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16. Abstract

This report summarizes the findings of Project 3-8-66-98, "Evaluation of Tensile Properties of Subbases for Use in New Rigid Pavement Design," and describes a series of research activities related to the development of a methodology for evaluating the tensile properties of stabilized materials and a structural design procedure for stabilized pavement layers.

This summary includes information developed on the tensile characteristics of asphalt-treated, cement-treated, and lime-treated materials, including the correlation of the indirect tensile test with the cohesiometer, the unconfined compressive test, and the Hveem stabilometer. In addition, the results of a limited series of fatigue tests conducted using the indirect tensile test are summarized.

The stabilized layer design procedure developed by the project and reported in Research Report 98-13 is discussed and summarized.

Finally, this report provides a summary of the findings and recommendations which have emanated from this project and provides a synthesis of implementation ideas for putting the findings of the project into practice. These include aspects which have already been put to use as well as those which are projected for the future.

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TENSILE PROPERTIES OF SUBBASES FOR USE IN RIGID PAVEMENT DESIGN

by

Thomas W. Kennedy
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Research Report Number 98-14F

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

Research Project 3-8-66-98

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

February 1973

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This report is the fourteenth and last in a series of reports from Project 3-8-66-98. The authors have served as co-principal investigators of the project, and many outstanding engineers and graduate students have worked on various aspects of the problem during the last six years. The work accomplished and summarized herein has varied widely, from the theoretical developments of elastic properties derived from material tests to the practical and pragmatic application of the indirect tensile methodology in Texas Highway District Laboratories. Testing has ranged from the complex investigation of fatigue properties to the practical evaluation of tensile strengths of field samples for Districts 8 and 17.

Throughout this project, a rather sophisticated statistical approach has been applied to the complex problem of relating from 10 to 14 variables in some meaningful way to a desired output or response. Without the practical application of these statistical techniques, under the guidance of Dr. Virgil L. Anderson, it would have been impossible to develop the findings which have been reported, with the degree of accuracy which is necessary to make them useful in the field. The use of these statistical techniques by others in civil engineering experimentation is strongly recommended. If the authors can be of any assistance in applying these methods, they would be happy to be contacted.

During the course of this project, there has been excellent cooperation from the sponsors. In particular, Messrs. Larry Buttler, James L. Brown, and Harvey J. Treybig have provided excellent assistance, which is gratefully appreciated. In addition, the support and encouragement of the numerous engineers from the Federal Highway Administration who have served as contact representatives at the division, regional, and national levels is acknowledged.

The assistance of the staff of the Center for Highway Research has been essential in the accomplishments which are summarized in this report. In particular, we would like to acknowledge the contributions of those graduate students and research engineers who have produced the majority of the research findings and have authored numerous reports. In alphabetical order, these are:

Robert F. Cauley, M.S.
William O. Hadley, Ph.D.
S. Paul Miller, M.S.
Raymond K. Moore, Ph.D.
Humberto Pendola, M.S.
Walter S. Tulloch, II, M.S.

Continuing management and direction for the project have been provided by William O. Hadley, James N. Anagnos, and Raymond K. Moore, who have not only authored a number of reports in their own right but have assisted with guidance on many phases of the work throughout the project.

Particular thanks are due to the administrative and technical staff of the Center for Highway Research, including Messrs Arthur Frakes, Editor; Pat Hardeman, Laboratory Technician; Harold Dalrymple, Instrumentation Engineer; and Ray Berwick, Administrative Assistant.

Additional help has been provided in one phase or another of the project by the following people, whose assistance is also acknowledged: Mr. Jimmy Holmes, Dr. Gerald Wagner, Dr. Joseph Kozuh, Mr. Stanley Stokes, Mr. Miguel Colina-Vargas, and Dr. Clyde E. Lee.

Thomas W. Kennedy
W. Ronald Hudson

February 1973

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. January 1968.

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. March 1969.

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. September 1969.

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. March 1970.

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. June 1970.

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. June 1970.

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. July 1970.

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. October 1970.

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. May 1971.

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. August 1972.

Report No. 98-11, "Improved Tensile Strength for Cement-Treated Bases and Subbases," by Robert F. Cauley and Thomas W. Kennedy, summarizes the findings of an evaluation and interpretation of the results from previous studies concerning the tensile and shrinkage characteristics of cement-treated materials. December 1972.

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. October 1971.

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. August 1972.

Report No. 98-14F, "Tensile Properties of Subbases for Use in Rigid Pavement Design," by Thomas W. Kennedy and W. Ronald Hudson, summarizes the approach, activities, and findings of a research project concerned with the evaluation of tensile properties of stabilized subbases for use in rigid pavement design. February 1973.

LIST OF REPORTS

There are fourteen reports from this project, numbered 98-1 through 98-14F. They are listed below in functional groups, for easy reference, rather than in numerical order.

TESTING TECHNIQUES

Research Report 98-1

Research Report 98-7

Research Report 98-10

ASPHALT-TREATED MATERIALS

Research Report 98-2

Research Report 98-6

Research Report 98-9

CEMENT-TREATED MATERIALS

Research Report 98-3

Research Report 98-8

Research Report 98-11

LIME-TREATED MATERIALS

Research Report 98-4

Research Report 98-5

FATIGUE PROPERTIES

Research Report 98-12

DESIGN OF STABILIZED PAVEMENT LAYERS

Research Report 98-13

SUMMARY

Research Report 98-14F

ABSTRACT

This report summarizes the findings of Project 3-8-66-98, "Evaluation of Tensile Properties of Subbases for Use in New Rigid Pavement Design," and describes a series of research activities related to the development of a methodology for evaluating the tensile properties of stabilized materials and a structural design procedure for stabilized pavement layers.

This summary includes information developed on the tensile characteristics of asphalt-treated, cement-treated, and lime-treated materials, including the correlation of the indirect tensile test with the cohesiometer, the unconfined compressive test, and the Hveem stabilometer. In addition, the results of a limited series of fatigue tests conducted using the indirect tensile test are summarized.

The stabilized layer design procedure developed by the project and reported in Research Report 98-13 is discussed and summarized.

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KEY WORDS: stabilized materials, subbase design, asphalt-treated, cement-treated, lime-treated, tensile, splitting tensile test, indirect tensile test, fatigue, pavement design, elastic properties, modulus of elasticity, Poisson's ratio.

SUMMARY

The indirect tensile test is a practical, inexpensive, and relatively easy method of determining tensile properties of pavement materials. This report describes a series of research activities related to the development of a methodology for testing stabilized materials and using the resulting properties in the design of pavement layers. Particular attention has been given to the design of stabilized subbases for portland cement concrete pavements; however, the methods are equally applicable for asphaltic concrete. The findings of the project are summarized herein and practical implementable ideas are discussed. This report does not provide the details of the experiments; these can be found in the various research reports.

IMPLEMENTATION STATEMENT

The indirect tensile test, the stabilized material mix property findings, and the stabilized layer design procedure developed on this project and summarized in this report can be implemented immediately by the Texas Highway Department and the Federal Highway Administration to improve pavement design and performance. In each of the previous reports from the project, 98-1 through 98-13, a section on implementation has been provided. In addition, Chapter 6 in this report discusses a variety of implementable items which should receive strong consideration.

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CHAPTER 1. INTRODUCTION

A rational design procedure for subbases is essential to the development of a systematic design procedure for better pavements. The importance of the tensile characteristics of the base and subbase of pavements has been demonstrated both from theoretical considerations and from field observations (Ref 10).

Tensile stresses are created in the individual layers of the roadway by moving traffic. As the pavement structure deflects under these traffic loads tensile stresses are created at the interfaces between layers. In addition, tensile stresses are created when a pavement material attempts to shrink or crack but is restrained by friction or other forces.

The increased use of stabilized subbases as a part of rigid pavement structures has stimulated interest in developing a design procedure for these stabilized materials. In conjunction with the development of such a procedure, information concerning the tensile properties of stabilized materials is needed since rigid pavement failure can result from loss of support which is caused by subbase cracking. In addition, flexible pavements can also fail due to the formation of tensile cracks in the subbase and base layers, with the cracks subsequently propagating upward through the surface level. Furthermore, information is needed on the fatigue behavior of stabilized materials subjected to repeated applications of tensile stresses.

