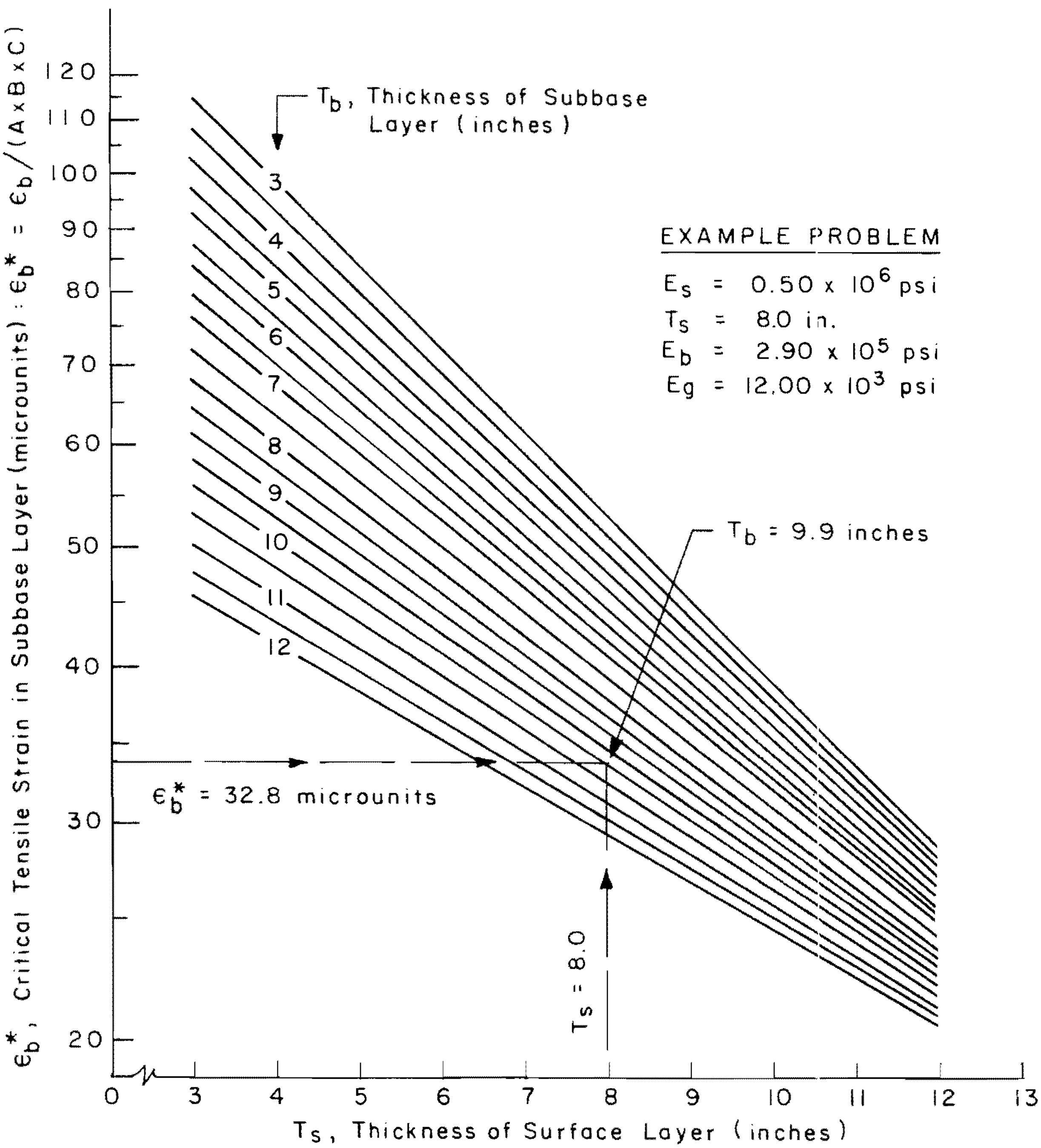


Fig A4.2d. Basic design curve for tensile strain in subbase layer: E_s between 0.5 x 10^6 and 3.5 x 10^6 psi.

Subbase Thickness Design Based Upon Compressive Strain in Subgrade ϵ_c

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A4.1).

Step 2 - Enter Fig A4.3a with modulus of elasticity of subgrade E_g = 12000 psi and determine correction term A of 0.88.

Step 3 - Enter Fig A4.3b with thickness of surface T_s = 8.0 inches and modulus of elasticity of the surface $E_s = 0.5 \times 10^5$ psi and determine correction term B of 1.37.

Step 4 - Enter Fig A4.3c with thickness of surface layer T_s = 8.0 inches and modulus of elasticity of the base layer $E_b = 2.90 \times 10^5$ psi and determine correction term C of 1.29.

Step 5 - Estimate a critical design strain by dividing design strain by correction terms A, B, and C, i.e., $\epsilon_c{}^* = \frac{\epsilon_c}{A \times B \times C} = \frac{420}{(0.88)(1.37)(1.29)} = 269$ microunits.

Step 6 - Enter Fig A4.3d with a critical design strain $\epsilon_c{}^*$ of 269 microunits and thickness of surface layer T_s = 8.0 inches to determine a subbase design thickness of 0.0 inch.

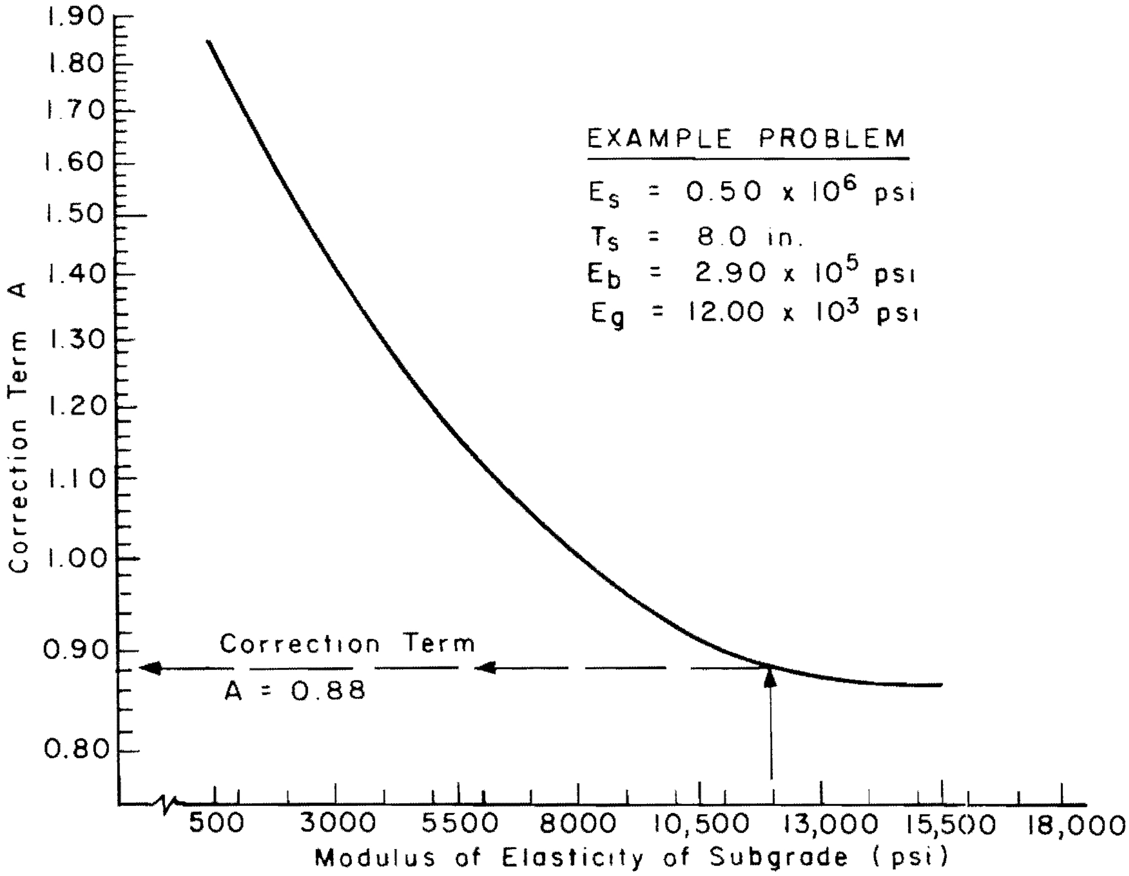


Fig A4.3a. Correction curve A for compressive strain in subgrade: E_s between 0.5×10^6 and 3.5×10^6 psi.

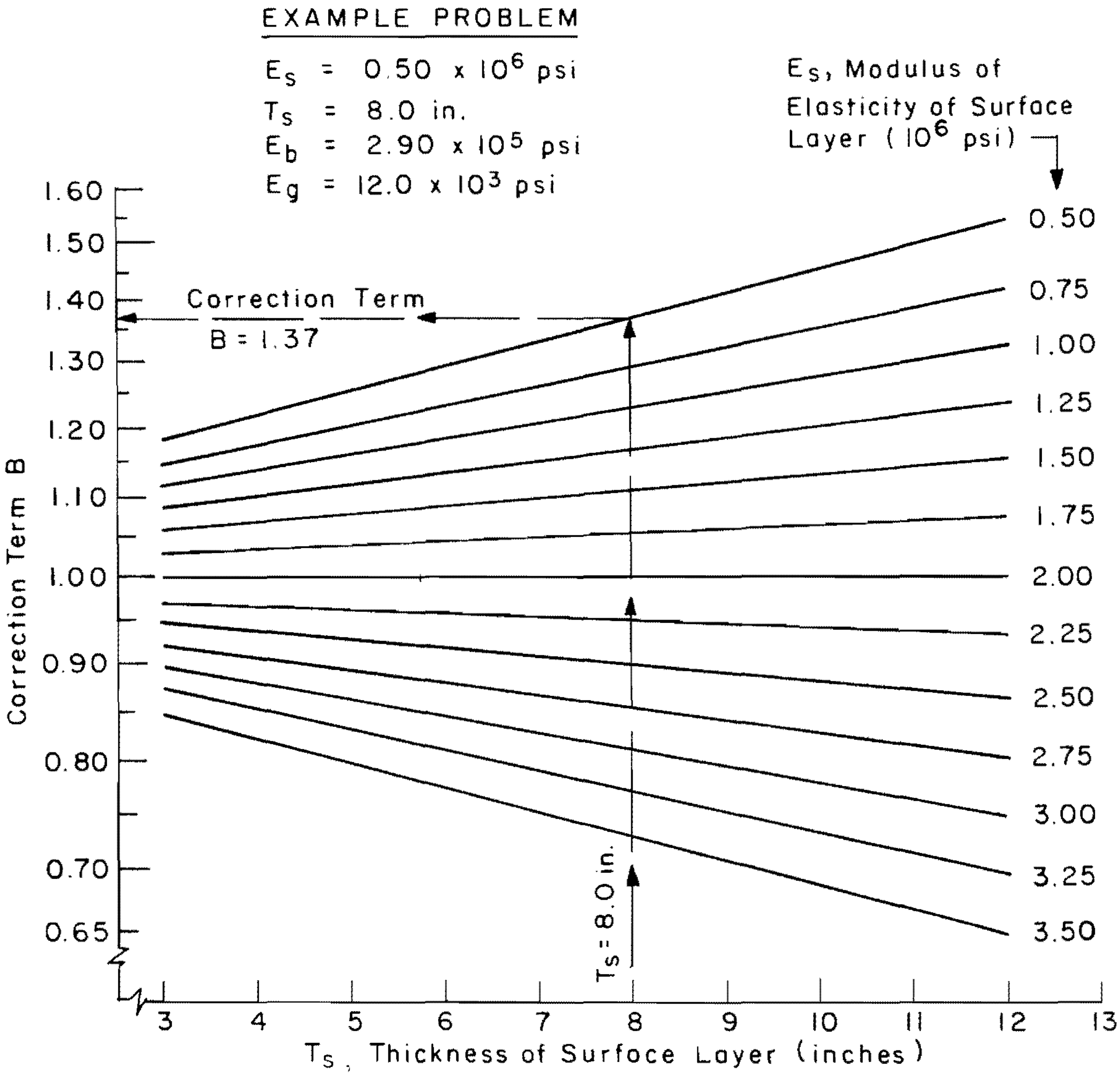


Fig A4.3b. Correction curve B for compressive strain in subgrade: E_s between 0.5×10^6 and 3.5×10^6 psi.

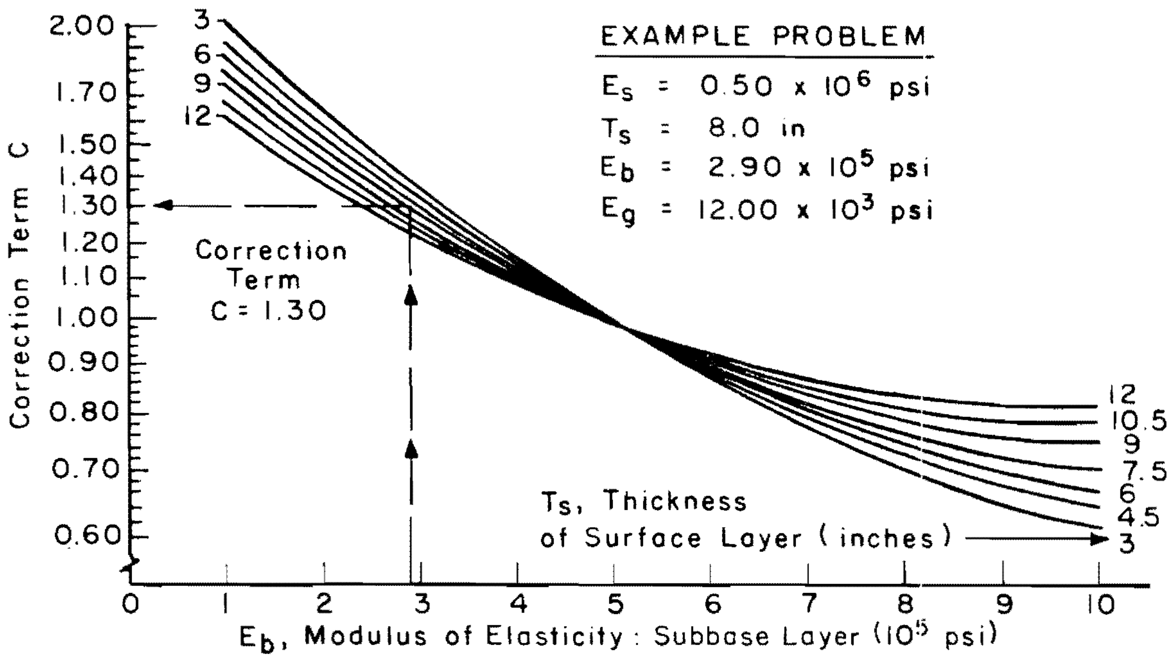


Fig A4.3c. Correction curve C for compressive strain in subgrade: E_s between 0.5×10^6 and 3.5×10^6 psi.

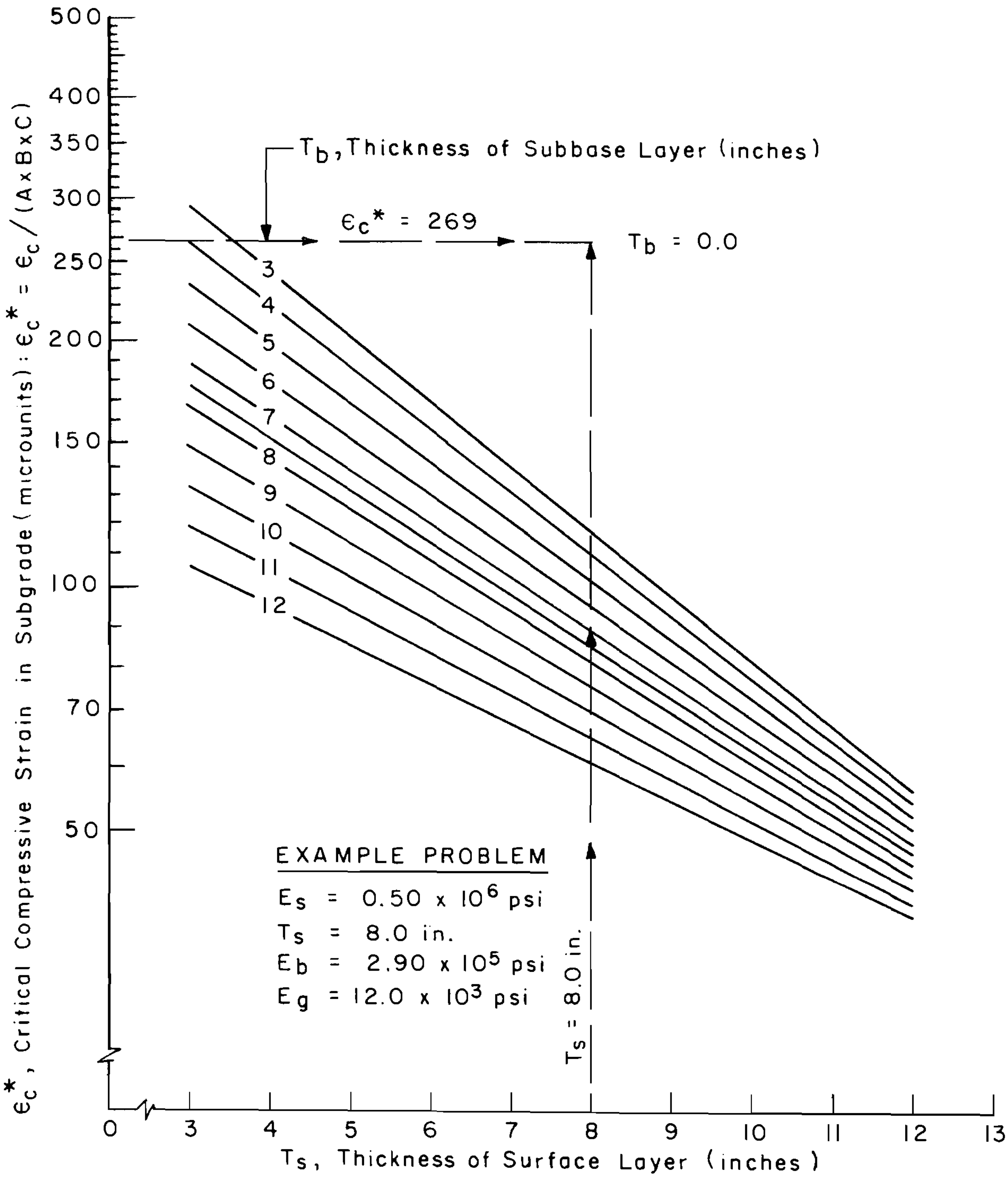


Fig A4.3d. Basic design curve: compressive strain in subgrade: E_s between 0.5×10^6 and 3.5×10^6 psi.

Subbase Thickness Design Based Upon Tensile Stress in Surface Layer σ_s

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A4.1).

Step 2 - Enter Fig A4.4a with thickness $T_s = 8.0$ inches and modulus of elasticity $E_s = 0.5 \times 10^6$ psi of the surface layer and determine a correction term A of 0.55.

Step 3 - Enter Fig A4.4b with thickness of surface layer $T_s = 8.0$ inches and modulus of elasticity of subbase layer $E_b = 2.90 \times 10^5$ psi and determine a correction term B of 1.27.

Step 4 - Estimate a critical design stress σ_s* by adding 55.0 to the design stress σ_s and dividing by correction terms A and B, i.e., $\sigma_s^* = \dfrac{\sigma_s + 55.0}{A \times B}$.

For the example problem, $\sigma_s^* = \dfrac{(30. + 55)}{(.55)(1.27)} = 121.3$ psi.

Step 5 - Enter Fig A4.4c with critical design stress σ_s* of 121.3 psi and thickness of surface layer $T_s = 8.0$ inches and determine a subbase design thickness T_b of 5.8 inches.