In recognition of these problems, Project 3-8-66-98, "Evaluation of Tensile Properties of Subbases for Use in New Rigid Pavement Design," was sponsored by the Texas Highway Department and the Federal Highway Administration and was conducted through the Center for Highway Research at the University of Texas at Austin in order to develop information on the tensile characteristics of pavement materials.

The primary goal of the project was to develop rational criteria and procedures for the design of stabilized subbases for rigid pavements based on the tensile properties of the materials involved. More specifically, the project goals can be subdivided into the following objectives:

(1) Develop a practical method or test for evaluating the tensile characteristics of stabilized materials.

(2) Develop information on the tensile properties of asphalt-treated, cement-treated, and lime-treated materials and the factors affecting these properties.

(3) Develop preliminary information on the fatigue characteristics of asphalt-treated, cement-treated, and lime-treated materials subjected to repetitive tensile stresses.

(4) Develop a rational structural design procedure for rigid pavement subbases.

APPROACH

Since there was essentially no information available on the tensile properties of stabilized materials at the beginning of this project, an attempt was made to systematically compile information needed for the development of a rational design procedure based on tensile properties.

The major phases of the project have been organized into a flow diagram, as shown in Fig 1. These major phases essentially correspond with the four specific objectives of the project.

PURPOSE OF THIS REPORT

The purpose of this report is to briefly summarize the activities, findings, and recommendations of this project. These findings are covered in more detail in the series of 13 reports dealing with different phases of the project at various stages during the past seven years. Anyone wishing more detail on any given aspect of the project should consult the appropriate report.

Chapter 2 of this report reviews the basic findings, developments, and recommendations concerning the indirect tensile test. Chapter 3 briefly summarizes the findings from the various experimental programs designed to evaluate the tensile and fatigue properties of asphalt-treated, cement-treated, and lime-treated materials. Chapter 4 reviews the basic development of a subbase design procedure for stabilized subbases and contains a great deal of detailed information, since this activity related very closely to the overall objectives of the project. Chapter 5 summarizes the findings and makes recommendations for future projects. Chapter 6 discusses methods of implementing the results of the project as rapidly and easily as possible.

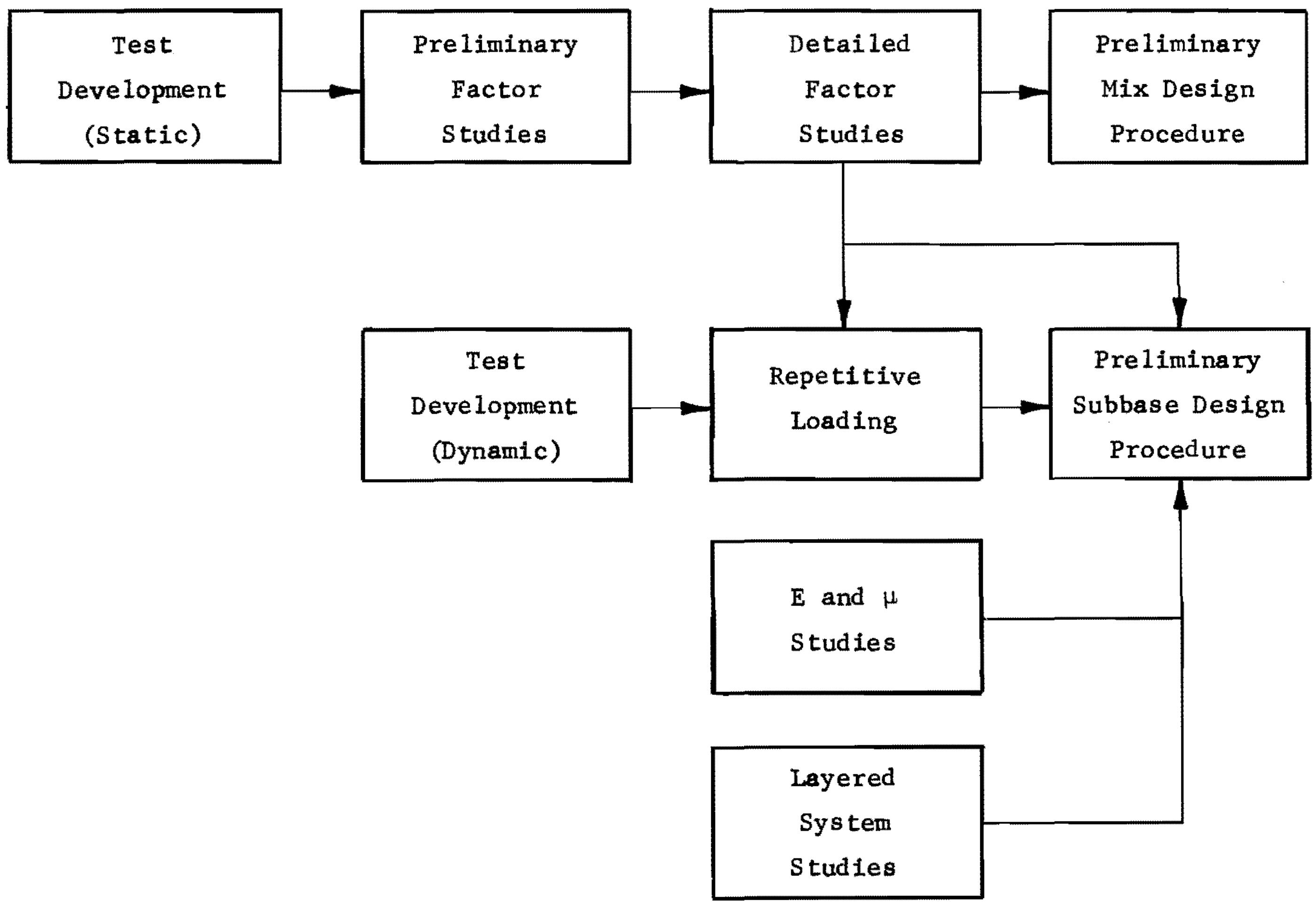

Fig 1. Generalized flow diagram for subbase project.

CHAPTER 2. TESTING METHOD

Various tests and modifications have been developed and used for evaluating the tensile characteristics of highway materials. These tests can be classified as (1) direct tensile tests, (2) bending tests, or (3) indirect tensile tests. Based on a literature review and an evaluation of experimental results obtained from the indirect tensile test, it was concluded that the indirect tensile test was the best test available at that time for estimating the tensile properties of stabilized materials and showed the most promise for practical future work in pavement design.

The indirect tensile test was developed simultaneously but independently in Brazil and in Japan. The test involves loading a cylindrical specimen with compressive loads distributed along two opposite generators (Fig 2). This condition results in a relatively uniform tensile stress perpendicular to and along the diametrical plane containing the applied load. Failure occurs as splitting along this loaded plane (Fig 3).

Previous use of this test had generally been on concrete or mortar specimens, but the test had been found satisfactory for the evaluation of the tensile characteristics of asphaltic concrete and lime-soil mixtures and had a number of advantages and two disadvantages. The main disadvantage is that the test loading conditions do not resemble those in the field. The second disadvantage is that the theory is more complex than the theory of the direct tensile test and the bending test. The five major advantages attributed to the test are that

(1) It is relatively simple.

(2) The type of specimen and equipment are the same as that used for compression testing.

(3) Failure is not seriously affected by surface conditions.

(4) Failure is initiated in a region of relatively uniform tensile stress.

(5) The coefficient of variation of the test results is low.

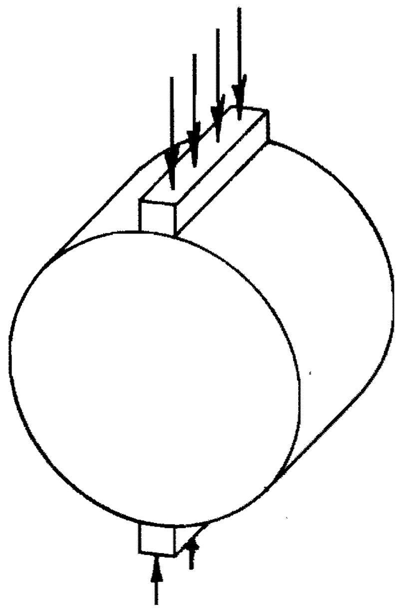

Fig 2. Cylindrical specimen with compressive load being applied.