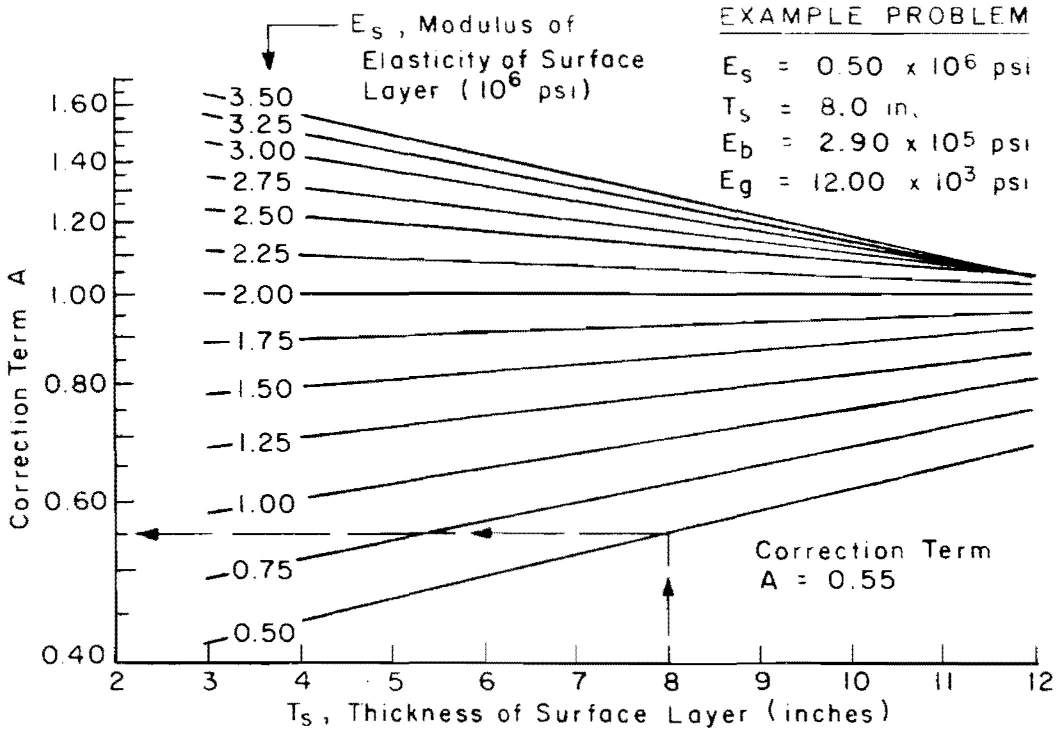


Fig A4.4a. Correction curve A for tensile stress function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

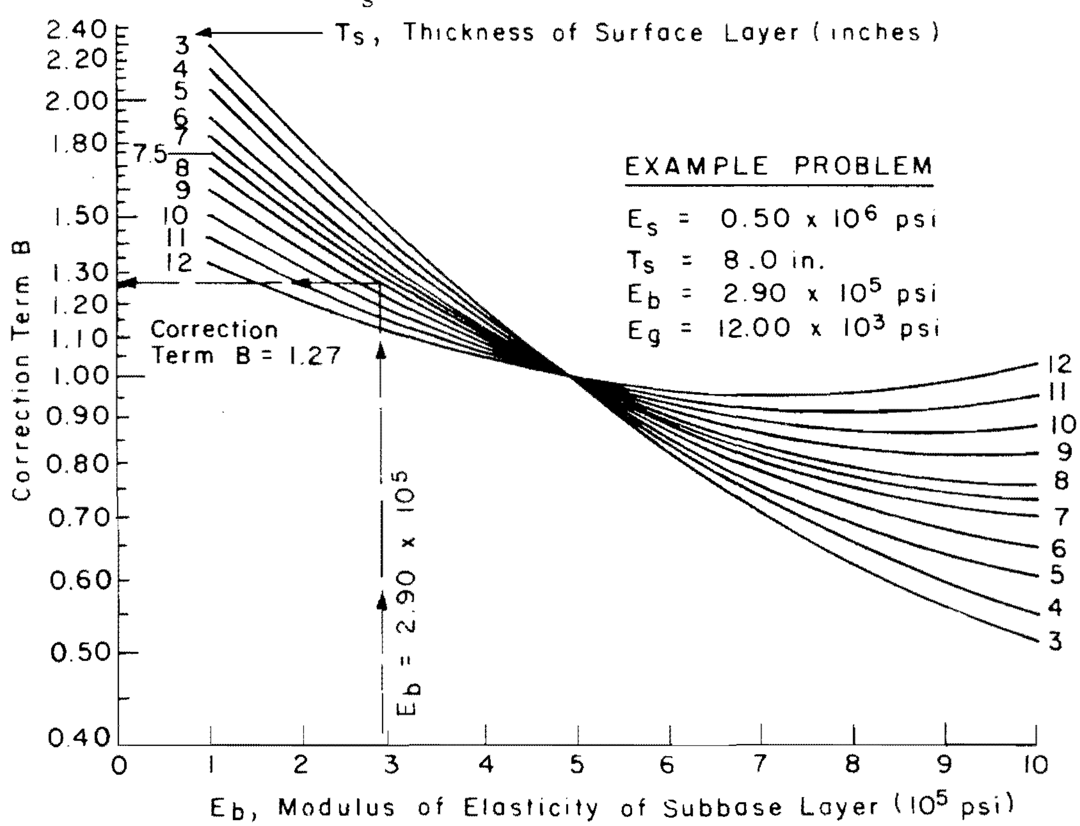


Fig A4.4b. Correction curve B for tensile stress function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

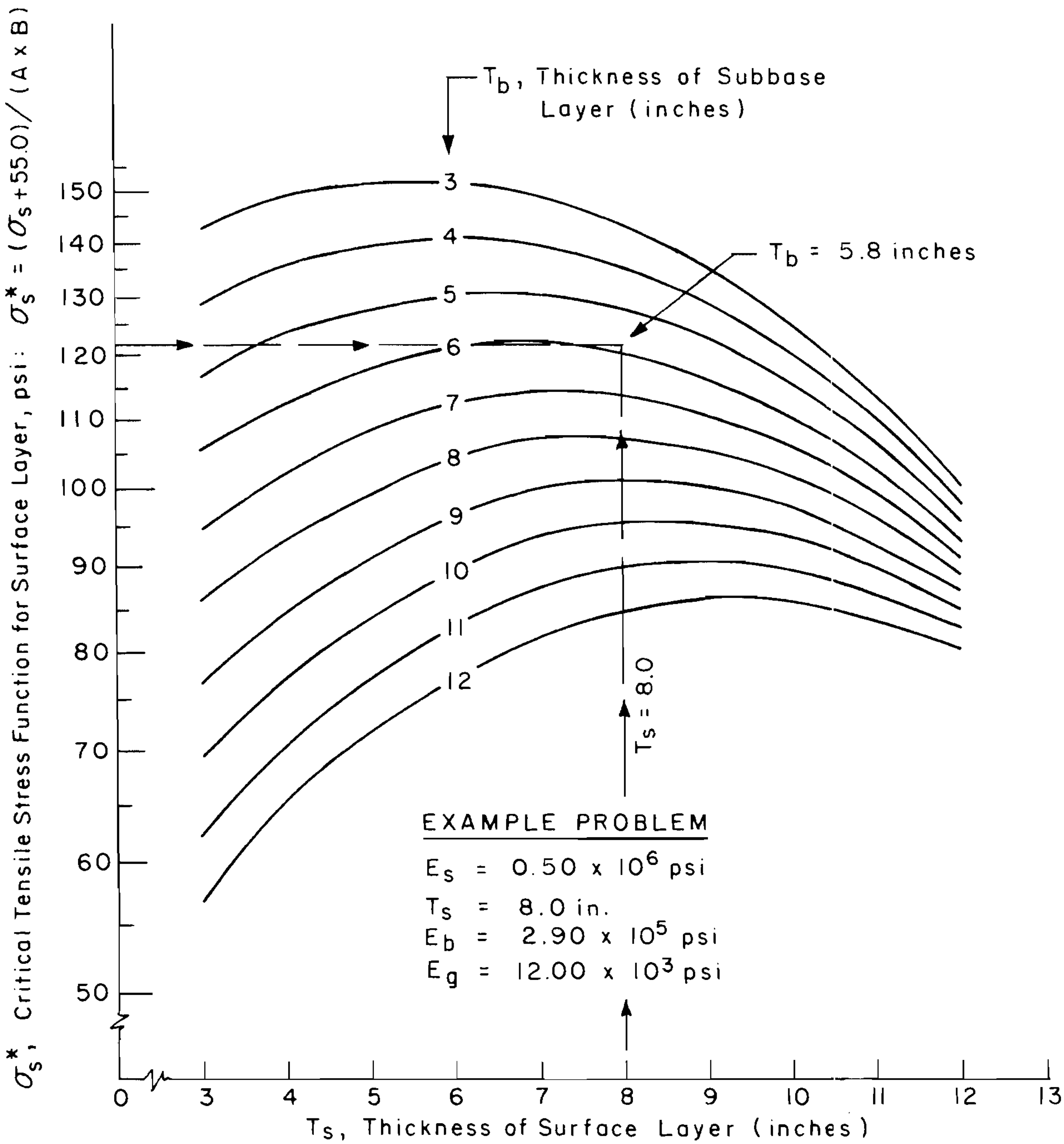


Fig A4.4c. Basic design curve for tensile stress function for surface layer: E_s between 0.5 x 10^6 and 3.5 x 10^6 psi.

Subbase Thickness Design Based Upon Tensile Strain in Surface Layer ε_s

Step 1 - Obtain proper information concerning material characterization of surface, subbase, and subgrade layers (see Table A4.1).

Step 2 - Enter Fig A4.5a with thickness $T_s = 8.0$ inches and modulus of elasticity $E_s = 0.5 \times 10^6$ psi of the surface layer and determine a correction term A of 1.027.

Step 3 - Enter Fig A4.5b with thickness of surface layer $T_s = 8.0$ inches and modulus of elasticity of subbase layer $E_b = 2.90 \times 10^5$ psi and determine a correction term B of .992.

Step 4 - Enter Fig A4.5c with modulus of elasticity of subbase layer $E_b = 2.90 \times 10^5$ psi and modulus of elasticity of surface layer $E_s = 0.5 \times 10^6$ psi and determine a correction term C of 1.25.

Step 5 - Estimate a critical design strain $\varepsilon_s{*}$ by adding 56.4 to the design strain ε_s and dividing by correction terms A, B, and C, i.e., $\varepsilon_s{*} = \dfrac{(\varepsilon_s + 56.4)}{A \times B \times C}$.

For the example problem, $\varepsilon_s{*} = \dfrac{(50 + 56.4) \text{ microunits}}{(1.027)(.992)(1.25)} = 83.9$ microunits.

Step 6 - Enter Fig A4.5d with critical design strain of 83.9 microunits and determine a subbase design thickness of approximately 1.9 inches.

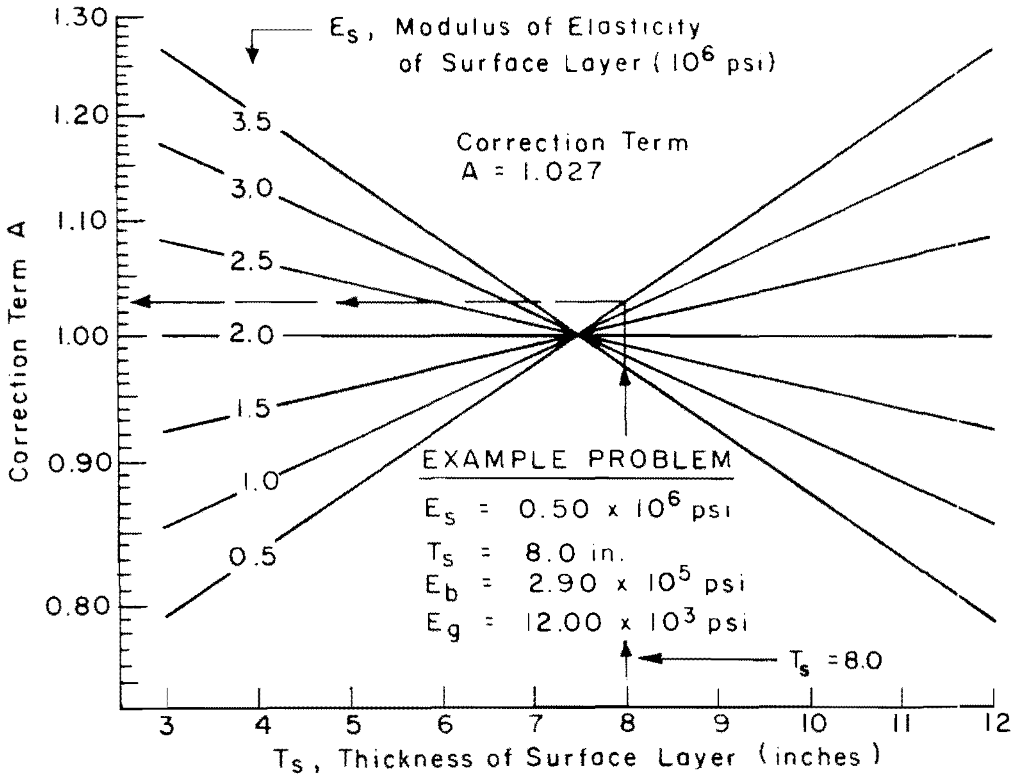


Fig A4.5a. Correction curve A for tensile strain function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

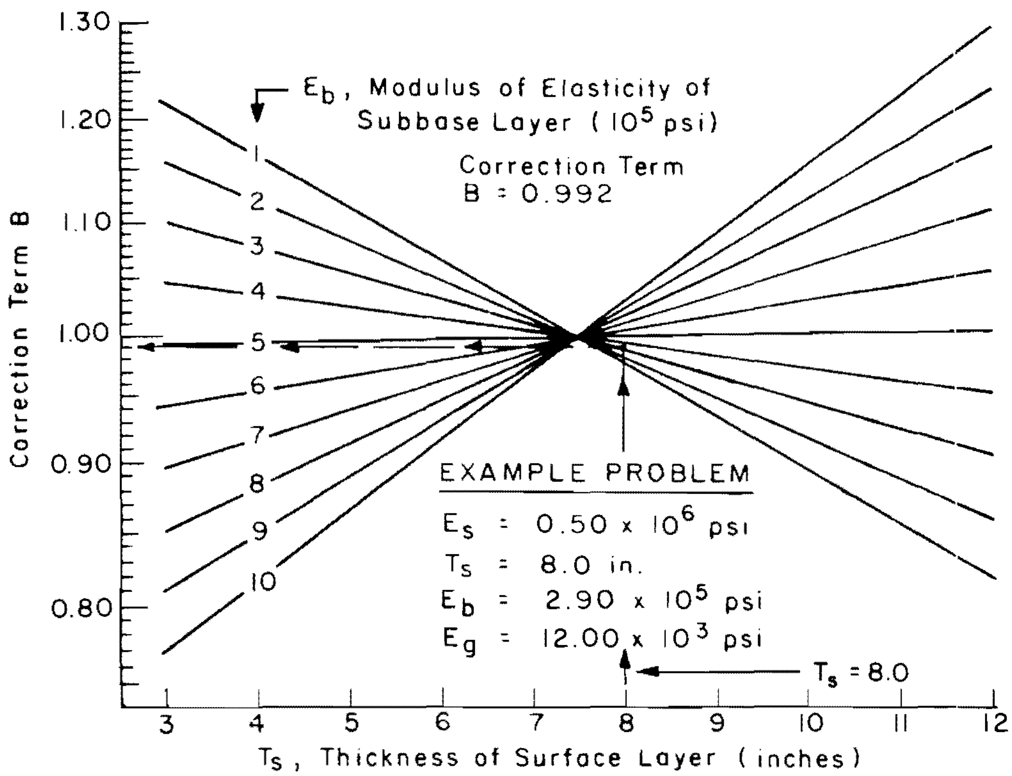


Fig A4.5b. Correction curve B for tensile strain function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

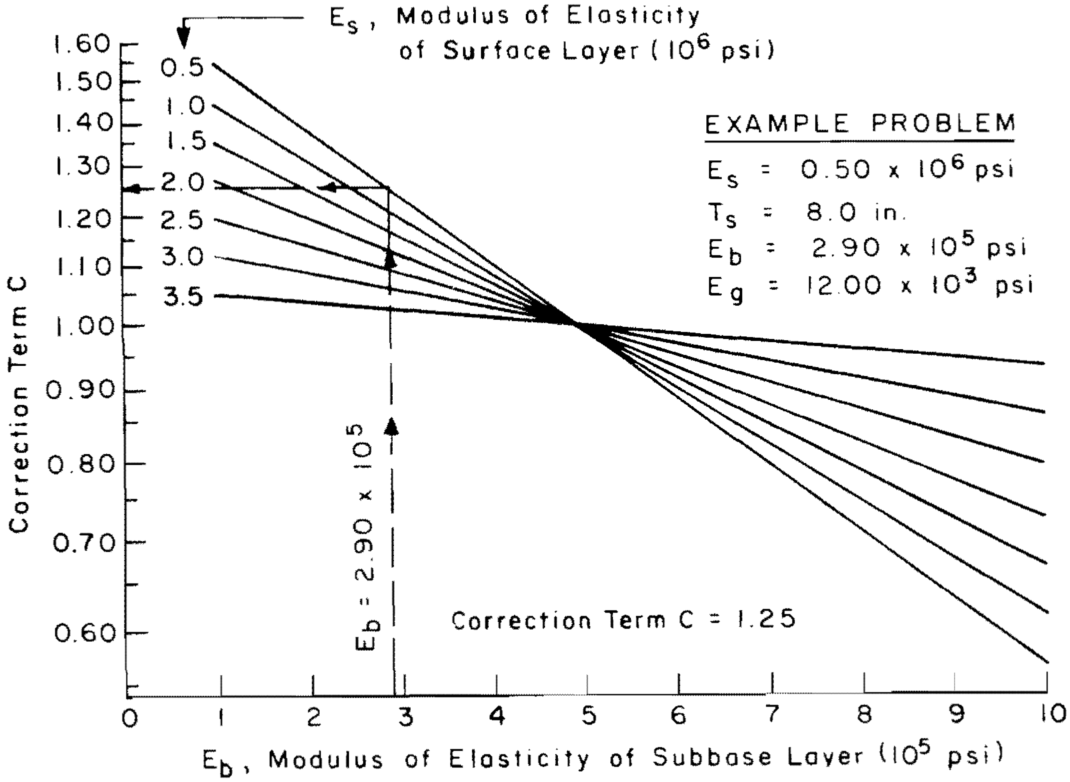


Fig A4.5c. Basic design curve: tensile strain function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

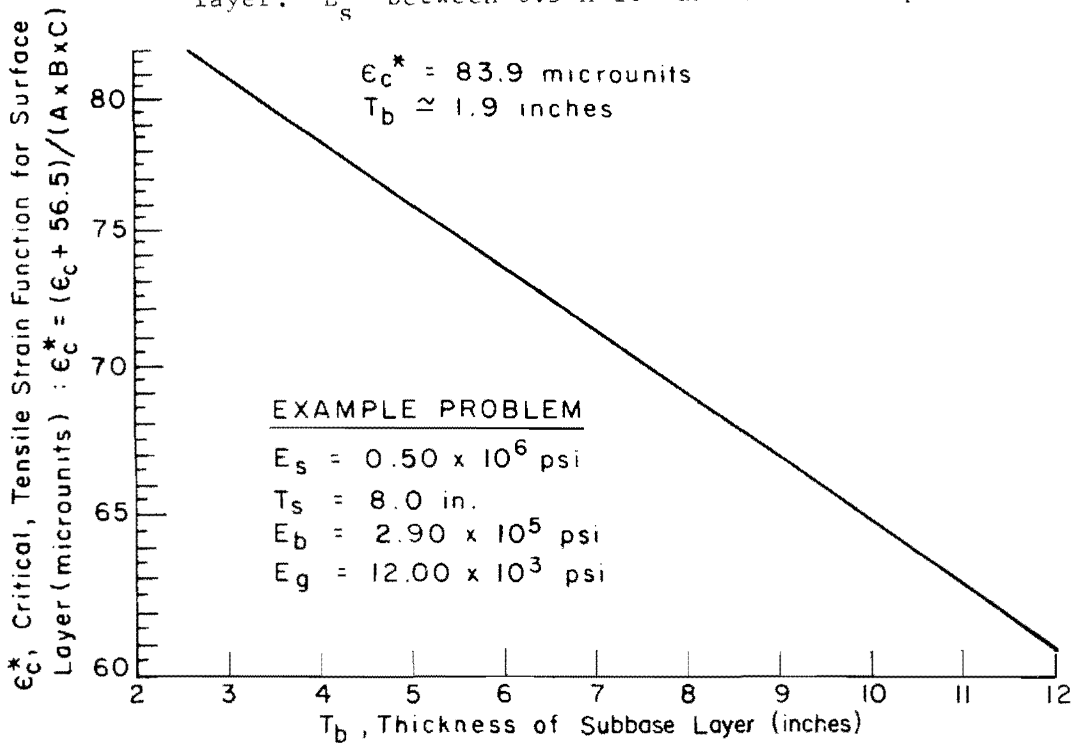


Fig A4.5d. Correction curve C for tensile strain function for surface layer: E_s between 0.5×10^6 and 3.5×10^6 psi.

APPENDIX 5

APPLICABILITY OF INDIRECT TENSILE TEST FOR ESTIMATING PROPERTIES OF A VARIETY OF STABILIZED PAVEMENT MATERIALS

APPENDIX 5. APPLICABILITY OF INDIRECT TENSILE TEST FOR ESTIMATING PROPERTIES OF A VARIETY OF STABILIZED PAVEMENT MATERIALS

The selection of a single technique for characterizing the properties of a variety of materials requires that the applicability of the test configuration to these materials be investigated or considered. This is especially true when the technique is considered to be applicable to a diverse variety of highway materials ranging from a brittle material such as portland cement concrete to a viscoelastic material such as asphalt concrete. The experimental work presented here was, therefore, conducted to investigate the applicability of the indirect tensile test for estimating the properties of various highway materials.

The testing program involved comparing values of modulus of elasticity and Poisson's ratio calculated from the total deformation relationships (Ref 3.2) with values obtained from the theoretical equations involving measured strain data for cylindrical specimens of aluminum, plexiglas, and two separate mixes each of asphalt-treated, cement-treated, and lime-treated materials. In addition, tests were completed on Taylor Marl clay. The aluminum specimens were used primarily to evaluate the accuracy of the relationships for an elastic material. All specimens were instrumented with rosette strain gages.

The test procedure for aluminum consisted of loading a thin circular specimen in increments of 800 (±10) pounds beginning at 800 pounds and ending with 8,000 pounds. Separate tests were run to obtain center strain and total deformation data. At each load level either the total deformations or center strains were measured. The strains were read from the strain indicators and recorded while deformations versus loads were plotted on x-y plotters.

The remaining materials were tested by applying an increasing load at a relatively slow loading rate so that strain measurements could be obtained. The load-total deformation was plotted on x-y plotters while the center strain data were recorded by a Honeywell data logging system. The asphalt-treated, cement-treated, lime-treated, and plexiglas specimens were tested at 55° F in a controlled environmental chamber. This test temperature was selected to offset the effect of slow loading rate on the asphalt-treated mixtures and to produce material properties similar to those obtained at a test temperature of 75° F and a loading rate of 2.0 inches per minute. Since the tests were to be completed at the same time, all of the above mentioned materials were also tested at 55° F. The Taylor Marl clay specimens in a semi-dry condition were tested at 75° F on a different day than the other materials.

Comparisons between estimated and measured strains for the different materials are presented in Figs A5.1 through A5.24, and the resulting estimates of material properties are included in Tables A5.1 and A5.2. Differences between material properties estimated from total deformation and center strain data are included in Table A5.3.

From Figs A5.1 and A5.2 it can be seen that there was excellent agreement between strain values for aluminum and, therefore, corresponding excellent agreement between material properties obtained from total deformation and center strain data, as can be seen in Tables A5.1 and A5.2. The modulus of elasticity and Poisson's ratio estimates agreed within 0.1 and 13.1 percent, respectively, while measured and estimated horizontal (tensile) and vertical (compressive) strains agreed within 6.0 percent and 16.0 percent, respectively.

The estimates of material properties for two different thicknesses of plexiglas are included in Tables A5.1 and A5.3. There was excellent agreement between properties estimated from center strain data and total deformation data. The average difference between the two estimates of modulus of elasticity was 6.0 percent while the average difference for Poisson's ratio estimates was 10.2 percent. Comparisons between measured and estimated tensile and compressive strains for the two thicknesses are presented in Figs A5.3 and A5.4, which indicate greater differences in the strains for the 2-inch-thick plexiglas specimen. The average differences in the strains for the 1-inch-thick specimen were 11.4 and 15.8, respectively, for tensile and compressive strains, and corresponding average differences for the 2-inch-thick specimen were 21.8 and 21.0. These larger differences for the thicker specimen may be due in part to stresses and strains developed along the z-axis which were not considered in plane stress analysis of the test results. Additionally, strains developed along the z-axis would create slight bulging at the ends of the specimen, therefore affecting strain results. This phenomenon could account for some of the differences between measured and estimated strains for both thicknesses. For both the tensile and compressive strains the measured values exceeded the estimated values.

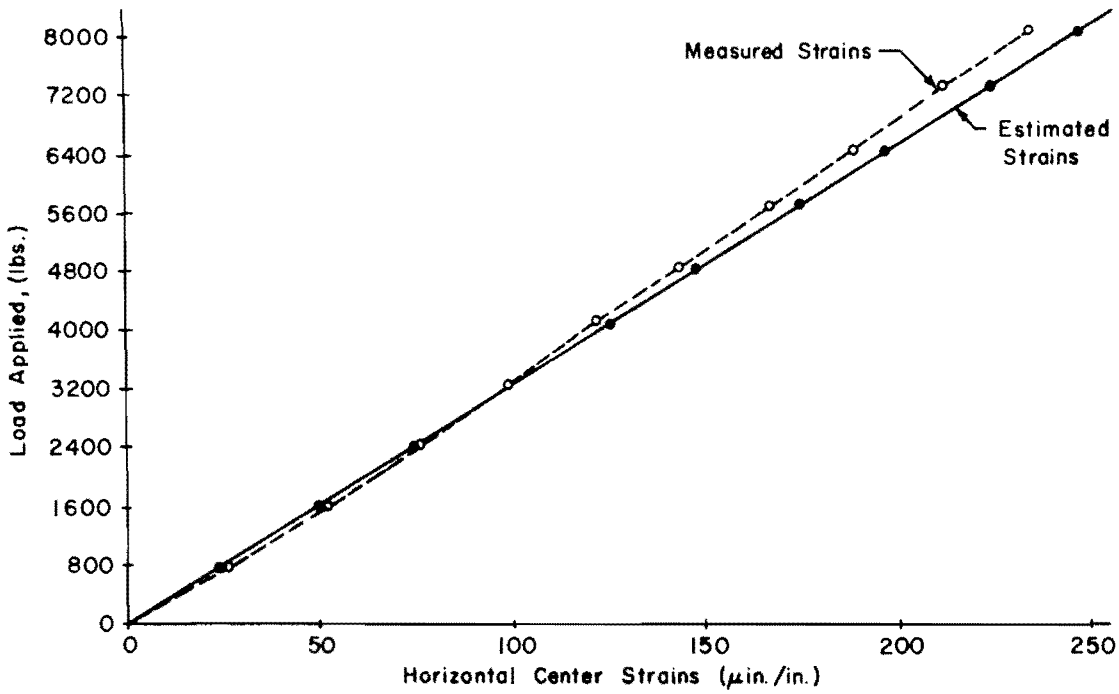


Fig A5.1. Comparison of measured and estimated horizontal strain.

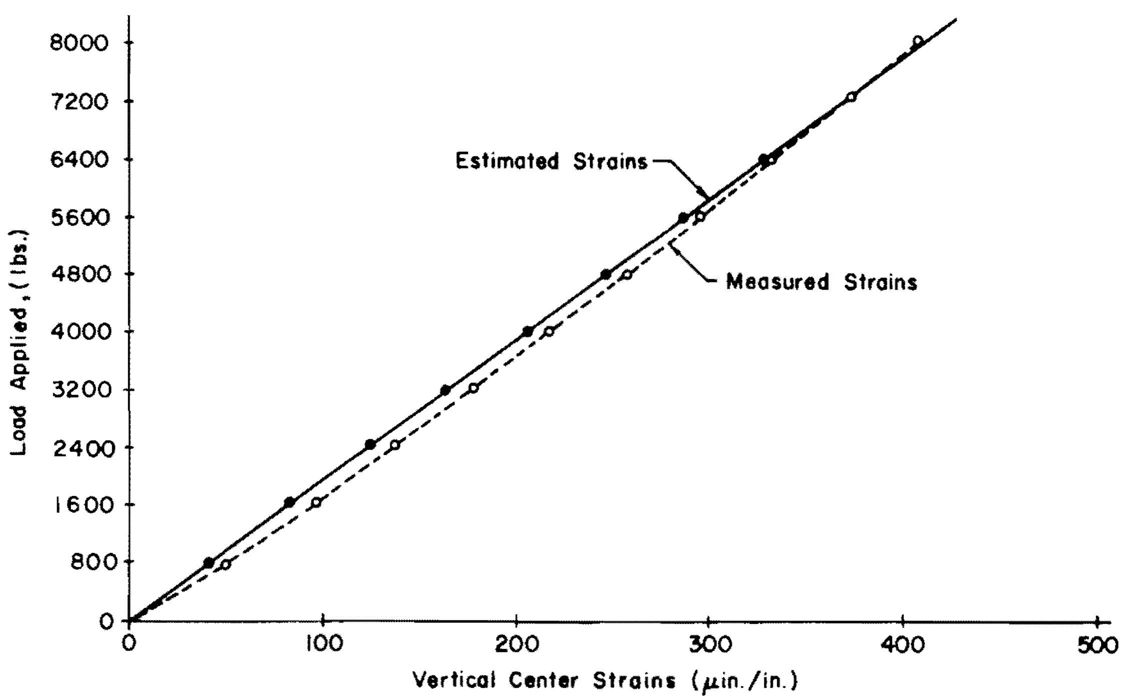


Fig A5.2. Comparison of measured and estimated vertical strains.

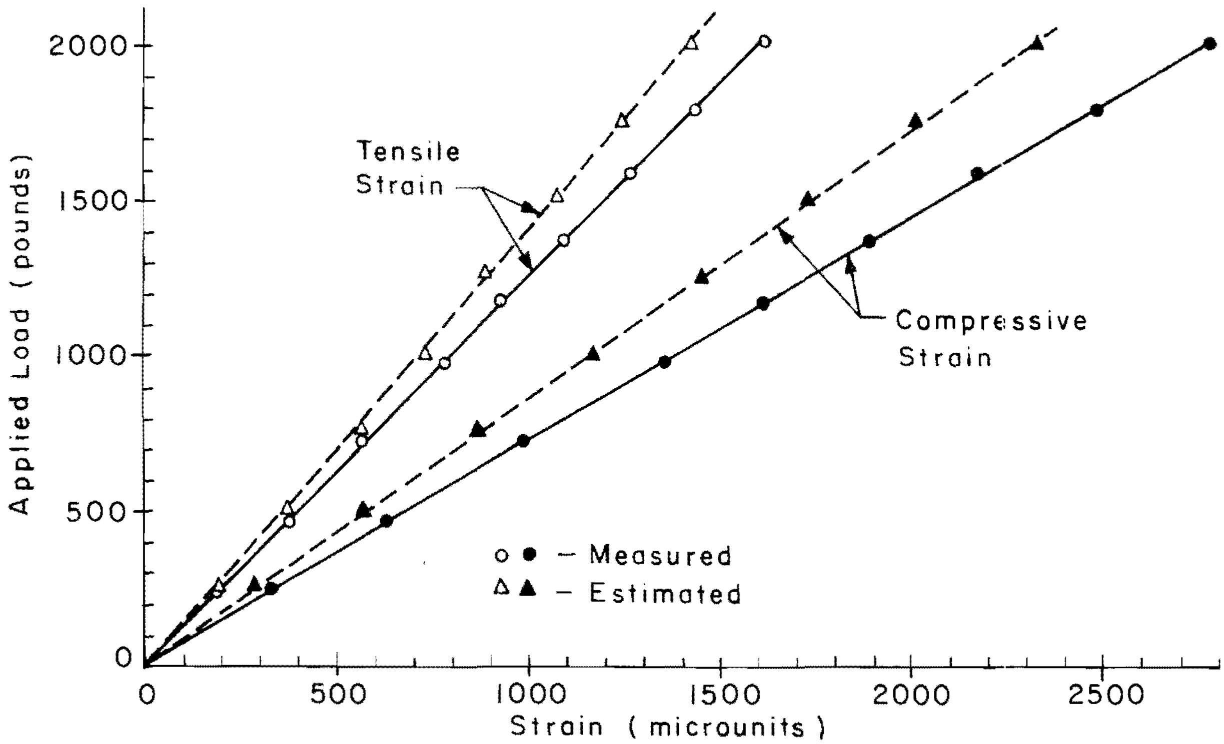


Fig A5.3. Comparison of estimated and measured strains for a 1-inch-thick plexiglas specimen (4-inch diameter).

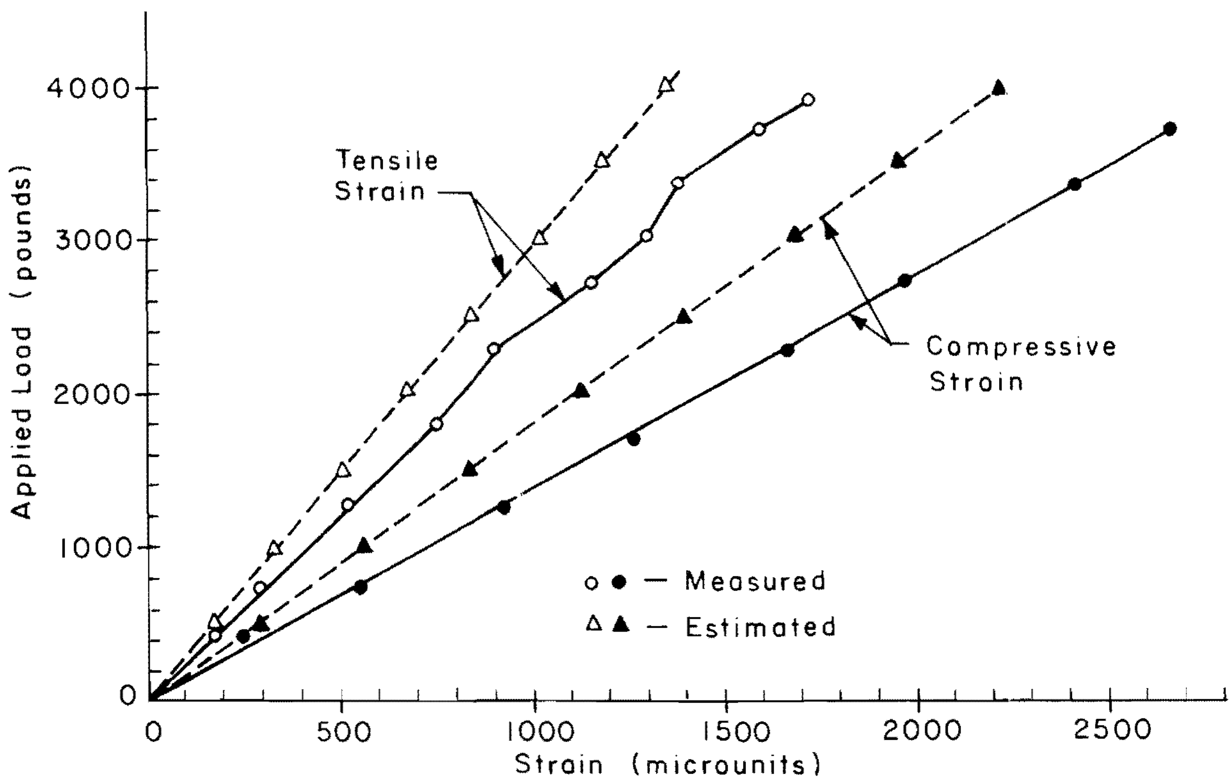


Fig A5.4. Comparison of estimated and measured strains for a 2-inch-thick plexiglas specimen (4-inch diameter).

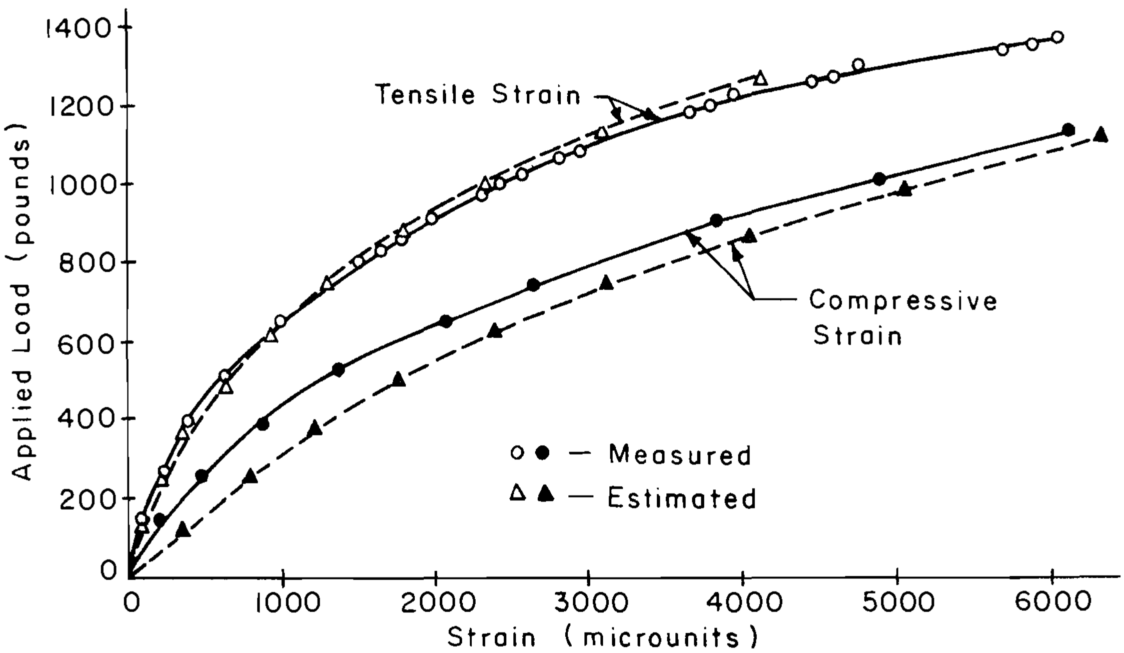


Fig A5.5. Comparison of measured and estimated strains, asphaltic specimen No. 1a.

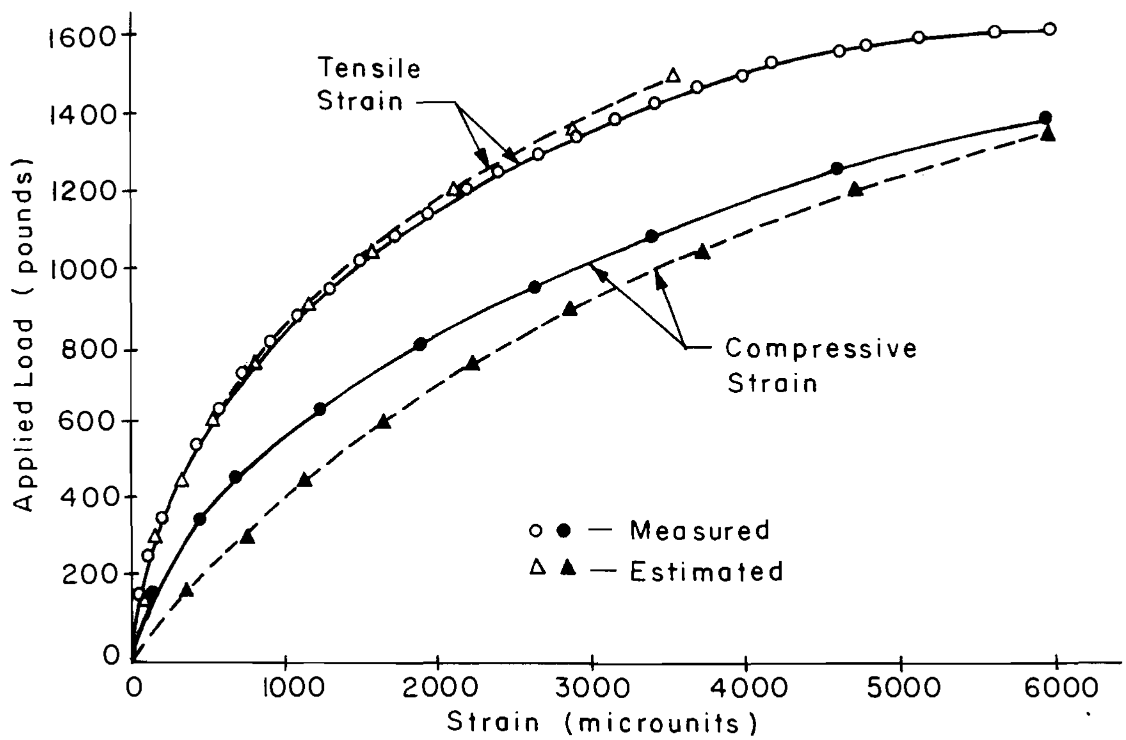


Fig A5.6. Comparison of measured and estimated strains, asphaltic specimen No. 2a.