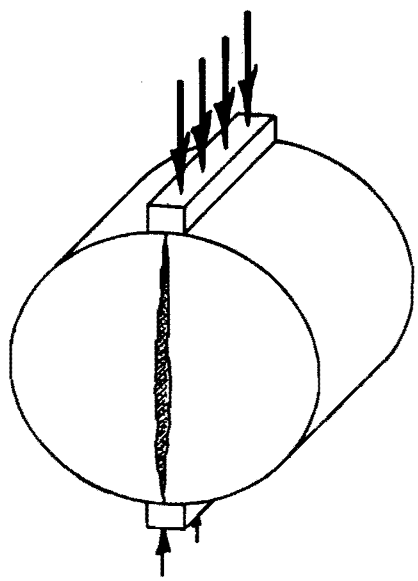

Fig 3. Specimen failing under compressive load.

INDIRECT TENSILE TEST

The indirect tensile test involves loading a cylindrical specimen with compressive loads which act parallel to and along the vertical diametrical plane, as shown in Fig 2. To distribute the load and maintain a constant loading area, the compressive load is applied through a half-inch-wide stainless steel loading strip which is curved at the interface with the specimen and has a radius equal to that of the specimen.

This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane, which ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter (Fig 3). The tensile stress in the center of the specimen (Fig 4) can be calculated using the following equation:

$$\sigma_T = \frac{2P}{\pi a h} \left(\sin 2\alpha - \frac{a}{2R}\right)$$

where

σ_T = indirect tensile stress;

P = total vertical load applied to specimen, in pounds;

a = width of loading strip, in inches;

h = height of specimen at beginning of test, in inches;

R = radius of specimen, in inches; and

2α = angle at the origin subtended by the width of loading strip.

When P is maximum, σ_T equals the indirect tensile strength S_T.

In addition, it is possible to estimate Poisson's ratio, modulus of elasticity, and tensile strains by measuring the vertical and horizontal deformations in the specimen during testing. The relationships required for these estimations are based on equations for stresses in a circular element subjected to short strip loading, which were developed by Hondros (Ref 9). These original equations were converted to strain distributions. The total deformations were then set equal to the integral of the strains along

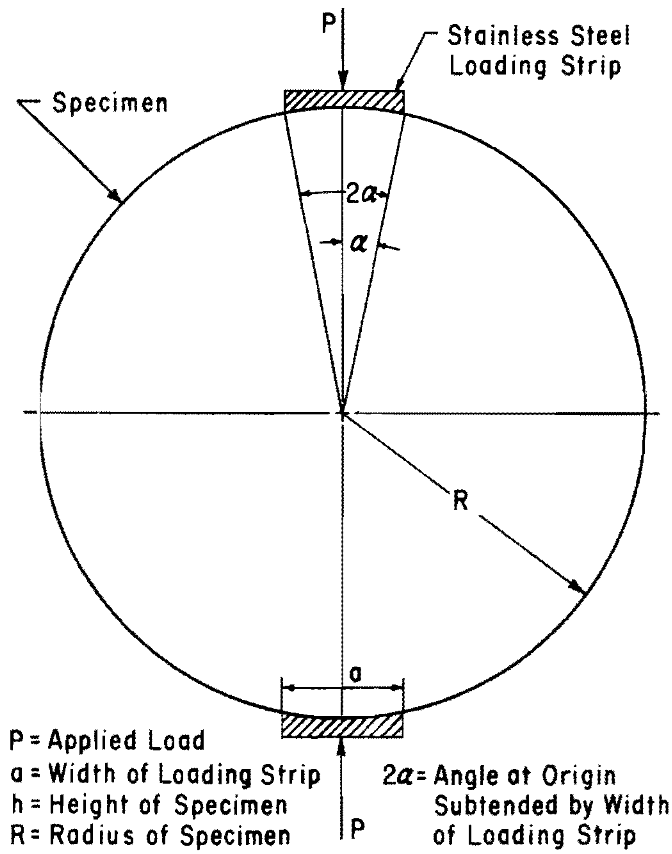

Fig 4. Indirect tensile test.

the vertical and horizontal diameters and were expressed as a function of modulus of elasticity and Poisson's ratio (Ref 5).

Thus, from the dimension of the specimen, the applied loads, and the resulting vertical and horizontal deformations of the specimens, it is possible to estimate indirect tensile strength, modulus of elasticity, Poisson's ratio, and tensile strains.

These relationships, which are contained in Ref 5, are rather complex and require integration of various mathematical functions. However, if a specimen diameter is assumed, the required integrations can be conducted and the relationships simplified.

In addition, since the basic testing equipment used by the project included an MTS closed-loop electrohydraulic loading system, it was necessary to develop other methods of conducting the test so that it could be readily used by other agencies and by District Laboratories of the Texas Highway Department.

PRACTICAL METHOD OF TESTING

In recognition of the need to simplify the test procedure and the method of estimating, a practical method of conducting the indirect tensile test and analyzing the test results to determine the tensile properties of all types of pavement materials except cohesionless materials was developed (Ref 2).

The method of testing was broken into two parts. The first describes the relatively simple equipment and test procedures required to obtain tensile strength. The second part describes equipment, test procedures, and a method of analysis to determine Poisson's ratio, modulus of elasticity, and tensile strains.

Equipment

The basic testing apparatus includes loading equipment capable of applying compressive loads at a controlled deformation rate, preferably 2 inches per minute, a means of measuring the applied load, and half-inch-wide curved-face loading strips, which are used to apply and distribute the load uniformly along the entire length of the specimen.

Determination of Indirect Tensile Strength. Any loading equipment which can apply compressive loads at a prescribed loading rate, can provide an accurate measure of the maximum load, and has a load capacity sufficient to fail the specimen can be used. In addition, since it is necessary to apply the load to the specimen through steel loading strips which must remain essentially parallel, a guided loading head with loading strips attached to the upper and lower parallel platens should be used. Such a device, which has been used at the Center for Highway Research, can be obtained by modifying a commercially available die set. The specifications and required modifications for this die set and the loading strips are contained in Ref 2.

The motorized gyratory press should be considered for loading specimens since this press is available in most of the District Laboratories and in the Materials and Tests Division of the Texas Highway Department and would require only minor modifications (Ref 2). The press is capable of applying compressive loads of up to 25,000 pounds at controlled deformation rates ranging from 0.05 to 10 inches per minute. If the gyratory press is used, the guided loading head probably should not be used; rather a different set of loading strips should be attached directly to the platens of the gyratory press, as shown in Ref 2, which contains machine drawings of the loading strips for use with the gyratory press, a list of equipment needed to perform the test, and a description of the modifications of the press.

Determination of Indirect Tensile Strength, Modulus of Elasticity, Poisson's Ratio, and Tensile Strains. In order to estimate the indirect tensile strength, Poisson's ratio, modulus of elasticity, and tensile strains, it is necessary to measure the vertical and horizontal deformations of the specimens and to relate these deformations to the applied load. Thus, deformation measuring equipment is required as is continuous load-deformation recording equipment.

A guided loading head with parallel platens such as the previously discussed die set with attached loading strips and a means of continuously measuring the horizontal and vertical deformations is required along with loading equipment capable of applying a compressive load at a controlled deformation rate. The gyratory press probably should not be used to apply the load since load-vertical and load-horizontal deformations must be continuously measured and recorded accurately. These measurements on specimens of stabilized materials have been satisfactorily obtained at the Center for Highway Research by using a linear variable differential transformer (Schaevitz Engineering Type 1000 DC-LVDT) to measure vertical deformation and a specially designed horizontal deflection device to measure horizontal deformations. The specifications for this device are contained in Ref 2. In addition, a load cell was used to measure the applied load.

Some means of continuously recording the loads and their corresponding vertical and horizontal deformations must be used since the rate of loading makes it impossible to manually record the observations. Such measurements have been made satisfactorily by continuously recording the load-deformation relationships on two x-y plotters.