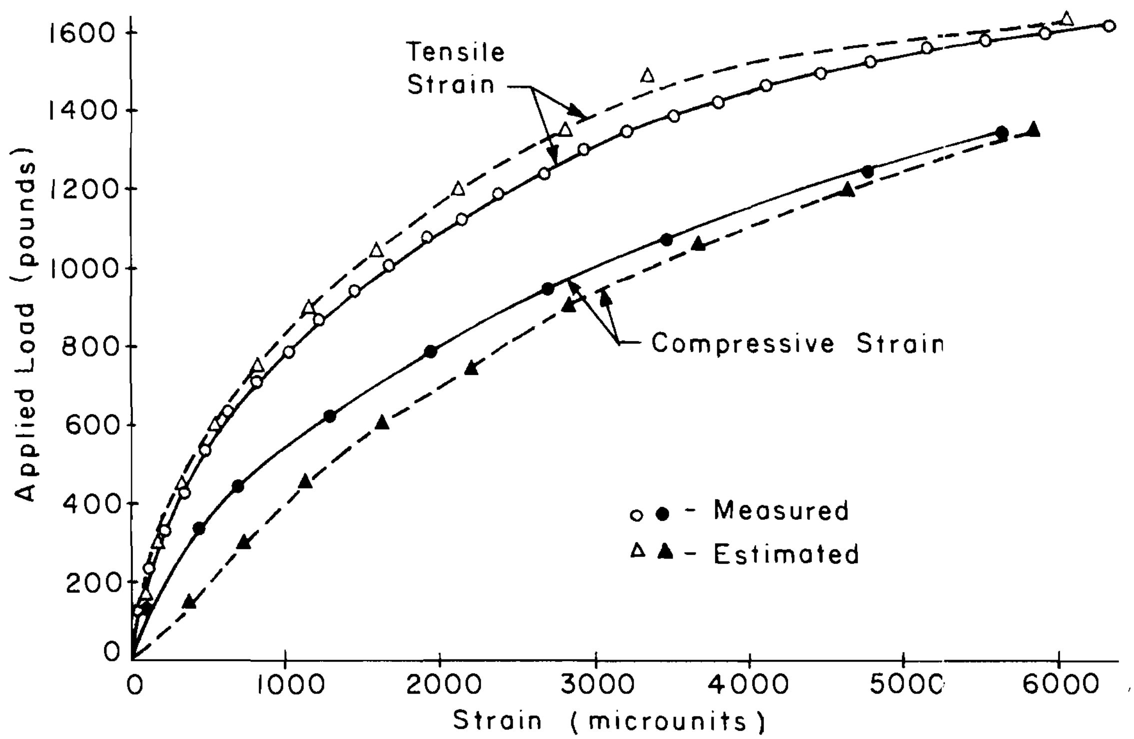


Fig A5.7. Comparison of measured and estimated strains, asphaltic specimen No. 3a.

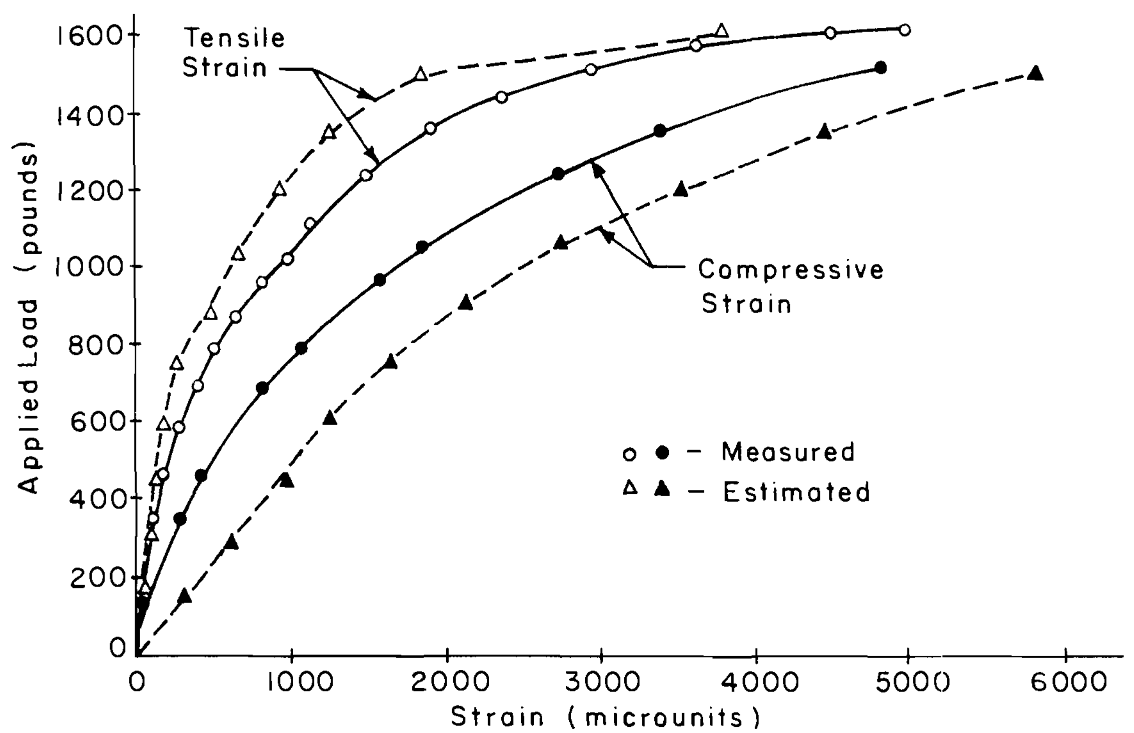


Fig A5.8. Comparison of measured and estimated strains, asphaltic specimen No. 4a.

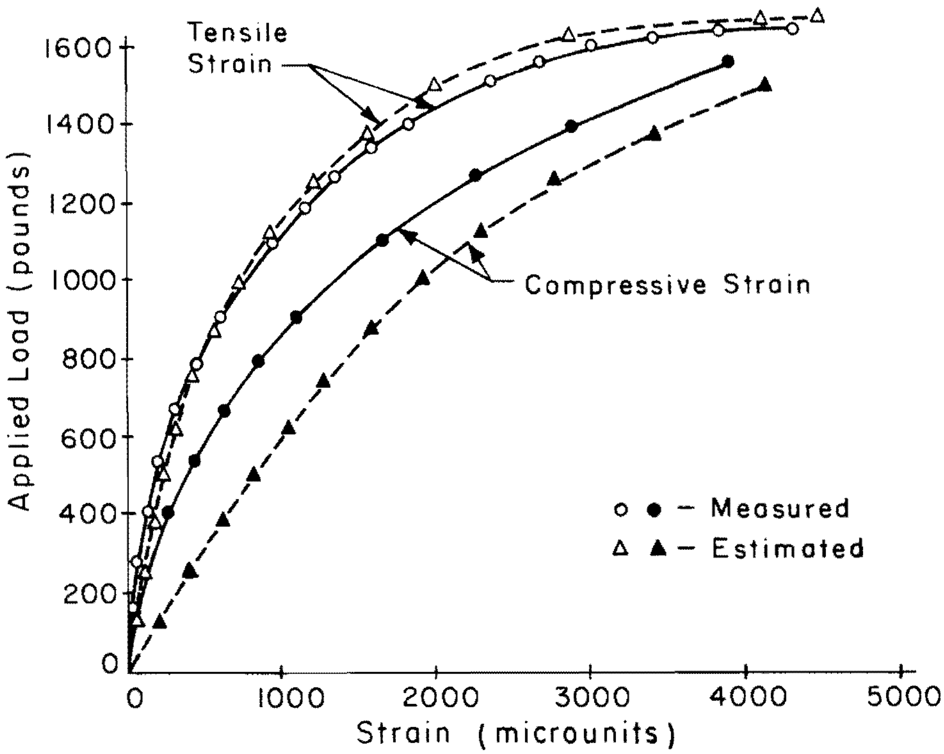


Fig A5.9. Comparison of measured and estimated strains, asphaltic specimen No. 5a.

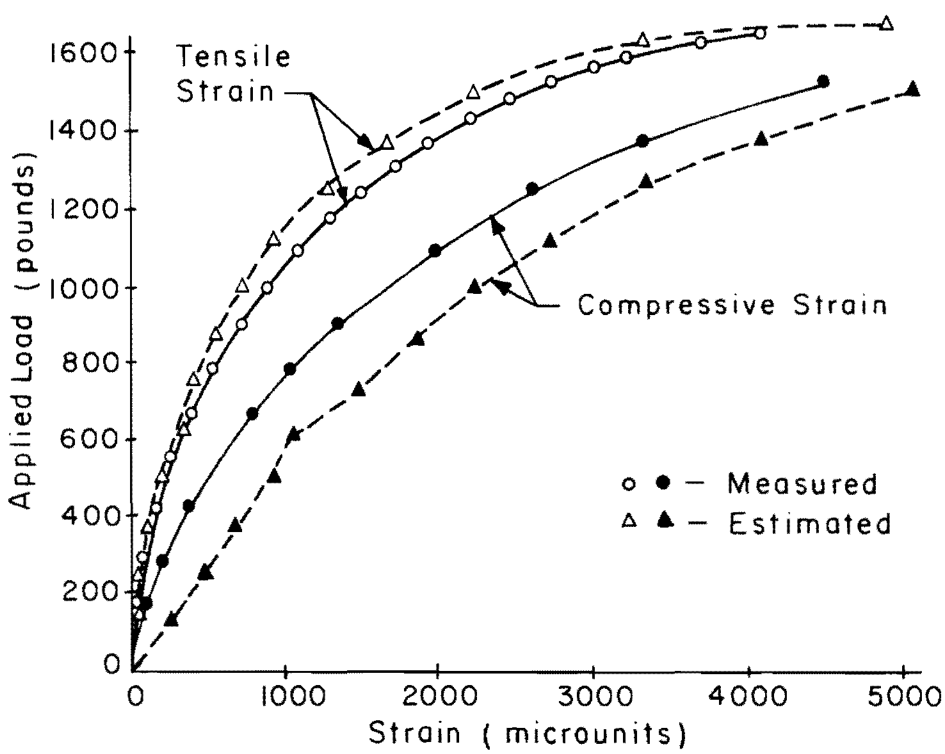


Fig A5.10. Comparison of measured and estimated strains, asphaltic specimen No. 6a.

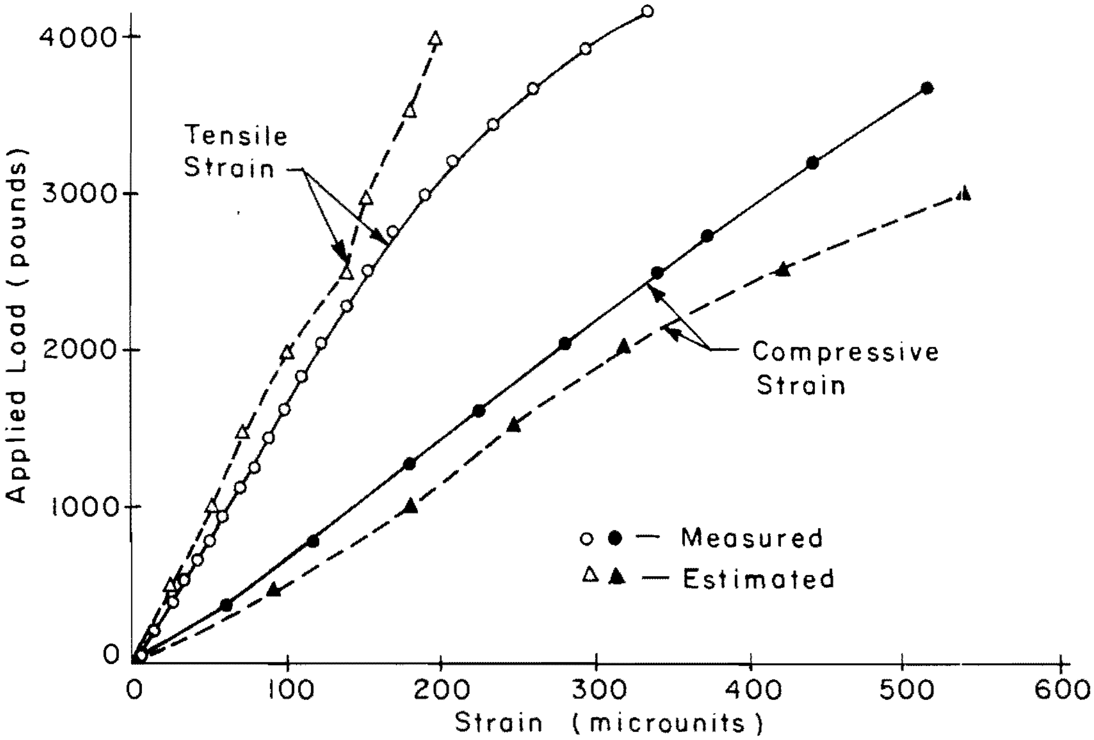


Fig A5.11. Comparison of estimated and measured strains, cement-treated specimen No. 7c.

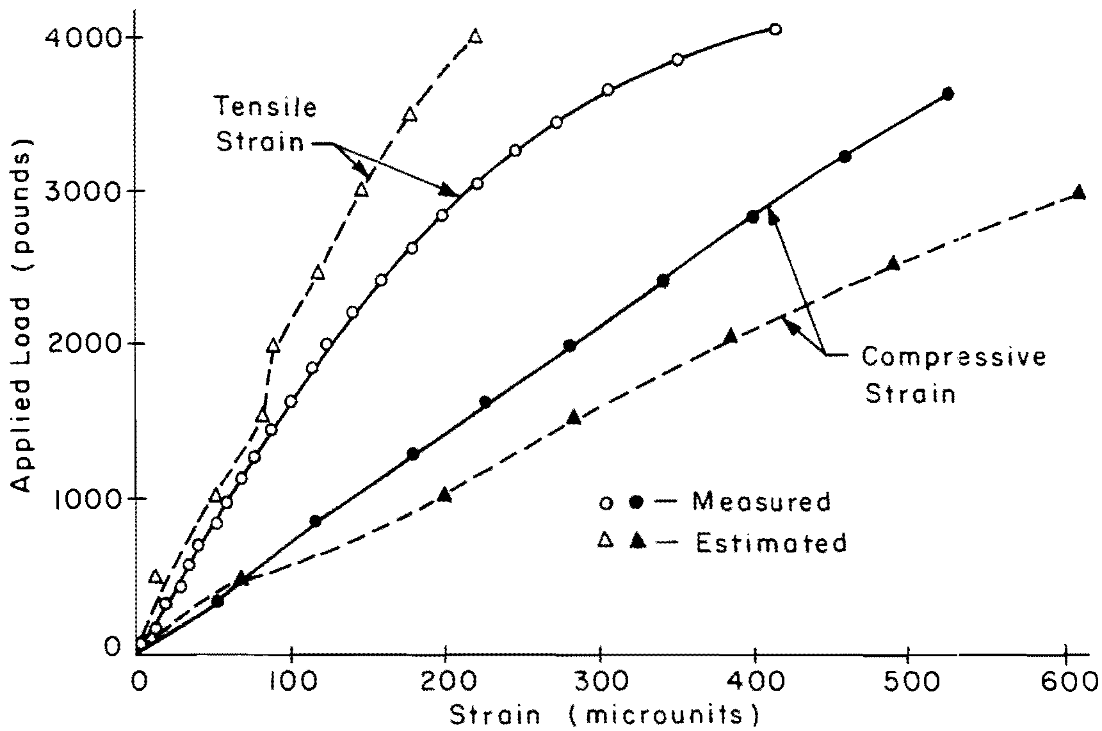


Fig A5.12. Comparison of estimated and measured strains, cement-treated specimen No. 8c.

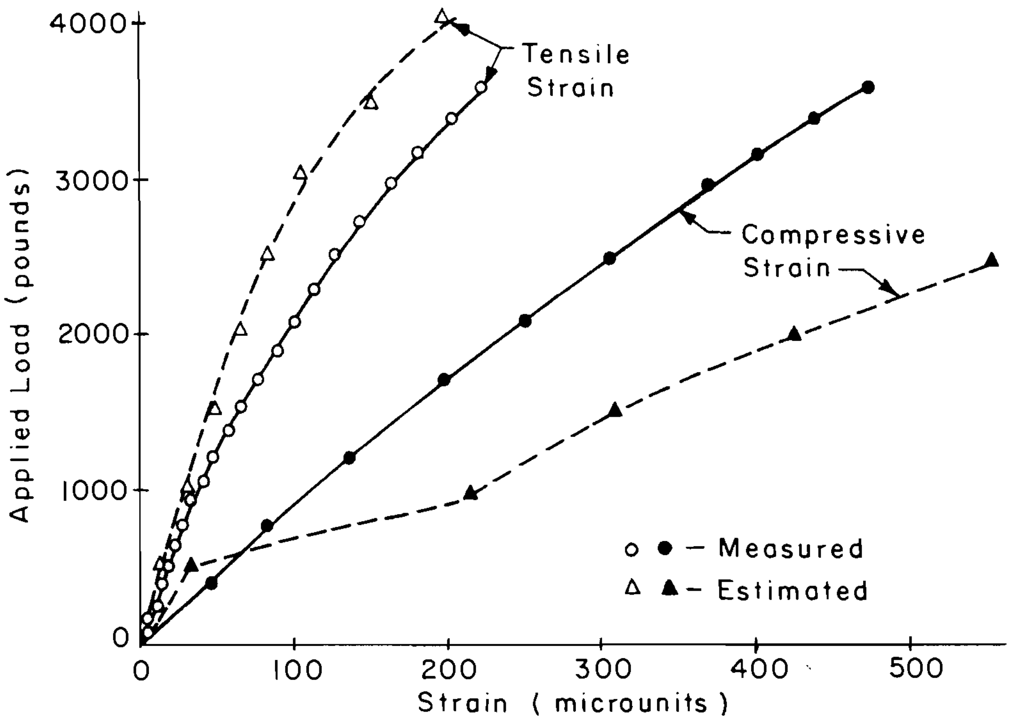


Fig A5.13. Comparison of measured and estimated strains, cement-treated specimen No. 9c.

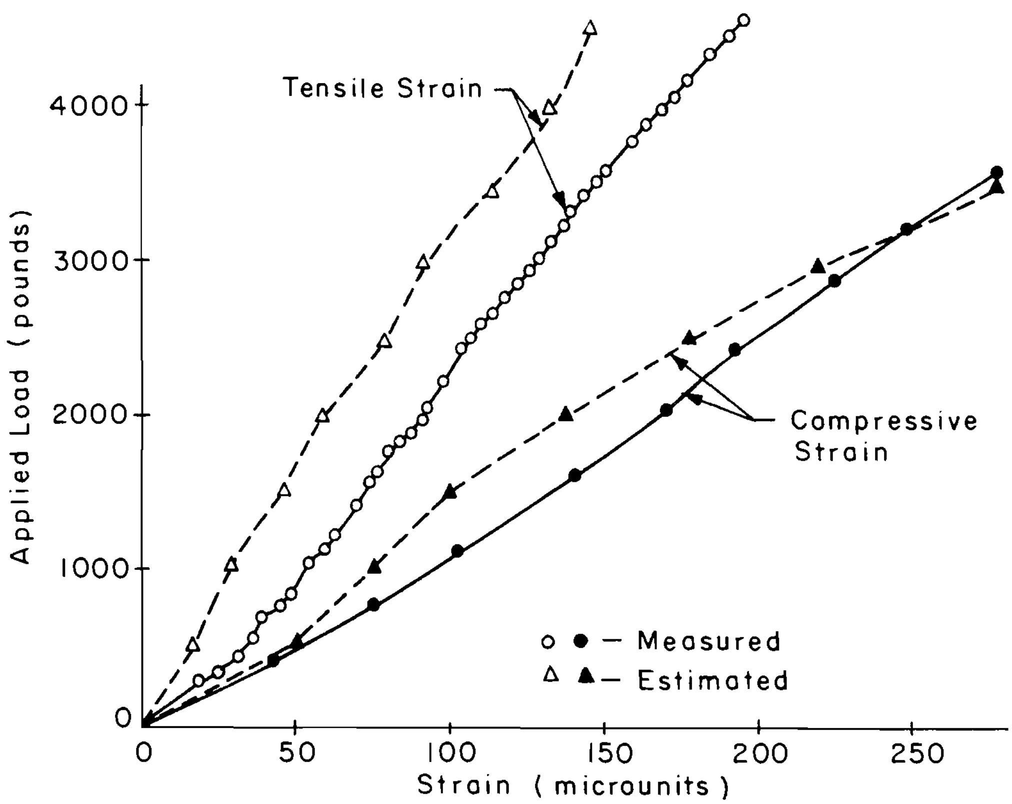


Fig A5.14. Comparison of measured and estimated strains, cement-treated specimen No. 10c.

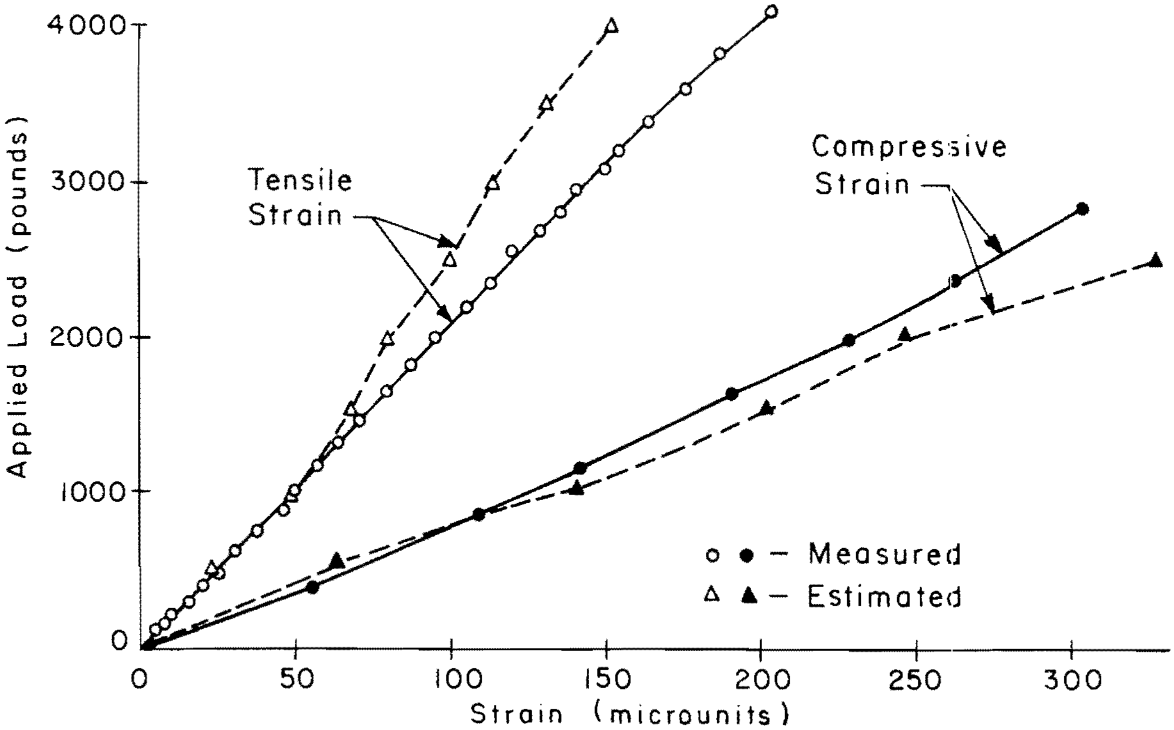


Fig A5.15. Comparison of measured and estimated strains, cement-treated specimen No. 11c.

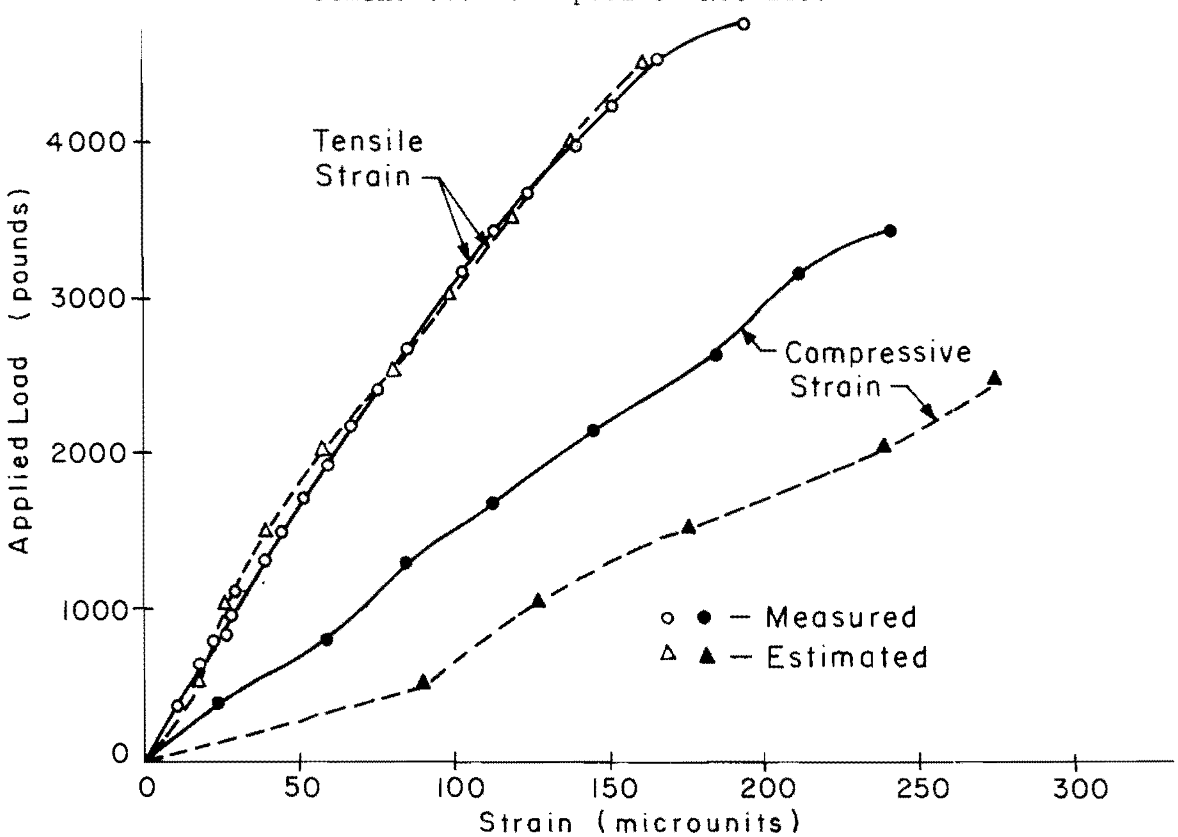


Fig A5.16. Comparison of measured and estimated strains, cement-treated specimen No. 12c.

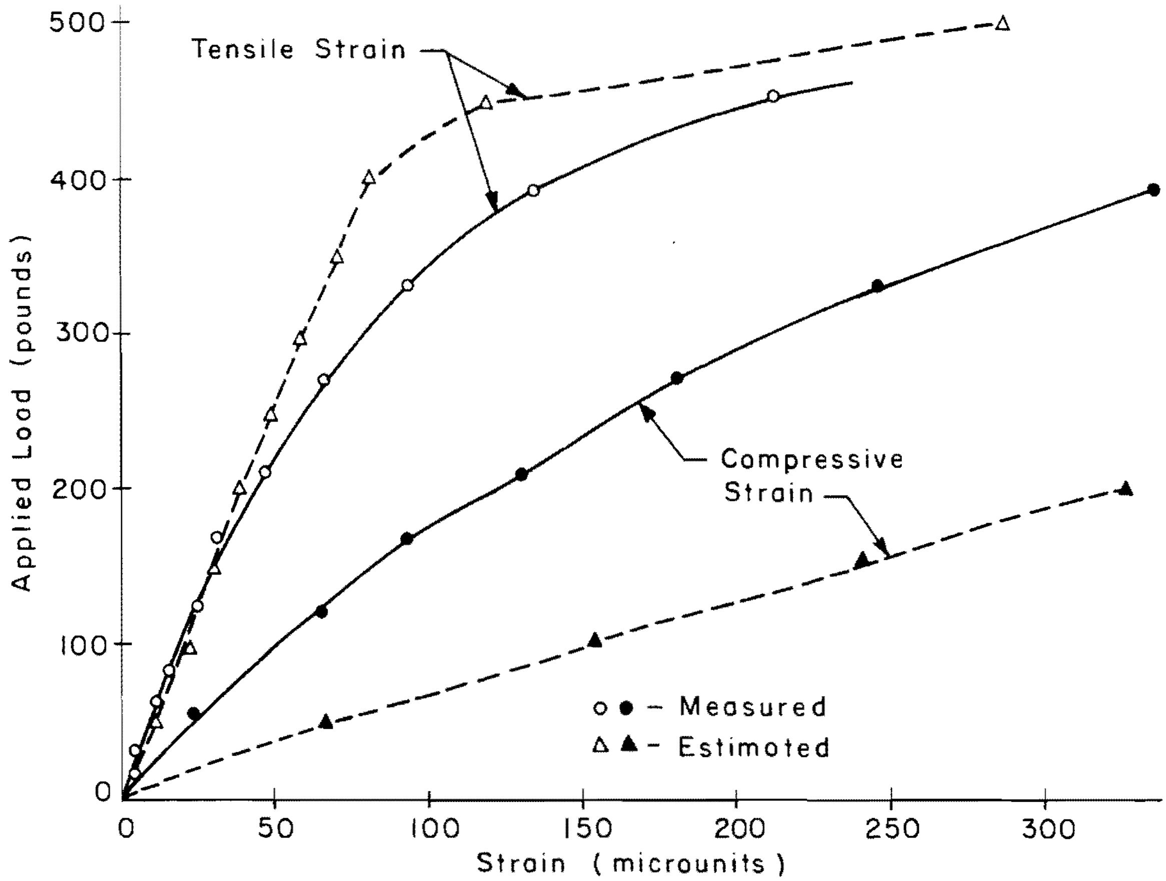


Fig A5.17. Comparison of measured and estimated strains, lime-treated specimen No. 13L.

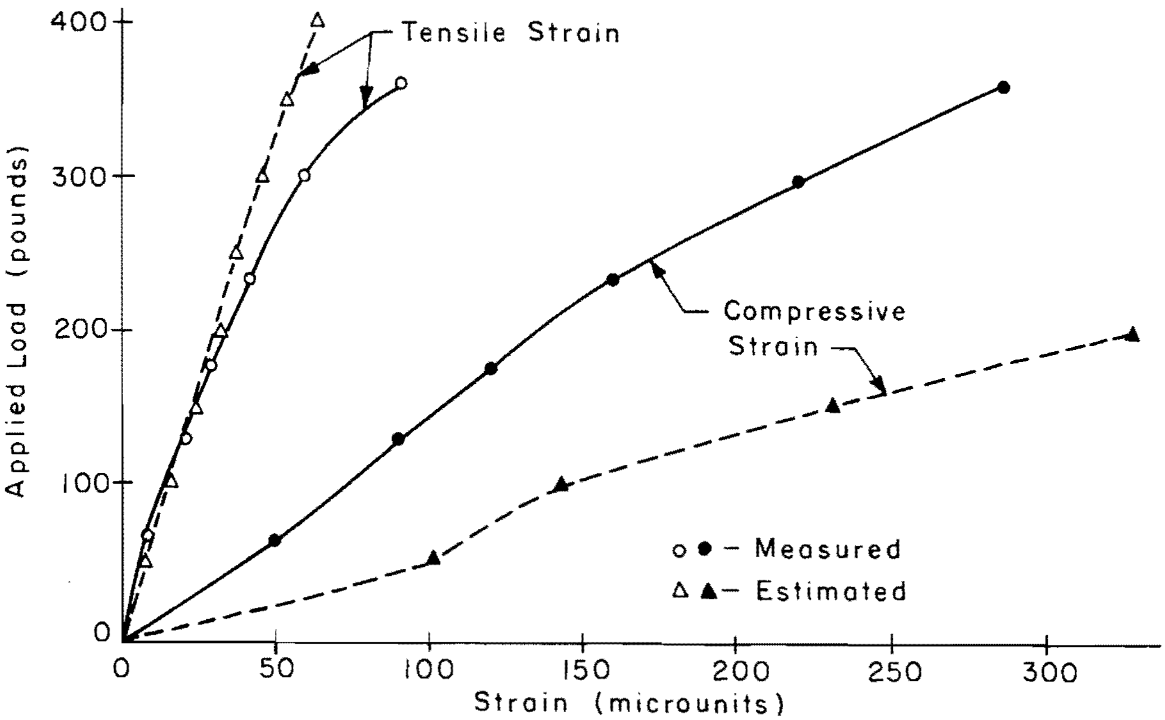


Fig A5.18. Comparison of measured and estimated strains, lime-treated specimen No. 14L.

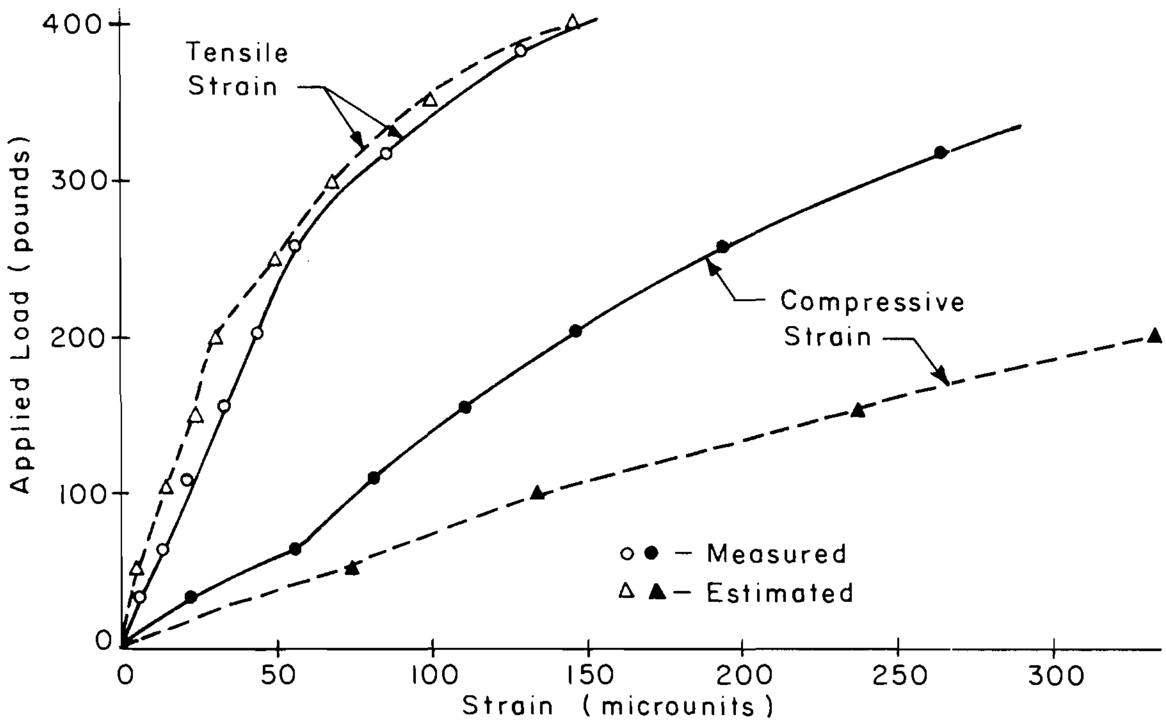


Fig A5.19. Comparison of measured and estimated strains, lime-treated specimen No. 15L.

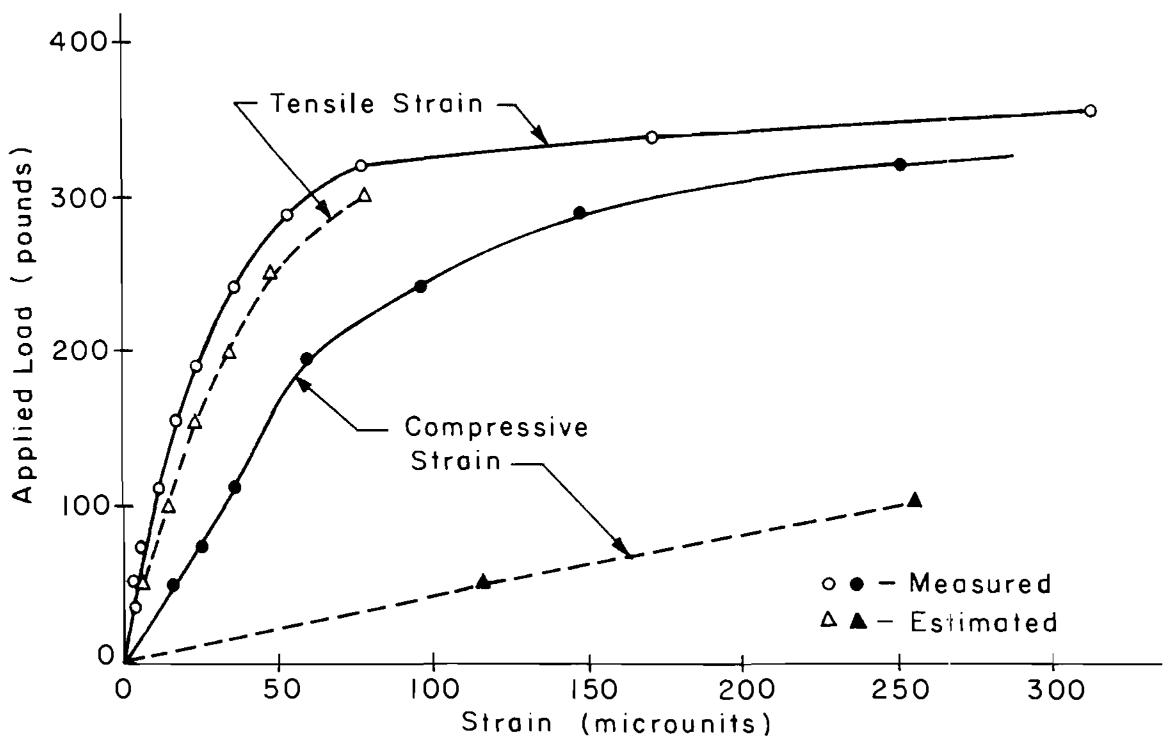


Fig A5.20. Comparison of measured and estimated strains, lime-treated specimen No. 16L.