If the Texas gyratory shear compactor is used, it is recommended that a pressure transducer be considered for monitoring the load. This transducer can be inserted into the pressure system, but the Center for Highway Research has not investigated this possibility. In addition, for materials exhibiting very small deformations per unit load it may be necessary to use equipment capable of measuring and recording deformations more precisely.

Calculation of Tensile Properties

By assuming a specimen diameter, it is possible to simplify the complex relationships required to estimate the tensile properties. The simplified relationships for calculating Poisson's ratio, modulus of elasticity, and failure strains for 4-inch and 6-inch-diameter specimens with a half-inch-wide curved loading strip are summarized in Table 1.

Summary of Test Details

The indirect tensile test can be used to evaluate all stabilized materials, and it is hoped that it can be used to evaluate all pavement materials except cohesionless materials. Thus, it will be possible to compare the behavioral characteristics of these materials on the same basis using the same test. The tensile properties obtained from this test are expressed in terms of standard engineering units, which are more meaningful than empirical numbers and which can be used in theoretical design procedures requiring the elastic constants of the materials involved. In addition, since the test is very simple to conduct and uses cylindrical specimens which are easily prepared, it can be used to control the quality of construction materials.

TABLE 1. EQUATIONS FOR CALCULATION OF TENSILE PROPERTIES

Tensile Property	Diameter of Specimen	
	4-Inch	6-Inch
Tensile strength S_T, psi	$0.156 \frac{P_{Fail}}{h}$	$0.105 \frac{P_{Fail}}{h}$
Poisson's ratio ν	$\frac{0.0673DR - 0.8954}{-0.2494DR - 0.0156}$	$\frac{0.04524DR - 0.6804}{-0.16648DR - 0.00694}$
Modulus of elasticity E, psi	$\frac{S_H}{h} \left[0.9976\nu + 0.2692\right]$	$\frac{S_H}{h} \left[0.9990\nu + 0.2712\right]$
Total tensile strain at failure ϵ_T	$X_{TF} \left[\frac{0.1185\nu + 0.03896}{0.2494\nu + 0.0673}\right]$	$X_{TF} \left[\frac{0.0793\nu + 0.0263}{0.1665\nu + 0.0452}\right]$

P_{Fail} = total load at failure (maximum load P_{max} or load at first break point), in pounds;

h = height of specimen, in inches;

X_{TF} = total horizontal deformation at failure (deformation at the maximum load or at first break point), in inches (Fig 4);

DR = deformation ratio $\frac{Y_T}{X_T}$ (the slope of line of best fit* between vertical deformation Y_T and the corresponding horizontal deformation X_T up to failure load P_{Fail});

S_H = horizontal tangent modulus $\frac{P}{X_T}$ (the slope of the line of best fit* between load P and total horizontal deformation X_T for loads up to failure load P_{Fail}).

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* It is recommended that the line of best fit be determined by the method of least squares.

CORRELATION OF INDIRECT TENSILE AND OTHER TEST VALUES

In the evaluation of the indirect tensile test and its application to the study of the tensile properties of stabilized materials, it was felt that an attempt should be made to determine whether indirect tensile strengths correlated with the strength parameters from other tests currently used by the Texas Highway Department. In addition, it was felt that a limited amount of testing should be conducted to determine whether the size of the specimen affected the test results. Thus, a series of small correlation experiments were designed and conducted as a part of the materials evaluation investigations conducted for asphalt-treated, cement-treated, and lime-treated materials. The results of the materials evaluation studies are summarized in Chapter 3; however, the results of the correlation and specimen size studies are contained in this chapter.

Correlation Studies

Two correlation experiments were conducted for both the cement-treated and lime-treated materials. These correlation experiments were designed to determine whether correlations exist between the indirect tensile strength and the strength values obtained from the unconfined compressive strength or the cohesiometer tests, both of which are currently used by the Texas Highway Department.

Lime-Treated Materials. Two series of specimens were prepared. One series, called the Center for Highway Research Correlation, was cured in accordance with procedures established by the Center for Highway Research (Ref 15). The second series of specimens was prepared and cured in accordance with standard Texas Highway Department procedures (Ref 14). The first experiment included 19 specimens and the second, 20 specimens. Good correlations were obtained for the individual tests; however, for a general comparison, correlations were run for the combined test results. A regression analysis was run on the combined data, and the results are plotted and shown in Ref 15.

Cement-Treated Materials. Two series of specimens were prepared. One series was cured in accordance with procedures which were currently being used in the materials evaluation investigation of cement-treated materials (Ref 1). The second series of specimens was prepared and cured in accordance with Texas Highway Department procedures for cement-treated materials (Ref 14).

Good correlations were obtained for both tests for both series of experiments. To illustrate the findings, the results of the combined series of tests are plotted in Figs 5 and 6, which also show the resulting regression equations and correlation coefficients. Complete information on these correlations is available in Ref 1.

Asphalt-Treated Materials. The correlation investigation for asphalt-treated materials was more extensive than that conducted for cement-treated and lime-treated materials. Rather than investigating only the indirect tensile strength, an attempt was made to establish correlations between the cohesiometer and stabilometer values and the elastic parameters from the indirect tensile test, i.e., tensile strength, tensile strain, modulus of elasticity, and Poisson's ratio.

As with the cement-treated and lime-treated materials, two series of specimens were prepared. The first was prepared according to procedures being used by the project in the evaluation of the tensile properties of asphalt-treated materials. The second series was prepared in accordance with Texas Highway Department standard procedures (Ref 7).

The correlations between the responses of the indirect tensile tests and both the cohesiometer and Hveem stabilometer tests were dependent upon the confines of the study. In the experiment utilizing Texas Highway Department procedures, five of the eight comparisons were found to exhibit no correlation:

(1) Poisson's ratio versus cohesiometer value,
(2) tensile strain versus cohesiometer,
(3) modulus of elasticity versus stability,
(4) tensile strength versus stability, and
(5) tensile strain versus stability.

In these five cases the responses were truly independent and the tensile properties could not be predicted from the corresponding Hveem parameters.

On the other hand, a range of test conditions was evaluated in the second experiment and correlation between the variables was found to exist for all the comparisons.

The following correlations were found to be acceptable for a general range of test conditions:

(1) modulus of elasticity versus cohesiometer value,
(2) tensile strength versus cohesiometer value,