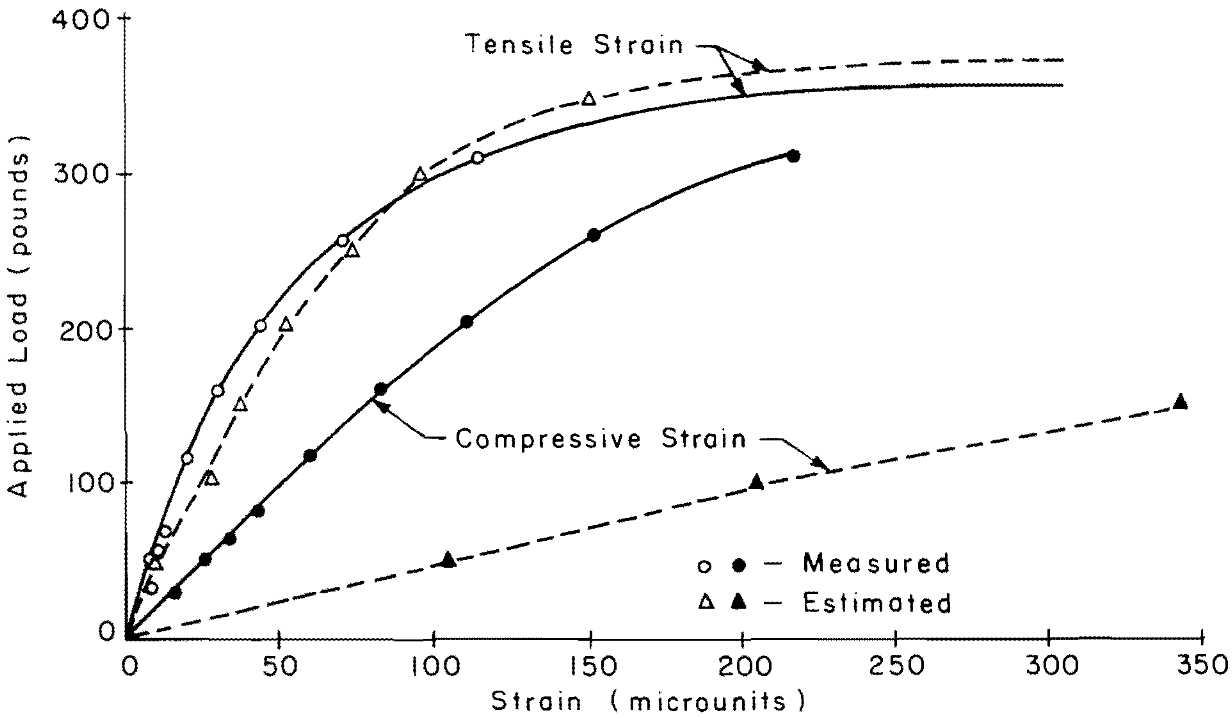


Fig A5.21. Comparison of measured and estimated strains, lime-treated specimen No. 17L.

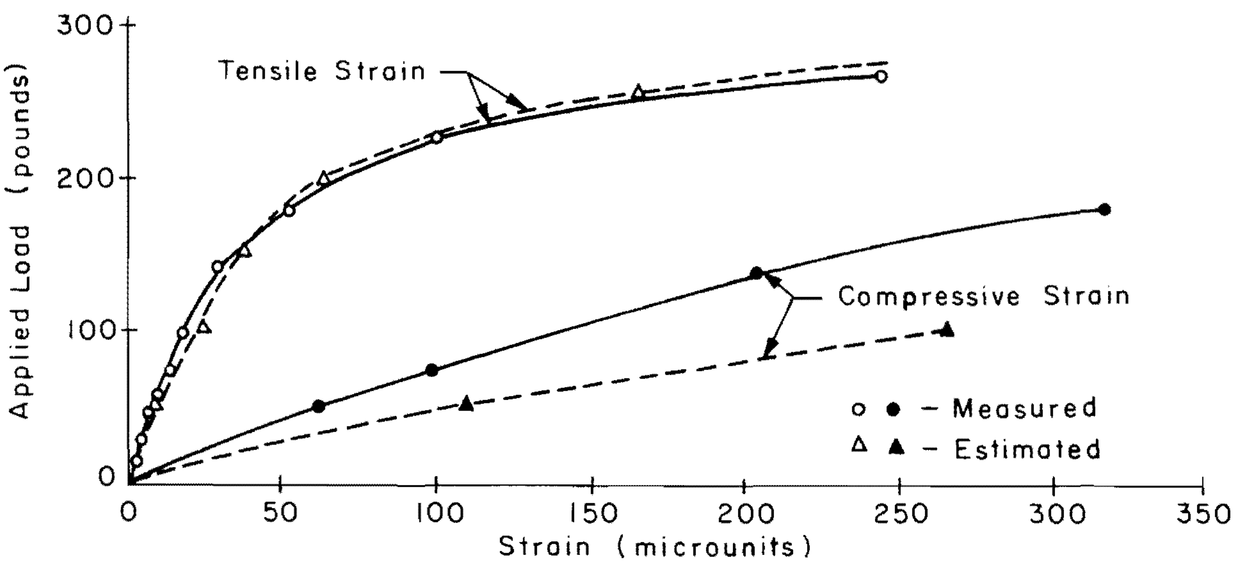


Fig A5.22. Comparison of measured and estimated strains, lime-treated specimen No. 18L.

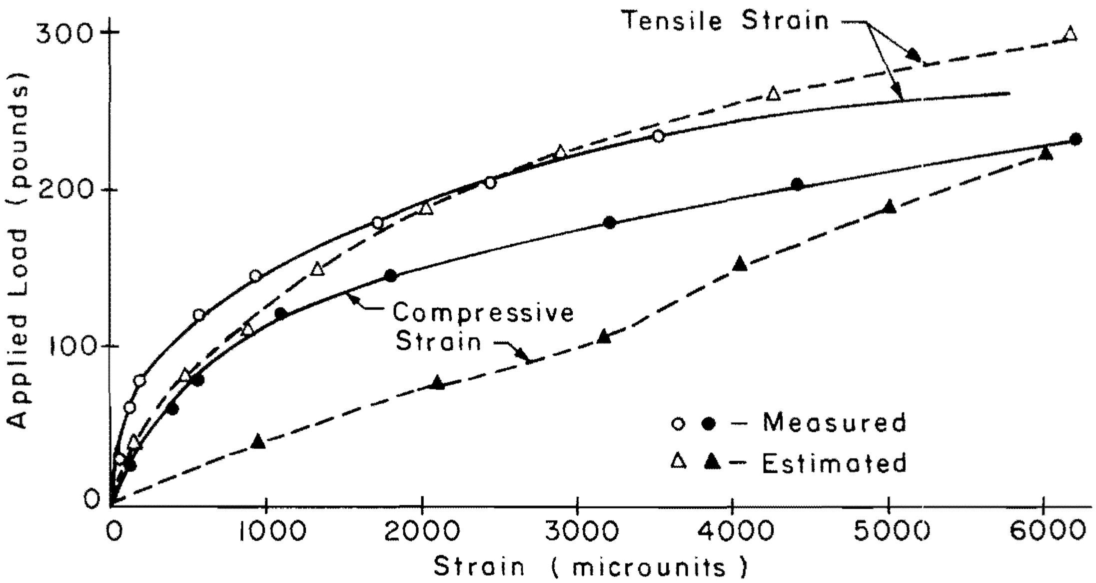


Fig A5.23. Comparison of measured and estimated strains, Taylor Marl clay specimen.

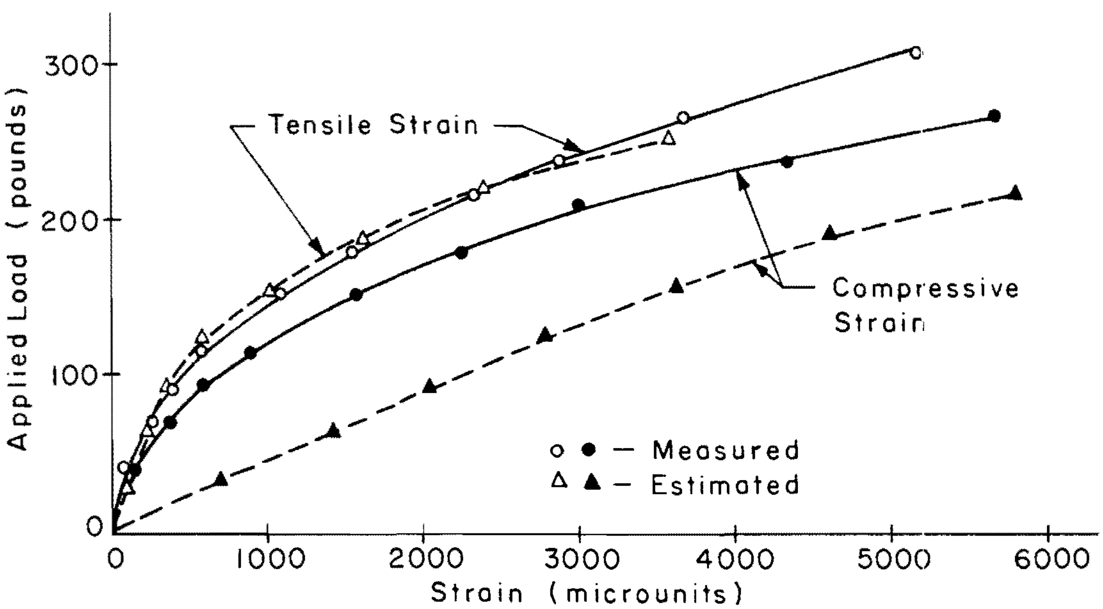


Fig A5.24. Comparison of measured and estimated strains, Taylor Marl clay specimen.

TABLE A5.1. ESTIMATES OF MATERIAL PROPERTIES FOR ALUMINUM AND PLEXIGLAS OBTAINED FROM INDIRECT TENSILE TEST

Material Type	Modulus of Elasticity From Total Deformation	Modulus of Elasticity From Center Strains	Poisson's Ratio From Total Deformation	Poisson's Ratio From Center Strains	Remarks
Aluminum (75° F)	10.432×10^6	10.419×10^6	.363	.321	4" diameter, 1" thick; average of ten tests.
Plexiglas I (55° F)	4.565×10^5	4.364×10^5	.358	.315	4" diameter, 1" thick; average of five tests.
Plexiglas II (55° F)	4.751×10^5	4.340×10^5	.352	.361	4" diameter, 2" thick; average of three tests.
Plexiglas average	4.635×10^5	4.355×10^5	.356	.332	Average of eight tests.

TABLE A5.2. ESTIMATES OF MATERIAL PROPERTIES FOR DIFFERENT HIGHWAY MATERIALS OBTAINED FROM INDIRECT TENSILE TEST

Material Type	Modulus of Elasticity From Total Deformation	Modulus of Elasticity From Center Strains	Poisson's Ratio From Total Deformation	Poisson's Ratio From Center Strains	Remarks
Asphaltic mix #1					
Specimen 1A	1.132×10^5	0.810×10^5	.440	.279	
Specimen 2A	1.264×10^5	1.088×10^5	.403	.260	Nominal 4" diameter and 2" thickness.
Specimen 3A	1.301×10^5	1.102×10^5	.425	.333	Test temperature = 55° F.
Specimen 19A	1.330×10^5	1.118×10^5	.383	.238	Loading rate = .05"/min.
Average	1.2568×10^5	1.0295×10^5	.4128	.2775	Average of four specimens.
Asphaltic mix #2					
Specimen 4A	2.136×10^5	2.146×10^5	.157	.347	Nominal 4" diameter and 2" thickness.
Specimen 5A	2.530×10^5	2.467×10^5	.353	.449	Test temperature = 55° F.
Specimen 6A	2.308×10^5	2.006×10^5	.337	.349	Loading rate = .05"/min.
Average	2.3170×10^5	2.2063×10^5	.2823	.3817	Average of three specimens.
Cement-Treated mix #1					
Specimen 7C	1.405×10^6	2.065×10^6	0	.254	
Specimen 8C	1.479×10^6	2.487×10^6	0	.425	Nominal 4" diameter and 2" thickness.
Specimen 9C	1.955×10^6	2.210×10^6	0	.182	Test temperature = 55° F.
Specimen 20C	1.498×10^6	2.069×10^6	0	.308	Loading rate = .05"/min.
Average	1.5843×10^6	2.2078×10^5	0	.2923	Average of four specimens.

(Continued)

TABLE A5.2 (Continued)

Material Type	Modulus of Elasticity From Total Deformation	Modulus of Elasticity From Center Strains	Poisson's Ratio From Total Deformation	Poisson's Ratio From Center Strains	Remarks
Cement-Treated mix #2					
Specimen 10C	3.172×10^6	2.898×10^6	.078	.250	Nominal 4" diameter and 2" thickness.
Specimen 11C	1.635×10^6	2.393×10^6	0	.189	Test Temperature = 55° F.
Specimen 12C	2.573×10^6	4.207×10^6	0	.263	Loading rate = .05"/min.
Average	2.460×10^6	3.1660×10^6	.0260	.234	Average of three specimens.
Lime-Treated mix #1					
Specimen 13L	4.069×10^5	6.320×10^5	.025	.393	
Specimen 14L	8.593×10^5	4.269×10^5	.248	0.0	Nominal 4" diameter and 2" thickness.
Specimen 15L	9.911×10^5	7.149×10^5	.356	.408	Test temperature = 55° F.
Specimen 21L	9.590×10^5	9.248×10^5	.328	.500	Loading rate = .05"/min.
Average	8.0408×10^5	6.7465×10^5	.2393	.3253	Average of four specimens.
Lime-Treated mix #2					
Specimen 16L	8.578×10^5	10.370×10^5	.500	.435	Nominal 4" diameter and 2" thickness.
Specimen 17L	6.986×10^5	6.470×10^5	.470	.243	Test temperature = 55° F.
Specimen 18L	7.737×10^5	4.957×10^5	.500	.334	Loading rate = .05"/min.
Average	7.7670×10^5	7.2657×10^5	.4900	.3373	Average of three specimens.
Taylor Marl clay					Nominal 4" diameter and
Specimen 1	2.387×10^4	3.054×10^4	.500	.381	2" thickness.
Specimen 2	2.318×10^4	2.307×10^4	.268	.367	Test temperature = 55° F. Loading rate = .05"/min.
Average	2.3525×10^4	2.6805×10^4	.384	.374	Average of two specimens.

TABLE A5.3. PERCENT DIFFERENCES IN MATERIAL PROPERTIES OBTAINED FROM TOTAL DEFORMATION AND CENTER STRAIN DATA

Material Type	Modulus of Elasticity	Poisson's Ratio	Tensile Strain Differences at 25% of P_{MAX}*	50%	75%	100%	Compressive Strain Differences at 25% of P_{MAX}*	50%	75%	100%
Aluminum										
Mean	0.1	13.1	Maximum difference = 6.0				Maximum difference = 16.0			
Deviation	-	-								
Plexiglas										
Mean	6.0	10.2	Average difference for 1" thickness = 11.4 ± 1.0 2" thickness = 21.8 ± 1.4				Average difference for 1" thickness = 15.8 ± 1.1 2" thickness = 21.0 ± 2.6			
Standard deviation	±3.9	±7.0								
Asphalt-Treated material										
Mean	15.9	40.1	13.1	10.6	11.9	24.8	99.6	37.7	17.3	6.9
Standard deviation	±12.0	±21.3	±12.4	±12.4	±10.3	±10.9	±31.3	±16.5	±14.2	±2.9
Cement-Treated material										
Mean	27.4	95.5	19.4	21.6	25.6	35.4	51.9	36.3	45.6	29.8
Standard deviation	±11.4	±10.9	±13.9	±11.5	±12.1	±8.0	±32.0	±21.7	±28.2	±17.7

(Continued)

* P_{MAX} is maximum load applied to the specimen.

TABLE A5.3 (Continued)

Material Type	Modulus of Elasticity	Poisson's Ratio	Tensile Strain Differences at of P_{MAX}*				Compressive Strain Differences at of P_{MAX}*			
			25%	50%	75%	100%	25%	50%	75%	100%
Lime-Treated material										
Mean	37.2	57.0	30.7	18.7	23.6	31.8	211.3	239.3	109.4	43.8
Standard deviation	±31.3	±35.5	±29.2	±10.7	±14.2	±13.2	±231	±205	±58	±54
Taylor Marl clay										
Mean	10.7	29.1	84	15.5	8.5	70.9	155	35.5	13.3	58.9

* P_{MAX} is maximum load applied to the specimen.

NOTE: percent difference $= \frac{V_{TD} - V_{CS}}{V_{CS}} \times 100$ where V_{TD} is material property estimated from total deformation and V_{CS} is material property estimated from center strain data.

In addition, the thickness of the plexiglas specimen had only a small effect on the estimated material properties as indicated in Table A5.4. All material properties agreed within 8 percent, with the exception of Poisson's ratio estimates from measured center strain data. Although a 14.6 percent difference in Poisson's ratio between a 1 and 2-inch-thick plexiglas specimen was found from center strain data, this difference represents a change in Poisson's ratio of only 0.045.

Good agreement between the estimated properties for the two different asphalt-treated mixtures was found, as indicated by the results in Tables A5.2 and A5.3. On the average the modulus of elasticity values differed by 15.9 percent while the Poisson's ratio values differed by 40.1 percent. It should also be noted that mix No. 1, which consisted of a sheet asphalt surface course material with 8 percent asphalt content, had a lower modulus of elasticity and a higher Poisson's ratio that mix No. 2, which consisted of a fine graded surface course material with 6.5 percent asphalt content. The differences between estimated and measured strains were calculated at four different points along the curve. The differences in tensile strains were fairly uniform over the range of the load strain curve and were approximately 12 to 13 percent. For compressive strains the differences were greater at the 1/4 point (difference of 100 percent) and decreased up to the maximum load (difference of 6.9 percent). From Figs A5.5 through A5.10 and Table A5.3 it is evident that there was better agreement between the tensile strains than the compressive strains in the initial portion of the load-strain curve. On the basis of these data the technique developed recently by Hadley et al (Ref 3.1) can be used to adequately evaluate the properties of asphalt-treated materials.

The estimated properties for the two cement-treated mixtures are included in Table A5.2 while differences in the properties estimated from the two different techniques are presented in Table A5.3. The modulus of elasticity values obtained from total deformation data were 27.4 percent less than the values obtained from center strain data. As indicated in Table A5.2 there was essentially no Poisson's ratio effect found from the analysis of total deformation data. Consequently the values were assumed to be zero, with the exception of specimen 10C, for which a value of 0.078 was obtained. This phenomenon, i.e., Poisson's ratio = 0.0, was not substantiated from the analysis of center

TABLE A5.4. CHANGES IN MATERIAL PROPERTIES DUE TO SPECIMEN THICKNESS BASED ON 1-INCH SPECIMEN PLEXIGLAS DISCS

Estimating Technique	Percent Differences* Modulus of Elasticity	Poisson's Ratio	Tensile Strain	Compressive Strain
Total deformation data	+4.1	-0.3	-4.7	-3.3
Center strain data	-0.5	+14.6	+7.8	+2.2

* Percent Difference $= \frac{V_2 - V_1}{V_1} \times 100$ where V_1 is the estimated material property for 1-inch-thick disc and V_2 is the estimated property for 2-inch-thick disc.

strain data; therefore, there was an effect due to Poisson's ratio at least in the interior of the circular specimen. This phenomenon was considered to be due to excessive vertical deformation of the specimen near the loading strip.

Since Poisson's ratio forms an important part of the equation used in the estimation of modulus of elasticity from total deformation data, a value of 0.0 directly produces a lower modulus value. A value of Poisson's ratio greater than 0.0 would produce an increased modulus of elasticity value from total deformation data which would approach the modulus obtained from center strain data. From Figs A5.11 through A5.16 it is evident that the tensile strains are generally in close agreement (20 to 25 percent difference). The compressive strains on the other hand agree within 30 to 50 percent throughout the load strain curve. One of the major findings with cement-treated materials was that Poisson's ratio values could not be evaluated from total deformation data with the present testing procedures. Future refinement of the test equipment may alleviate this problem; however, for its present use assumptions concerning Poisson's ratio values must be made in order to provide better estimates of modulus of elasticity.

The results of indirect tensile tests on two different lime-treated mixtures are also included in Tables A5.2 and A5.3. The load-strain data for all the specimens tested are presented in Figs A5.17 through A5.22. The estimates of modulus of elasticity and Poisson's ratio from total deformation and center strain data differed by 37.2 percent and 57.0 percent, respectively. In addition, the measured and estimated tensile strains generally agreed within 19 to 32 percent over the range of the load-strain curve. Based on these data the indirect tensile test can also be used to adequately evaluate modulus of elasticity and tensile strains of lime-treated materials.

A Taylor Marl clay was also tested in indirect tensile test to evaluate the applicability of the test for estimating the material properties of other cohesive highway materials. The specimens were tested in a semi-dry condition; therefore, the modulus of elasticity values presented in Table A5.2 are higher than expected. In addition, Poisson's ratio values other than 0.5 were obtained for the dry condition. From the results in Table A5.3 it can be seen that the material properties for the two specimens included here were in very good agreement. The values of modulus of elasticity differed by approximately 11.0 percent while the Poisson's ratio values differed by about 29 percent.