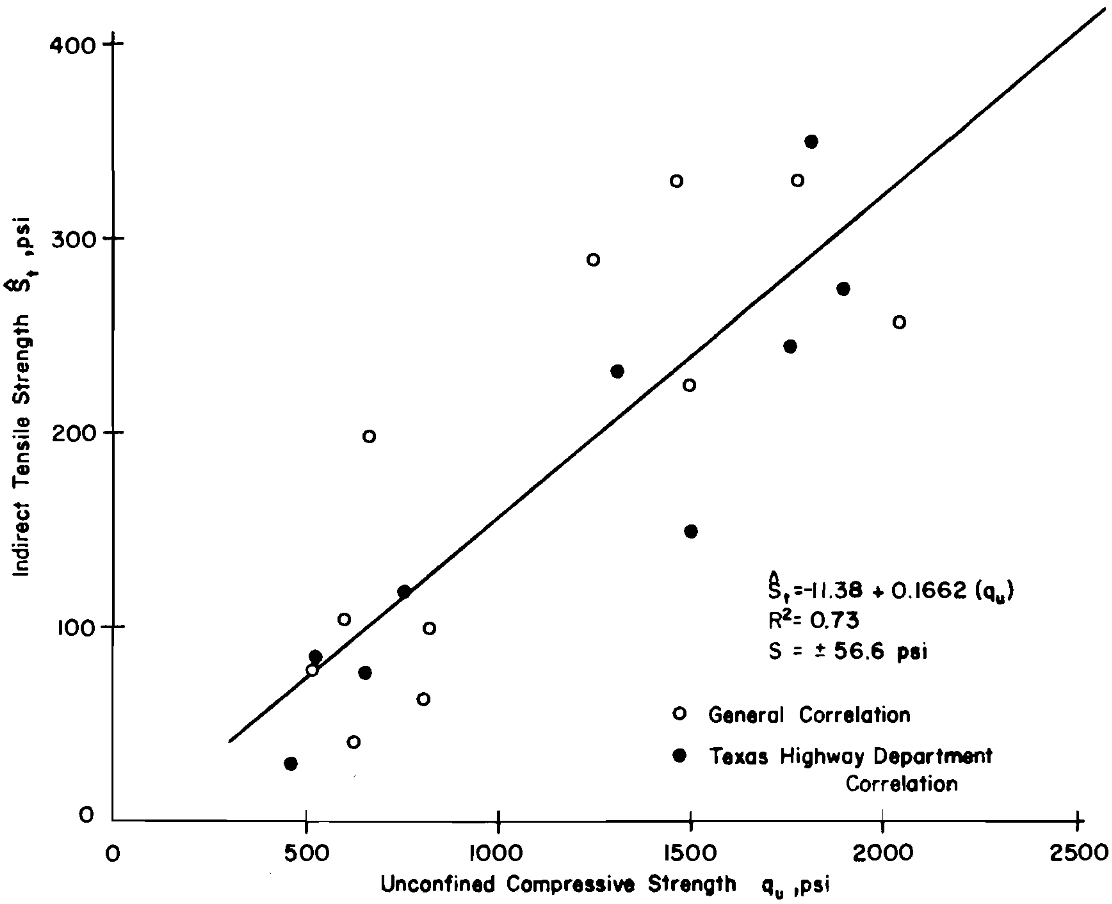

Fig 5. Indirect tensile strength-unconfined compressive strength for combined data.

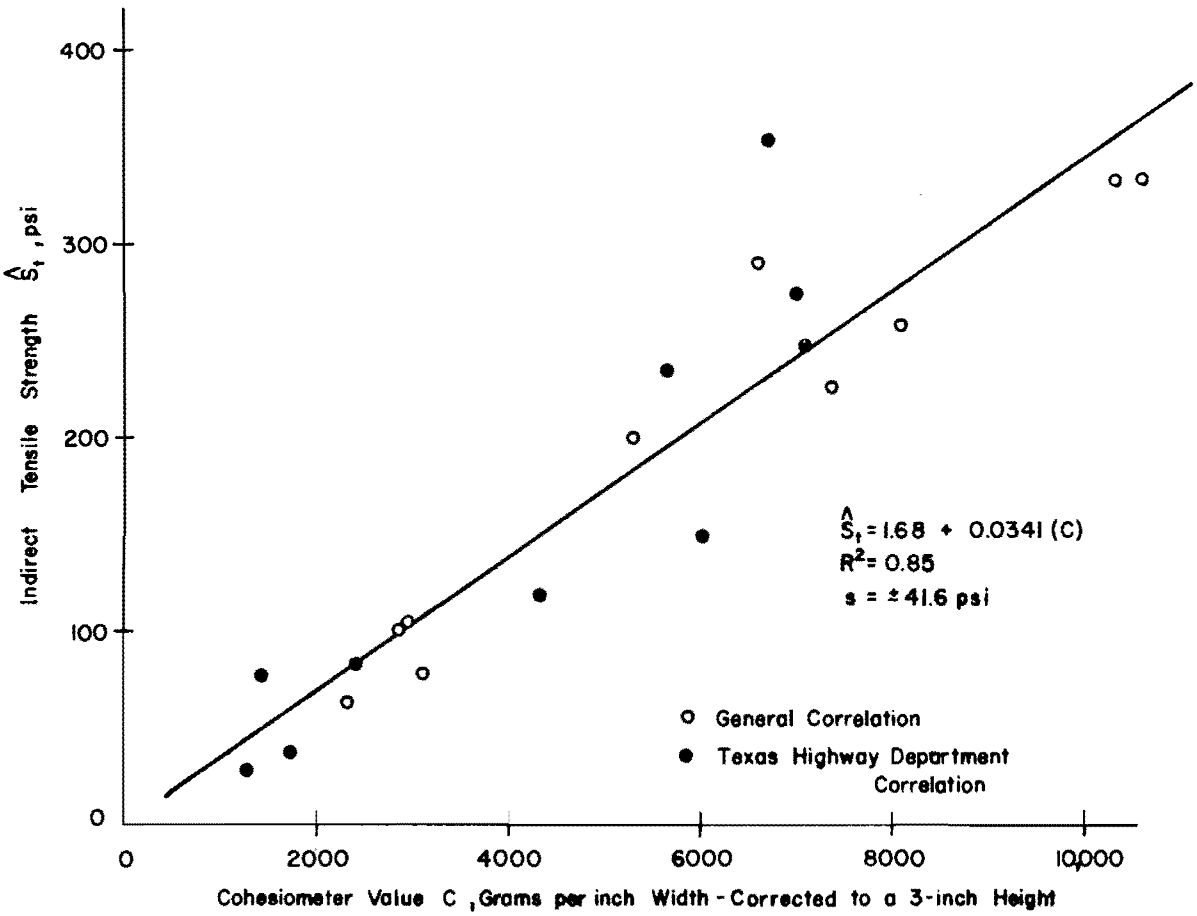

Fig 6. Indirect tensile strength-cohesiometer value for combined data.

(3) tensile strain versus cohesiometer value,
(4) Poisson's ratio versus stability, and
(5) tensile strain versus stability.

These can be used for estimating properties over a wide range of conditions, but one must be aware of errors associated with them as indicated by the confidence bounds.

In the case of the Texas Highway Department's standard test conditions, the only acceptable correlation involved the modulus of elasticity and the cohesiometer value. The correlation equation for those parameters which were found to correlate are contained in Ref 7.

SPECIMEN SIZE CORRELATION

During the course of the project there was some concern as to the effect of specimen size on the results of splitting tensile tests. In order to evaluate this problem, several studies were made comparing 4-inch-diameter specimens with 6-inch-diameter specimens (Refs 15 and 1). Typical results of these comparisons are shown in Fig 7. Analyses of variance were conducted, and it was found that specimen size did not have a significant effect on tensile strength at the 5 percent level. This observation is supported by a review of the literature (Ref 1). It appears from results of this project that indirect tensile test results for specimens with a diameter-particle-size ratio greater than four are quite satisfactory for specimen sizes in the range of 4 to 8 inches.

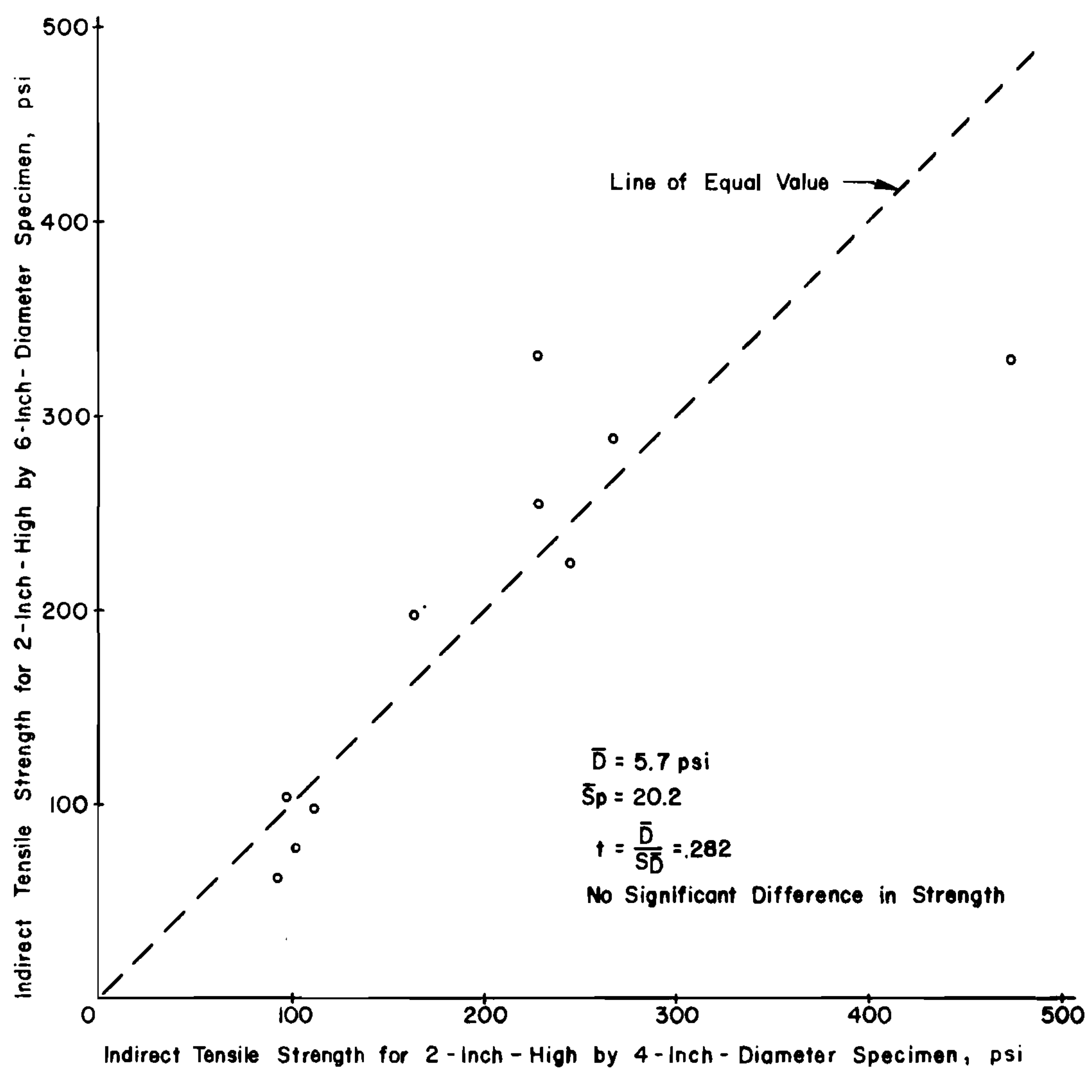

Fig 7. Indirect tensile strength relationships for Specimen Size Study (Ref 1).

CHAPTER 3. MATERIALS EVALUATION

Prior to the beginning of this project, a great deal of effort had been expended to evaluate the effect of various mixture, construction, and environmental factors on the strength characteristics of asphalt-treated, cement-treated, and lime-treated materials. However, little effort had been made to evaluate the effects of these factors on the tensile properties of these materials although it was often assumed that the tensile behavioral characteristics were the same.

Thus, it was necessary to devote a considerable portion of the research effort to materials evaluation studies for each of the three materials. These studies primarily involved static testing, although a small portion was devoted to a preliminary evaluation of all three materials under repeated indirect tensile test loads.

The static portion was subdivided into two basic phases - a preliminary evaluation of the tensile properties of each material and the factors affecting these properties and a more detailed evaluation of the tensile characteristics of all three materials. Thus, for each material, three major investigations were conducted:

(1) preliminary evaluation of tensile properties,
(2) detailed evaluation of tensile properties, and
(3) preliminary evaluation of the tensile-fatigue properties.

TENSILE PROPERTIES OF ASPHALTIC MATERIALS

Preliminary Study

Report 98-2 summarizes the findings of the preliminary investigation which involved the evaluation of the factors affecting the tensile characteristics of asphalt-treated materials subjected to static tensile stresses. The purpose of the experiment was to evaluate the factors and interactions between them which significantly affected the tensile characteristics of asphalt-treated materials and to develop a preliminary regression model which could be used to predict the tensile properties of asphalt-treated materials.

Preliminary Experimental Program. A fractional-factorial experiment design was used in this study to establish the factors and interactions which significantly affect the tensile properties of asphalt-treated materials by investigating eight different factors at two levels. The factors and levels are given in Table 2.

Using these factors and levels, an experiment involving 68 test specimens was conducted. Each specimen was tested in indirect tension and the tensile strength and horizontal failure deformations were recorded and analyzed.

Results of Preliminary Study. Based on the results of this early study, the following conclusions were drawn:

(1) There were six main effects, twelve two-way interactions, and three three-way interactions which had highly significant effects (α = 0.01) on the tensile strength of asphalt-treated materials and were considered to be of practical significance to the engineer.

(2) There were five main effects, one two-way interaction, and two three-way interactions which had highly significant effects (α = 0.01) on the horizontal deformation of asphalt-treated materials.

(3) The existence of such a large number of highly significant main effects and interactions illustrates the complexity of the relationship between tensile properties of asphalt-treated materials and a number of independent factors.

(4) Since there are a number of interactions between factors which are important in establishing the tensile properties, it is not adequate to consider only main effects, because consideration must be given also to any interaction effect in predicting the value of the particular property.

(5) In general, it was found that tensile strength was increased by

   (a) increasing the asphalt content from 3.5 to 7.0 percent,

   (b) increasing the compaction temperature from 200° F to 300° F,

   (c) using impact rather than gyratory shear compaction,

   (d) increasing the mixing temperature from 250° F to 350° F,

   (e) using AC-20 rather than AC-5 asphalt cement, and

   (f) using crushed limestone rather than rounded gravel aggregate.

(6) In general it was found that horizontal failure deformation was increased by

   (a) increasing the asphalt content from 3.5 to 7.0 percent,

   (b) decreasing the mixing temperature from 350° F to 250° F,

   (c) using crushed limestone rather than rounded gravel aggregate,

   (d) decreasing the compaction temperature from 300° F to 200° F, and

   (e) using a coarse gradation rather than a fine gradation.

TABLE 2. FACTORS AND LEVELS SELECTED FOR EXPERIMENTAL PROGRAM

	Level	
Factor	Low	High
Aggregate type	Crushed limestone	Rounded gravel
Aggregate gradation	Fine	Coarse
Asphalt viscosity (specification)	AC-5	AC-20
Asphalt content, %	3.5	7.0
Compaction type	Marshall impact	Texas gyratory shear
Mixing temperature, °F	250	350
Compaction temperature, °F	200	300
Curing temperature, °F	40	110

(7) Within the confines of this study, asphalt content appears to have the greatest effect on the tensile strength of asphalt-treated highway materials. This is evidenced by the fact that the main effect of asphalt content, seven two-way interactions involving asphalt content, and two three-way interactions involving asphalt content had highly significant effects on tensile strength.

Detailed Experimental Program

The objectives of this detailed experimental program, which is reported in Research Report 98-9 (Ref 8), were to evaluate the nonlinear effects of all quantitative factors on the tensile properties of asphalt-treated materials and to develop equations for estimating the tensile properties in terms of the more important mixture and construction variables.

Experimental Program. The indirect tensile test was used to evaluate the effects produced on five different tensile properties by seven different factors (Table 3) previously found to be important (Ref 6). An experiment design was used which allowed the nonlinear effects of all the factors except aggregate type to be evaluated.

The tensile properties evaluated in this series were

(1) tensile strength,
(2) elastic tensile strain,
(3) modulus of elasticity,
(4) Poisson's ratio, and
(5) total tensile strain.

A discussion of the indirect tensile test and the techniques for estimating tensile strength, modulus of elasticity, Poisson's ratio, and tensile strains, as well as examples of the method of estimating all five variables, is included in Ref 8.

The data were analyzed using regression techniques in which equations for estimating the five properties were developed by fitting a curve to a set of data points so that the sum of the squares of the difference between the actual value and the estimated value of the response variable was minimized. These curves were then used to evaluate the effect of the seven factors, e.g., asphalt content and compaction temperature. In addition, the relationships between two tensile properties, tensile strength and modulus of elasticity, and two other mixture properties, density and percent air voids, were investigated and are reported in Ref 8.

TABLE 3. FACTORS AND LEVELS SELECTED FOR EXPERIMENTAL PROGRAM

	Levels				
Factor	-2	-1	0	+1	+2
Aggregate type		Limestone		Gravel	
Aggregate gradation		Fine (2 mm)*	Medium (4 mm)	Coarse (6 mm)	
Asphalt cement type		AC-5 (8.5)**	AC-10 (9.0)	AC-20 (9.7)	
Asphalt content, %	4.0	5.5	7.0	8.5	10.0
Mixing temperature, °F		250	300	350	
Compaction temperature, °F		200	250	300	
Curing temperature, °F		40	75	110	

*Diameter of particles which are coarser than 40 percent of mixture by weight.