The test curves presented in Figs A5.23 and A5.24 also indicate good agreement between estimated and measured tensile strains (approximately 10 to 15 percent in the middle portion of the curve).

SUMMARY

The theoretical equations developed recently (Ref 3.1) for estimating material properties from total deformation data were verified from the results of tests on thin aluminum and plexiglas discs. The modulus of elasticity, Poisson's ratio, and tensile strains were in excellent agreement with those values obtained from center strain data using Hondros' equations (Ref 4.1). Based upon the test data presented here, the technique using total deformation data can be used to adequately estimate the tensile properties of asphalt-treated, lime-treated, and cement-treated materials. One of the major findings with the cement-treated materials, however, was that Poisson's ratio values could not be adequately evaluated from total deformation data. Future refinement of the test equipment may alleviate this problem; however, for present use, assumptions concerning Poisson's ratio values must be made in order to provide better estimates of modulus of elasticity. In addition, from this study, there is limited evidence that the technique can also be used to estimate the properties of clay materials.

APPENDIX 6

EFFECTS OF TEMPERATURE AND LOADING RATE ON THE PROPERTIES OF ASPHALTIC MATERIALS

APPENDIX 6. EFFECTS OF TEMPERATURE AND LOADING RATE ON THE PROPERTIES OF ASPHALTIC MATERIALS

INTRODUCTION

The use of asphalt-stabilized pavement layers creates a special problem for the design of a pavement section because material properties such as modulus of elasticity, Poisson's ratio, tensile strength, and tensile strain at failure are a function of both the rate of application of load and the temperature of the stabilized layer. Therefore, an important part of this design approach is a requirement for a technique with which to evaluate the effects of temperature and rate of loading for asphalt stabilized mixtures. This appendix is concerned with the development of a set of equations and curves depicting the relationship between material properties and temperature and rate of loading for use with asphalt-stabilized mixtures.

Available Test Results

A detailed evaluation of the effects of temperature and loading rate on the tensile strength of a crushed limestone-asphalt mixture tested in indirect tension was conducted by Hudson and Kennedy (Ref 4.3). The results of the study are shown in Fig A6.1 and indicate the relative effects of temperature and loading rate. This study also provided a means of evaluating the functional relationship between material properties and the two variables for a crushed limestone aggregate-asphalt mixture. The major factors involved in the study are presented in Table A6.1.

A better representation of the effects of temperature and loading rate are presented in Fig A6.2 by rearranging the data, with log tensile strength on the ordinate scale and log loading rate on the abscissa scale. From these plots it can be seen that the temperature at time of test exhibits a greater influence on tensile strength than the rate of loading.

The development of a technique for estimating modulus of elasticity, Poisson's ratio, and tensile test (Ref 2.25) provided the means for further analysis of the data collected by Hudson and Kennedy (Ref 4.3). Additional analyses were conducted in order to provide information concerning the effects of loading rate and temperature on modulus of elasticity, tensile strain at

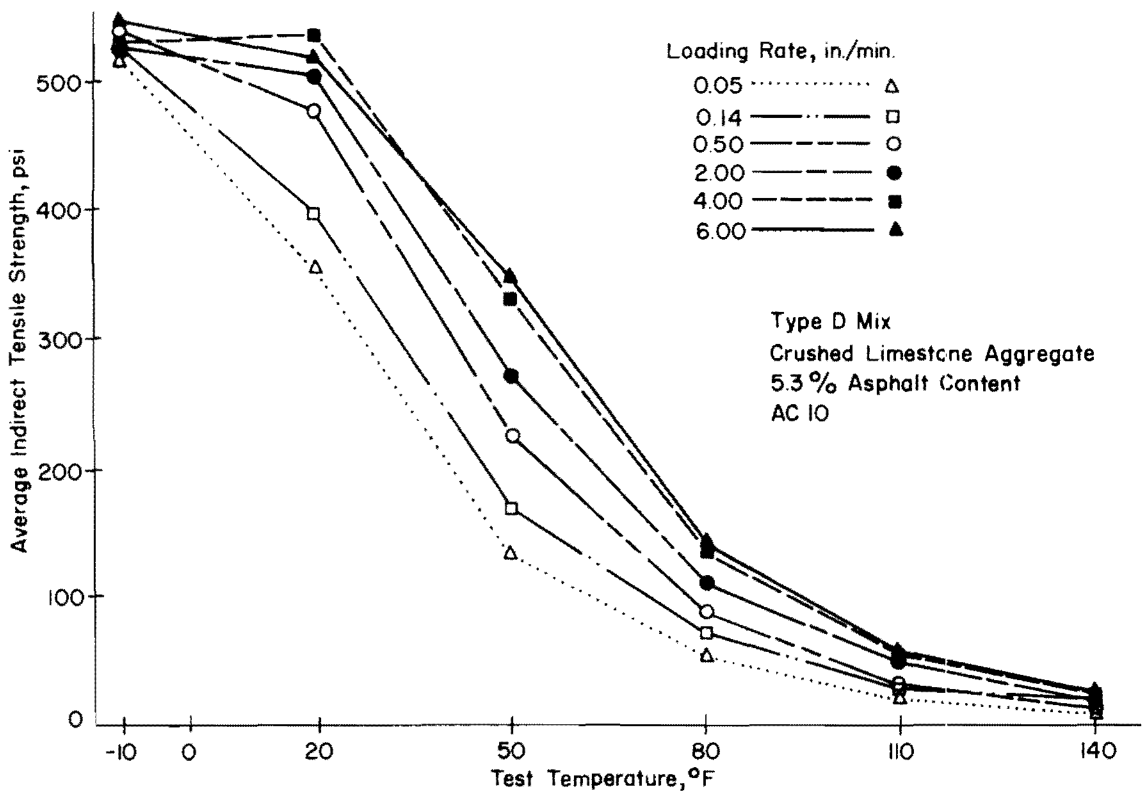


Fig A6.1. Indirect tensile strength versus test temperature and loading rate (Ref 4.3).

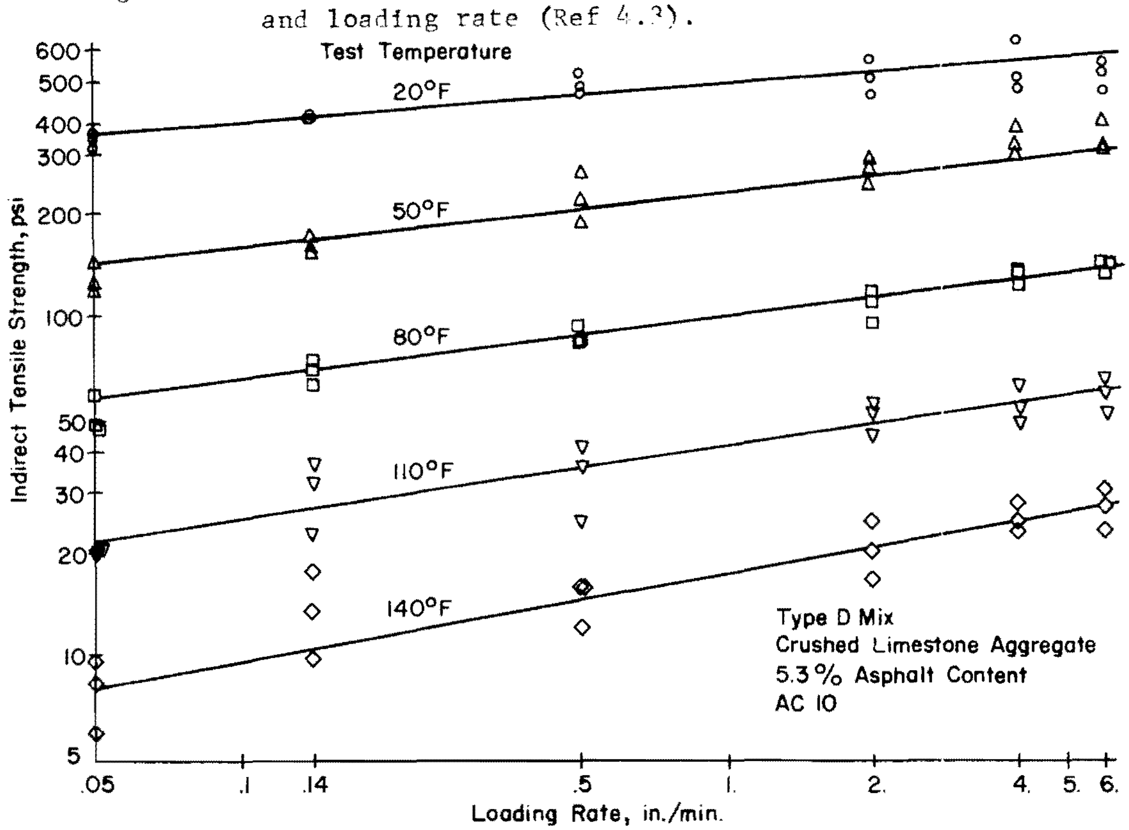


Fig A6.2. Log tensile strength versus temperature and loading rate (after Ref 4.3).

TABLE A6.1. FACTORS INVOLVED IN HUDSON AND KENNEDY STUDY (Ref 4.3)

Aggregate Type: Crushed Limestone

Gradation: THD Type D

Asphalt Cement Type: Cosden AC-10

Asphalt Content: 5.3%

Loading Rates: .05, .14, .5, 2.0, 4.0, and 6.0 inches/minute

Test Temperatures: -10, 20, 50, 80, 110, and 140° F failure, and Poisson's ratio of an asphalt-stabilized material. These properties were estimated as discussed in Ref 2.25. The tensile strain at failure is a measure of the elastic strain created in a material at failure and is directly proportional to tensile strength and Poisson's ratio and inversely proportional to modulus of elasticity. The results of the additional analysis are presented in Fig A6.3 for modulus of elasticity, in Fig A6.4 for tensile strain at failure, and in Fig A6.5 for Poisson's ratio.

It is interesting to note that both tensile strength and modulus of elasticity values were increased by increasing the loading rate and decreasing temperature at time of test while tensile strain (at failure) values decreased with similar changes in loading rate and temperature. Therefore at decreased temperatures and/or higher loading rates the asphalt-treated mixtures reacted in a more brittle fashion exhibiting higher modulus and strength values but lower failure strains. In general, higher temperatures and lower loading rates produced higher Poisson's ratio values. For all of these properties there is an apparent linear relationship with the logarithm of loading rate.

Development of Equations

To insure minimized testing requirements in future design problems it was desired that estimated changes in tensile strength, tensile strain, and modulus of elasticity caused by changes in temperature and rate of loading be a function of some standard test result. As a consequence the equations were developed by normalizing about values representative of the standard test conditions recommended for indirect tensile test (Ref 4.3), i.e., 75° F and a loading rate of 2.0 inches/minute.

The normalizing technique was used with the results presented in Figs A6.2 through A6.5 to establish by regression analysis techniques those trends which affect index numbers* for tensile strength, tensile strain, and modulus of elasticity. Regression analysis techniques were also used for an evaluation of factors affecting Poisson's ratio of the asphalt-treated mixtures. Actual values of Poisson's ratio were used in this analysis because the effects of temperature and loading rate on this particular material property were of more

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* The normalized values are not estimated values of material properties but index numbers which can be used to obtain these estimates by multiplying the numbers times the material properties obtained from the indirect tensile test at standard test conditions.

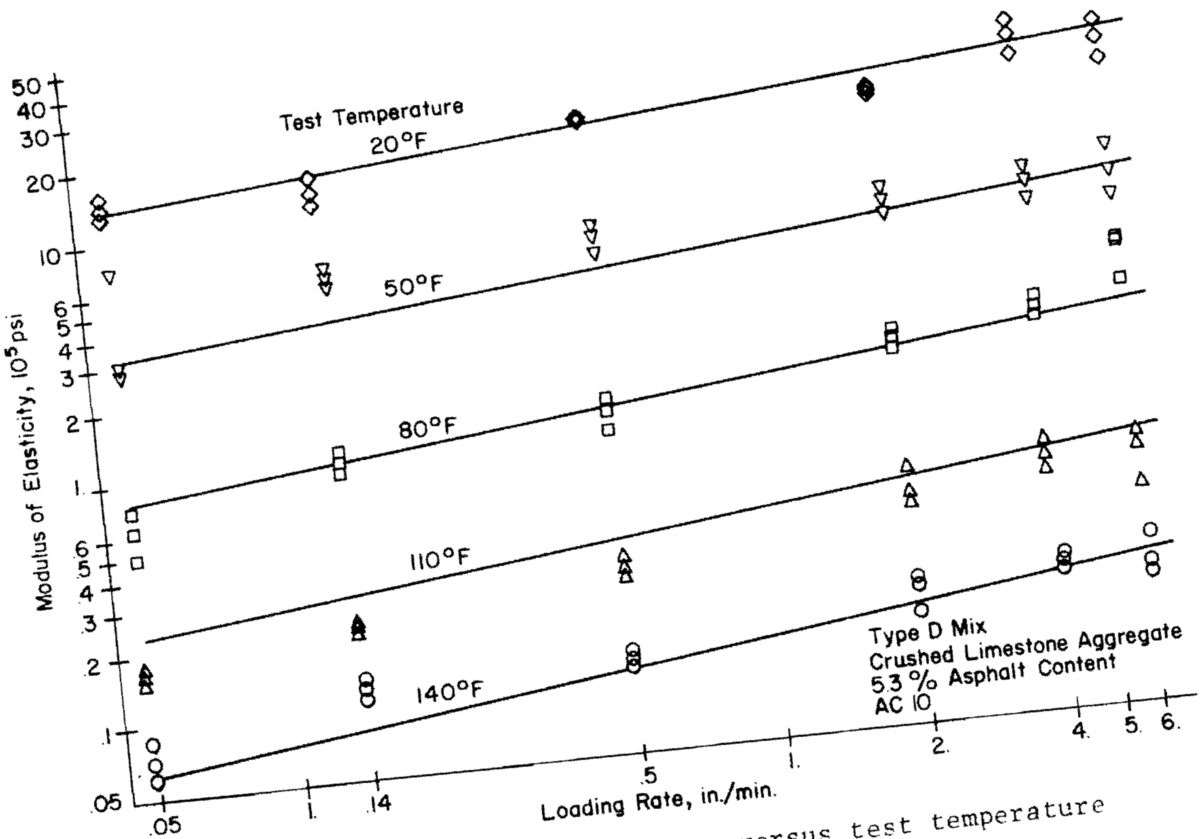

Fig A6.3. Modulus of elasticity versus test temperature and loading rate (after Ref 4.3).

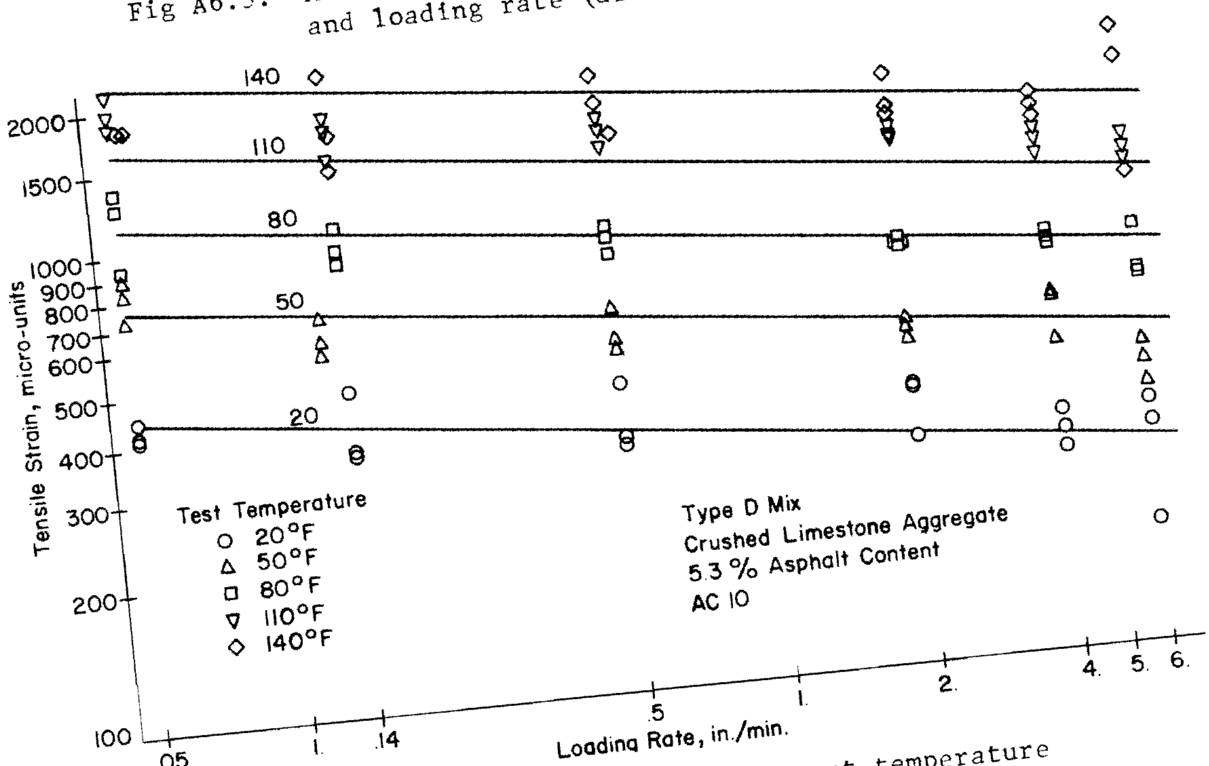

Fig A6.4. Tensile strain versus test temperature and loading rate (after Ref 4.3).

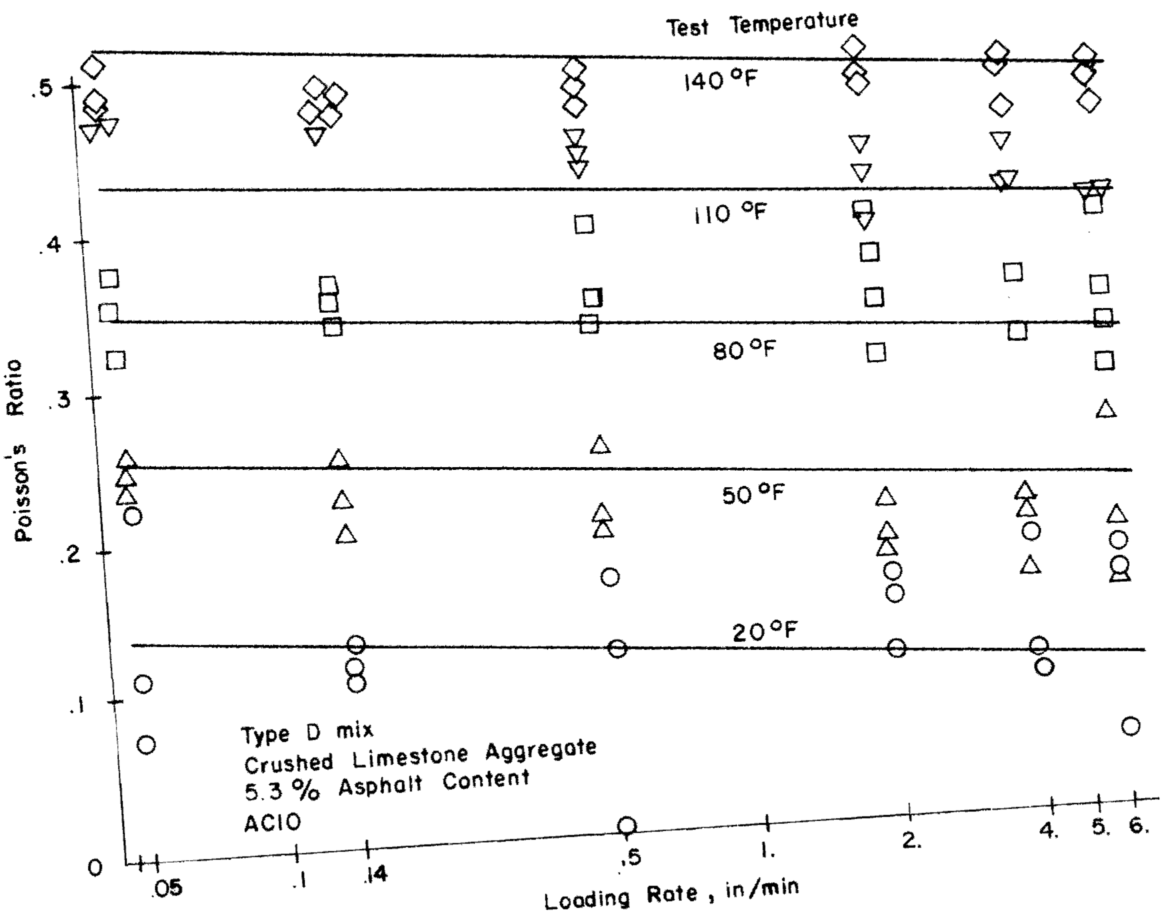

Fig A6.5. Poisson's ratio versus test temperature and loading rate (after Ref 4.3).

value. The regression equations obtained are presented in Table A6.2, along with pertinent data concerning their use. Although there were test results available for test temperatures of -10° F, the values were not included in this analysis because it is doubtful that in Texas the pavement layers beneath the surface layer are ever subjected to such low temperatures.