**Slope of relationship between the logarithm of the temperature and the logarithm of the viscosity between 140° F and 275° F.

Results of Detailed Study. The analysis of the data indicated those factors which significantly affected the five tensile properties and which should be considered in determining the value for each of the tensile properties. The factors found to be important are listed in Table 4.

Estimates of the five tensile properties for a variety of combinations of factors are included in Ref 2 in the form of tables and graphical relationships. These relationships indicate that compaction temperature had a substantial effect on the tensile properties of asphalt-treated materials. This finding may explain some of the differences observed between laboratory and field results, since most laboratory procedures involve preparation of materials at certain fixed compaction temperatures. If the mixtures are compacted in the field at temperatures much different from those used in the laboratory tests, then, as indicated by the results of the study, the mixture would not perform in the field as predicted in the laboratory.

Equations presented in the report can be used to estimate the modulus of elasticity, Poisson's ratio, tensile strength, and tensile strain at failure of asphalt-treated materials for various combinations of the factors and levels of the factors studied. The equations for modulus of elasticity, tensile strength, and elastic tensile strain were shown to be very reliable and can be used to estimate these three properties. On the other hand, the equations for Poisson's ratio and total tensile strain at failure were not as reliable as the others, but they still provide better estimates of the two properties than has been previously possible. In all cases, the decision as to whether or not to use these equations must be based on the error which can be tolerated.

The findings of this investigation indicate that the indirect tensile test can be used to obtain optimum mixture designs since optimum asphalt contents were detected for the modulus of elasticity and tensile strength. The optimum asphalt content was dependent upon aggregate type, aggregate gradation, and compaction temperature. Although a set of design tests may be needed to complement the results, the table presented in Ref 2 can be used to provide preliminary estimates.

TENSILE PROPERTIES OF LIME-TREATED MATERIALS

Preliminary Study

Ref 11 summarizes the findings of the preliminary investigation which involved the evaluation of the factors affecting the tensile characteristics

TABLE 4. FACTORS AFFECTING THE ELASTIC AND TENSILE PROPERTIES OF ASPHALT-TREATED MATERIALS

Tensile Property (75° F)	Important Factors
Modulus of elasticity and tensile strength	Aggregate type Aggregate gradation Asphalt cement type Asphalt content Compaction temperature
Poisson's ratio	Aggregate type Aggregate gradation Asphalt content Compaction temperature
Total tensile strain at failure	Aggregate type Asphalt content Compaction temperature
Elastic tensile strain at failure	Aggregate type Asphalt cement type Asphalt content Compaction temperature

of lime-treated materials subjected to static tensile stresses. The purpose of the experiment was to evaluate the factors and the interactions between them which significantly affect the tensile characteristics of lime-treated materials and to develop a preliminary regression model which could be used to predict the tensile strength of lime-treated materials.

Experimental Program. On the basis of a literature review, eight factors were selected for evaluation. The effects of these eight factors and of the interactions between these factors were evaluated, by using a fractional factorial experiment design consisting of three experimental blocks and involving eight factors at two or more levels. The factors and levels investigated are shown in Table 5.

Using these factors and levels, an experiment involving 250 specimens was conducted. Each specimen was tested in indirect tension. The tensile strengths were recorded and analyzed in Ref 11.

Results of Preliminary Study

Seven of the eight factors evaluated in the preliminary study produced significant effects on the indirect tensile strength. It was found that the average tensile strength was significantly increased by

(1) using impact compaction rather than gyratory shear compaction,
(2) using 100 percent clay rather than a mixture of clay and gravel,
(3) curing at a temperature of 110° F rather than 40° F,
(4) using a high compactive effort,
(5) increasing the lime content from 2 to 6 percent,
(6) using sealed rather than air-dried curing, and
(7) curing for six weeks rather than two weeks.

In addition to the main effects, eleven two-factor interactions, ten three-factor interactions, and three four-factor interactions were found to be significant.

The only main effect which was not significant involved molding water content. Although not significant as a main effect, it was involved in a number of highly significant interaction effects. In addition, curing time, although significant, had very little practical effect, probably because the longest curing time was still too short to allow for significant strength gains.

Since there were a large number of interactions which had significant effects on the tensile strength of lime-treated materials, it is inadequate to

TABLE 5. FACTORS AND LEVELS SELECTED FOR STUDY

Factor	Level: Low		Level: Medium		Level: High	Variable Type
A - Compactive effort	Low		-		High	Qualitative
B - Compaction type	Impact		-		Gyratory shear	Qualitative
C - Curing procedure	Air-dried		-		Sealed	Qualitative
D - Molding water content, % by weight	8	10	12	16	20	Quantitative
E - Lime content, % by weight	2		4		6	Quantitative
F - Curing temperature, °F	40		75		110	Quantitative
G - Curing time, weeks	2		4		6	Quantitative
H - Clay content, % by weight	15		50		100	Quantitative

refer only to main effects; rather, the interactions between the factors involved must be considered in order to predict tensile strength correctly.

The significant effects appear to be dominated by compactive effort, treatment type, and curing temperature, all of which appeared as main effects and occurred in many interaction effects. The most important of these factors was treatment type, which contained the confounded factors of water content and clay content. Evaluation of treatment type indicated that both water content and clay content were important and that they also interacted to produce a significant effect.

Detailed Study

The results from a more detailed study were reported in Ref 14. The primary purpose of this study was to determine more closely the nature of the effects on tensile strength produced by the more important factors.

Experimental Program. A design was selected which provided an economical means of studying the curvilinear, interaction, and main effects of a number of factors. This design consisted of a 2^5 full-factorial with 32 cells, ten star points, and six center points. The factors and levels are given in Table 6.

The tensile strength and horizontal failure deformation values were recorded and analyzed for 48 specimens.

Results of Detailed Study. All five factors included in the study, compactive effort, lime content, clay content, molding water content, and curing temperature, had a significant effect on the indirect tensile strength, either as a main effect or as an interaction. The quadratic effects, interactions, and main factors which affected the tensile strength of the lime-treated materials were

(1) quadratic effects
   (a) curing temperature
   (b) molding water content
(2) interactions
   (a) curing temperature x clay content
   (b) molding water content x clay content
   (c) molding water content x curing temperature
   (d) lime content x curing temperature

TABLE 6. FACTORS AND LEVELS IN THE FACTOR EVALUATION EXPERIMENT

Factor	Level -2	-1	0	+1	+2
Compactive effort, blows per layer*	75	100	125	150	175
Molding water content, %	8.0	10.5	13.0	15.5	18.0
Lime content, %	0.0	1.5	3.0	4.5	6.0
Curing temperature, °F	50	75	100	125	150
Clay content, %	25.0	37.5	50.0	62.5	75.0

*18-inch drop, 10-lb hammer.

(3) main effects

(a) curing temperature

(b) lime content

(c) compactive effort

(d) molding water content

As previously observed, the indirect tensile strength was increased by

(1) increasing the curing temperature,

(2) increasing the lime content, and

(3) increasing the compactive effort.

In addition, it was found that the strength increase associated with increased curing temperature was greater in the higher temperature ranges. It was also observed that strength was maximum at an intermediate molding water content and that, therefore, there appeared to be an optimum molding water content for strength, as expected.

Probably the most important factor affecting the indirect tensile strength was curing temperature. It produced the largest main effect, as shown by the analysis of variance. In addition, it was found to produce a significant quadratic effect and appeared in three out of the four significant two-factor interactions.

An equation containing ten variables that predicts the indirect tensile strength for any combination of the levels of the independent variables resulted from the regression analysis. This regression equation had a multiple correlation coefficient of 0.94 and a standard error of estimate of 4.03 psi.

The factors and interactions which produced highly significant effects on the vertical failure deformations of lime-treated materials were

(1) quadratic effects

(a) molding water content

(b) clay content

(2) main effects

(a) molding water content

(b) lime content

No interaction effects were found to be significant and only three of the five factors studied, lime content, clay content, and molding water content, were significant as either a main or a quadratic effect.