Curves based upon these equations are presented in Figs A6.6 through A6.8 and indicate the effect of temperature and loading rate on index numbers for tensile strength, tensile strain, and modulus of elasticity. Poisson's ratio estimates are included in Fig A6.9 for a variety of temperatures and loading rates.

These figures can be used to estimate changes in the tensile properties of asphalt-treated mixtures similar to those evaluated by Hudson and Kennedy over the range of temperatures and loading rates indicated in the figures. For example, for high rate of loading, the tensile strength index number varies from .25 of the standard test value for a representative hot summer day (140° F) to 4.0 of the standard value for a cold winter day (30° F). For the same conditions the tensile strain index number varies from 1.6 to .45 of the standard test results while the modulus of elasticity index number varies from 0.10 to 9.0.

Since the functional relationships presented in Table A6.2 and shown in Figs A6.6 through A6.9 were developed for only one asphalt-treated mixture, the reliability of the results cannot be accepted for general use with a wide range of treated materials without further analysis. Changes in asphalt content, gradation, or asphalt cement type may affect the relationship between the tensile properties and the effects of temperature and loading rate; therefore, the results presented here must be augmented by future studies of a variety of asphalt-treated materials in order to develop the equations and curves required for general application. At present the relationships presented in Figs A6.6 through A6.9 provide the best information available concerning the effects of temperature and loading rate on tensile properties and can be used in conjunction with this design system to provide estimates of tensile properties for a variety of loading rates and temperatures.

Application of Loading Rate-Temperature Results to Design of Asphaltic Materials

Careful consideration must be given to the conditions under which the properties of the asphaltic materials are selected for use in the design equations

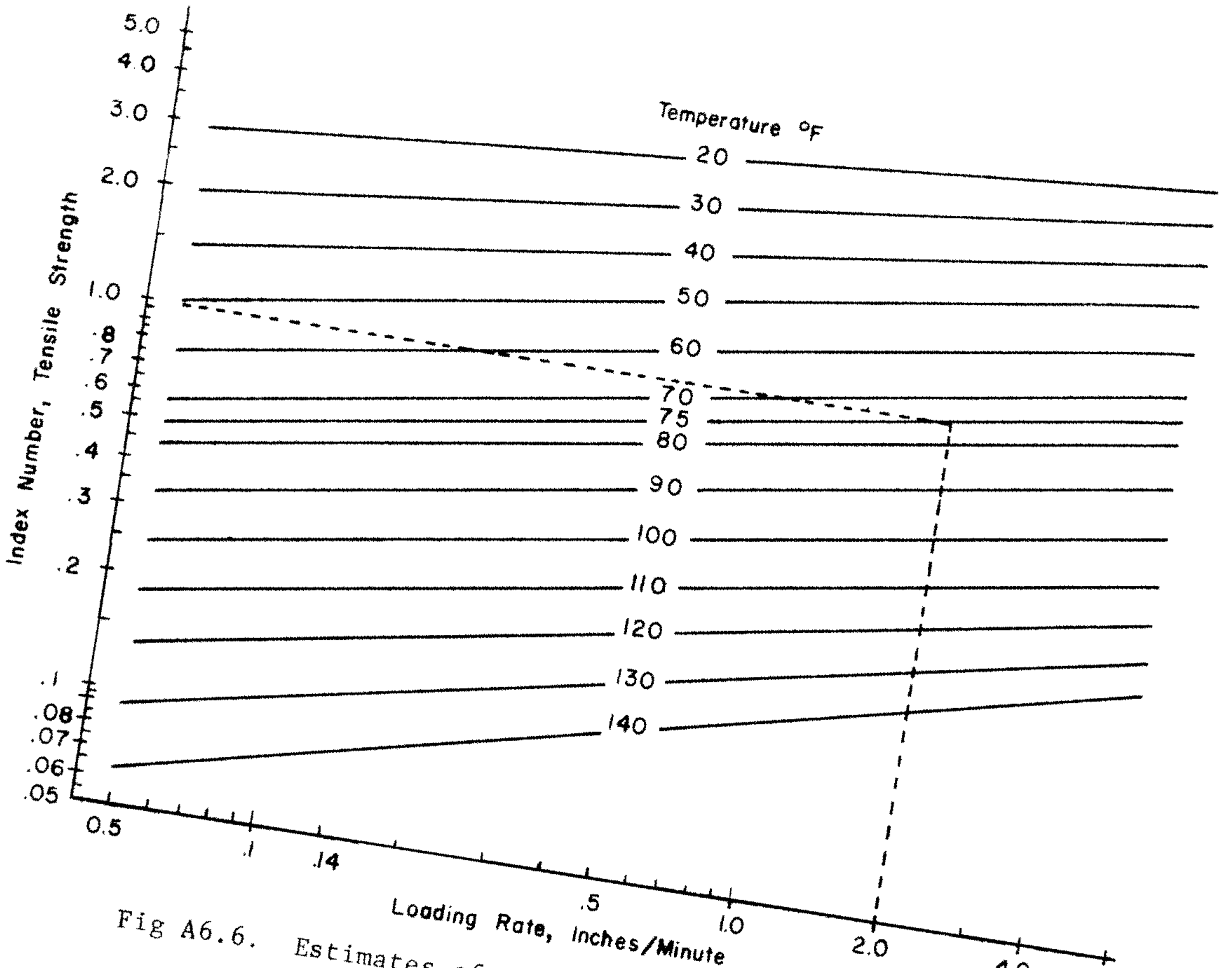

Fig A6.6. Estimates of tensile strength index numbers.

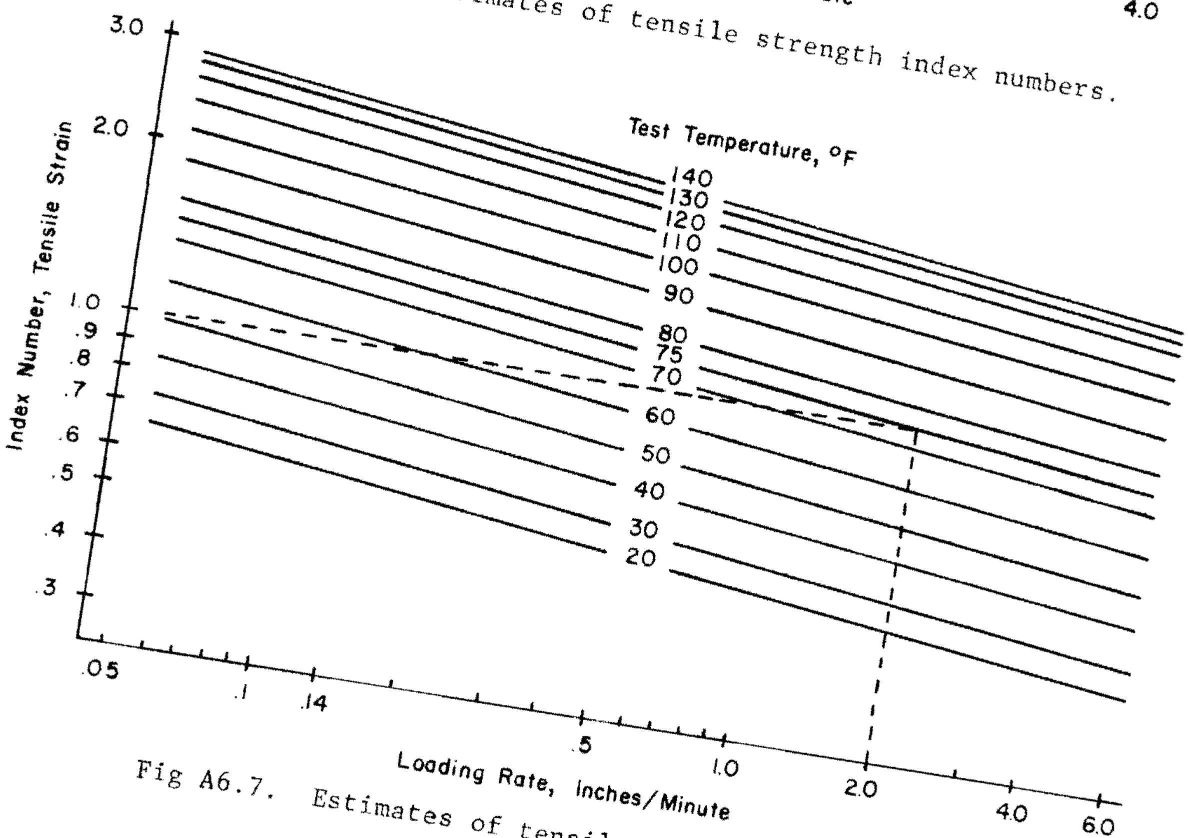

Fig A6.7. Estimates of tensile strain index numbers.

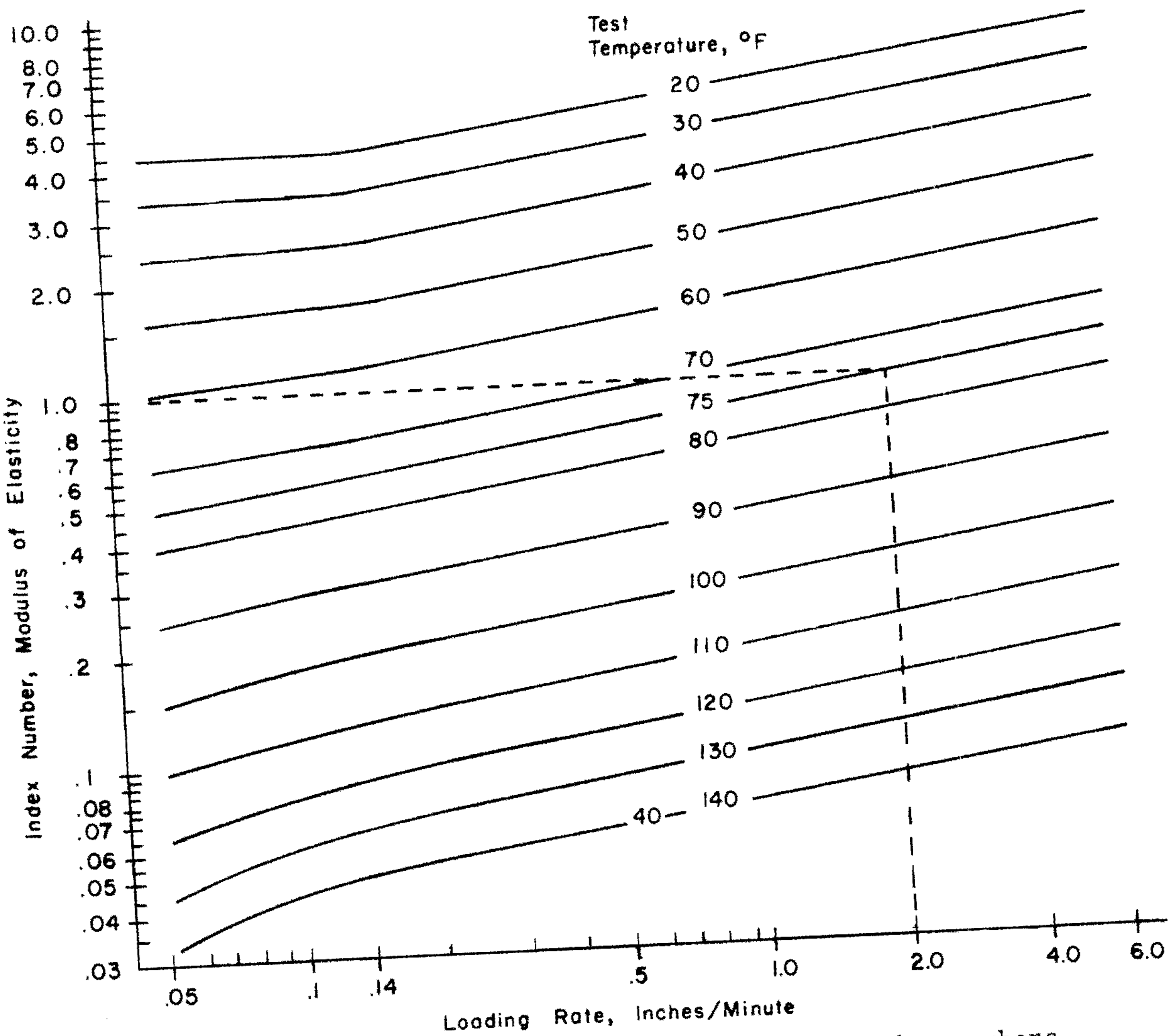

Fig A6.8. Estimates of modulus of elasticity index numbers.

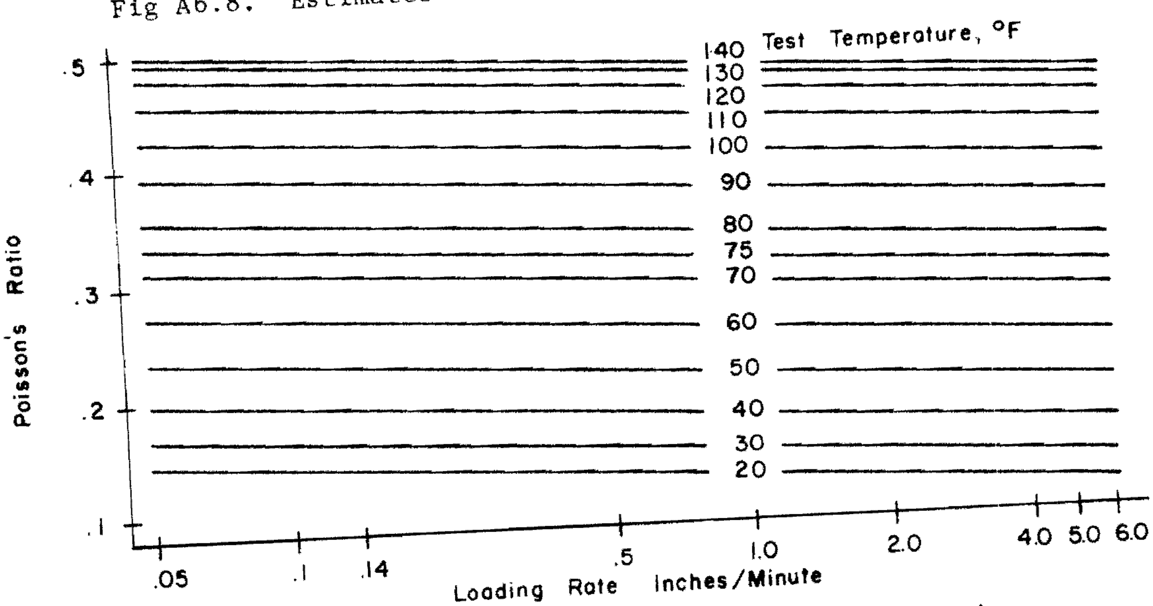

Fig A6.9. Estimates of Poisson's ratio for various temperatures and loading rates.

presented in Chapter 3. The temperature and rate of loading (or time of loading) used to estimate the changes in material properties should be representative of the expected field conditions. The equations presented in this appendix can be used to obtain estimates of material properties provided appropriate temperature and loading rate values are available. With the aid of a computer the loading rate-temperature equations could be used in conjunction with the design equations to determine the critical design thickness of asphaltic layers for the range of temperatures expected to occur in the pavement layer over any selected time period.

Under actual conditions the temperature of the asphaltic material at a given locale varies not only on an hourly, daily, monthly, and seasonal basis, but also with the location of the asphaltic layer in the pavement structure. Similarly, the rate of loading (or time of loading) experienced by the asphaltic layer depends upon a number of factors, including speed and weight of the vehicle as well as the rigidity of the pavement structure. Additionally, the rate of loading (or time of loading) depends upon the location of the asphaltic layer in the pavement structure since the wheels of a moving vehicle deflect the lower layers less than the surface layer.

Estimates of temperature distribution in flexible type pavements can be obtained from theory (Refs 2.10, 4.30, and 4.31) and actual test results (Refs 4.31 through 4.35); however, similar estimates for composite pavements, i.e., portland cement concrete surface with asphaltic base, cannot at present be obtained, primarily due to lack of actual field data for this type structure. Dempsey and Thompson (Ref 4.36) have proposed a heat-transfer model representative of a multi-layered pavement system for evaluating frost action and temperature-related effects. This computer analysis technique may provide an answer to this problem; however, further information is required concerning the technique. There is, therefore, at present no systematic technique available for general use in estimating the temperatures which are expected to occur in asphaltic bases and subbases beneath a portland cement concrete surface.

A relationship between rate of loading (or time of loading) used in laboratory tests and the rate actually created in the pavement structure due to moving vehicle loads has not been developed. This may be due to the almost instantaneous rate of loading produced in the pavement structure by the moving vehicles and the influence of material properties and thicknesses of the layers.

Therefore, the selection of a loading rate which is representative of actual conditions cannot be quantitatively established. For design purposes, however, it is necessary to establish at least a qualitative measure of loading rate which can be representative of a fast or slow loading rate. The fast loading rate would then be applicable to the design of most highways, and the slow loading rate would be applicable for design of very low speed facilities for which frequent stops or delays are expected, i.e., some city streets and parking lot areas. The selection process is arbitrary but nevertheless must be completed for ease in design. From Fig A6.1 it can be seen that the results for loading rates of 2.0, 4.0, and 6.0 inches per minute are very close and indicate that an additional increase above a loading rate of 6.0 inches per minute would produce minimal increases in the material properties. Similarly, in Fig A6.1 the tensile strength results for a loading rate of .05 per minute are not much different than the results for a loading rate of 0.14 inches per minute and a decrease below a rate of .05 inches per minute is not expected to produce much lower tensile strengths. Based upon the above premises a loading rate of 6.0 inches is recommended as the fast loading rate, while a rate of 0.05 inches per minute is recommended as representative of a slow loading rate. Curves for this purpose, based upon Figs A6.6 through A6.8, relating changes in material properties to temperature for the two loading conditions have been developed and are presented in Figs 4.3 through 4.5 of Chapter 4.

The design temperatures recommended for use with these curves are the average ambient temperatures for the two design periods. These temperatures are expected to approximate those attained in the base or subbase layer of the pavement structure during the summer and winter months.

SUMMARY

The equations and curves presented in this appendix should be augmented in the future with a method for estimating the temperature distribution in composite pavements so that the equations can effectively be used in the design of asphaltic pavement layers. The equations and curves presented here, however, can be used to obtain estimates of properties of asphaltic materials for use in the design equations if estimates of the expected pavement temperatures are assumed or obtained from existing temperature data.

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William O. Hadley, a Research Associate while with the Center for Highway Research at The University of Texas at Austin, has had experience in the areas of highway design, power plant construction, and missile complex construction at Cape Kennedy, Florida. He is the author of several technical papers and reports and has been involved in researching and evaluating the use of asphalt-treated subbases in rigid pavement construction.

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Thomas W. Kennedy is an Associate Professor of Civil Engineering at The University of Texas at Austin. His experience includes work with the Illinois Division of Highways and research at the University of Illinois and the Center for Highway Research at The University of Texas at Austin, where he has conducted extensive investigations in the areas of (1) highway geometrics, (2) concrete durability, (3) tensile strength of stabilized subbase materials, and (4) time-dependent deformation of concrete and has contributed numerous publications in the field of transportation engineering. He is a member of several professional societies and has participated in committee work for the Highway Research Board and the American Concrete Institute.