The factors and interactions which produced highly significant effects on the horizontal failure deformations of lime-treated materials were

(1) quadratic effect - lime content

(2) interaction effect - clay content x molding water content

(3) main effects

   (a) clay content

   (b) lime content

TENSILE PROPERTIES OF CEMENT-TREATED MATERIALS

In addition to the preliminary and detailed experimental investigations, an analysis was conducted in which tensile strength characteristics were related to the shrinkage and shrinkage cracking characteristics. As a result of the latter analysis, recommendations concerning the construction of cement-treated bases and subbases were made and modifications to the currently used THD mixture design procedure were recommended for the purpose of improving tensile strength and minimizing shrinkage cracking.

Preliminary Experiment

The purpose of the preliminary experiment, which was reported in Report 98-3, was to evaluate the factors and the interactions between them which significantly affect the tensile characteristics of cement-treated materials and to develop a preliminary regression model which could be used to predict the tensile strength of cement-treated materials.

Experimental Program. On the basis of a literature review, nine factors were selected for evaluation. The effects of these nine factors and of the interactions between these factors were evaluated by using a fractional-factorial experiment design involving the nine factors at two levels. In addition, for five of these factors a midpoint level was introduced to allow nonlinear effects to be investigated. The factors and levels investigated are shown in Table 7.

With these factors and levels, an experiment involving 180 specimens was conducted. Each specimen was tested in indirect tension and the tensile strengths were recorded and analyzed in Report 98-3 (Ref 13).

TABLE 7. FACTORS AND LEVELS SELECTED FOR THE EXPERIMENT

Factor	Level		
	Low	Medium	High
Molding water content, %	3	5	7
Curing time, days	7	14	21
Aggregate gradation	Fine	Medium	Coarse
Type of curing	Air dried	-	Sealed
Aggregate type	Gravel	-	Limestone
Curing temperature, °F	40	75	110
Compactive effort	Low	-	High
Type of Compaction	Impact	-	Gyratory shear
Cement content, %	4	6	8

Results of Preliminary Study. Based on the results of the study, the following conclusions were drawn:

(1) There were seven main effects, eleven two-way interactions, two three-way interactions, and one four-way interaction which had a significant effect on the tensile strength of cement-treated materials. In addition, it was felt that these highly significant effects were, for the most part, of practical significance to the engineer.

(2) The large number of interactions significant at a probability level of 0.01 indicate the complexity of the relationships between tensile strength and the factors involved.

(3) Since there are a large number of interactions which have a significant effect on the tensile strength of cement-treated materials, it is not adequate to consider only the main effects; rather, the interactions between the factors involved must be considered in order to predict tensile strength.

(4) In general, it was found that the tensile strength was increased by

  (a) increasing the molding water content from 3 to 7 percent,

  (b) using sealed rather than air-dried curing,

  (c) increasing the cement content from 4 to 8 percent,

  (d) using crushed limestone rather than rounded gravel aggregates,

  (e) using a high compactive effort,

  (f) curing for 20 rather than 7 days, and

  (g) using impact compaction rather than gyratory shear compaction.

(5) Molding water content was the most important factor affecting the strength of the cement-treated materials, since it was a highly significant main effect and was involved in six of the eleven highly significant two-way interaction effects.

(6) In general, any factor which could be expected to increase the strength of the cement matrix or improve the bond between the cement matrix and soil particles resulted in increased strengths.

(7) Significant nonlinear effects were produced by molding water content, cement content, and curing time.

Detailed Experiment

Based on the findings of the preliminary experiment, a second experiment was designed and conducted to determine the nature of the effects on tensile strength produced by the more important factors.

Experimental Program. In order to study the curvilinear, interaction, and main effects of the factors affecting the tensile properties of cement-treated materials with a minimum number of observations, a statistical design composed of a 2^6 full-factorial was selected, including 20 star-point specimens and 12 center-point specimens. The factors and levels utilized in the experiment are presented in Table 8.

The failure loads and horizontal and vertical failure deformations, along with densities and water contents at the time of testing, were recorded.

Results of Detailed Study. Four of the factors included in the main experiment investigation, cement content, aggregate type, molding water content, and curing temperature, had a significant effect on the indirect tensile strength, as either a main effect or an interaction. The factors studied that did not enter the analysis of variance were aggregate gradation and compactive effort. The tensile strengths were increased significantly, as expected, by the following main effects:

(1) increasing the cement content;

(2) using crushed limestone aggregate rather than rounded gravel;

(3) increasing the molding water content to some optimum value, above which increasing the water content decreased the strength; and

(4) increasing the curing temperature.

However, the interaction of the factors investigated proved to be more informative. Two of the three significant interactions, cement content x aggregate type and molding water content x aggregate type, indicated that the tensile strengths for limestone specimens were not only higher but were also affected to a greater extent than the rounded gravel specimens.

The third significant interaction, molding water content x cement content, indicated the need for an adequate amount of water for the proper hydration of portland cement. In addition, a significant quadratic effect was detected, which indicated that there was an optimum water content for the strength of the materials tested.

From these main effects and interactions, a predictive equation was developed to estimate tensile strengths; it accounts for 96.4 percent of the observed variations within an estimated error of ±29.0 psi.

APPLICATION OF RESULTS

Since it has been well established that tensile stresses are created due to traffic loads and shrinkage and that cracking will occur if these tensile stresses exceed the tensile strength of the cement-treated material, an attempt was made to analyze tensile strength information obtained in the two experimental

TABLE 8. EXPERIMENTAL FACTORS AND LEVELS

Factor	Level -2	Level -1	Level 0	Level +1	Level +2
Molding water content, %	4.0	5.25	6.5	7.75	9.0
Aggregate gradation	Fine	Fine +	Medium	Medium +	Coarse
Curing temperature, °F	50	75	100	100	150
Compactive effort*	60	85	110	135	160
Cement content, %	2	4	6	8	10
Aggregate type		Seguin gravel		Crushed limestone	

*Gage pressure on Texas Highway Department gyratory shear compactor for 4-inch-diameter specimens.

studies, to relate this information to the findings from studies concerned with shrinkage and shrinkage cracking of cement-treated materials, and to develop a procedure for incorporating tensile strength considerations in the design of cement-treated materials.

The effects on tensile strength produced by eight factors previously shown to be important are analyzed in detail and effects are evaluated in terms of their significance and relationship to shrinkage cracking of cement-treated materials. These factors included type of soil, cement content, molding water content, density and compactive effort, and curing conditions.

It was concluded that there was an optimum water content which produced maximum tensile strength and minimum shrinkage cracking for a given soil type and cement content. It was also found that the tensile strength increased and cracking decreased with a decrease in the amount of cohesive material in the mixture, an increase in cement content, sealed curing, and extended curing periods.

Based on these evaluations, a modification of the Texas Highway Department mix design procedure was proposed. This modification involved the determination of the compaction water content which would produce maximum tensile strength for a given cement content. In addition, recommendations regarding the construction of cement-treated bases and subbases for improved tensile strength and reduced shrinkage cracking were made.

MIX DESIGN

The design of cement-treated mixtures is concerned with establishing the cement content, the molding water content, and the compactive effort which will result in a material with sufficient strength and durability to resist load and environmental stresses.

It is, therefore, suggested that additional tests be added to the mix design procedure currently used by the Texas Highway Department. The present mix design procedure requires that a cement content be chosen which will produce a minimum average compressive strength of 650[1] psi at the age of seven days.

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[1] An unconfined compressive strength of 650 psi corresponds with an indirect tensile strength of approximately 75 psi, according to the correlations reported in Ref 1.

Normally, three test cylinders are prepared, cured, and tested in accordance with test method Tex-120E (Ref 14) for each of the following cement contents: 4 percent, 6 percent, and 8 percent. From these tests, the cement content required to produce a cement-treated base material with a seven-day compressive strength of 650 psi is determined by the engineer.

Procedure for Supplementary Tests

In addition to specimens prepared as a part of the above procedure, it is recommended that supplementary specimens be prepared to determine the cement content and molding water content which will produce maximum tensile strength. The following steps may be used to establish a cement content and compaction water content which will improve tensile strength and reduce shrinkage cracking. Since this procedure is a supplement to that used by the Texas Highway Department, its use is intended for those soil types currently specified in Texas Highway Department specifications (Ref 21). Generally, good quality granular materials are economically available in the State of Texas and, for a mix design involving these materials, cement contents of 4 percent, 6 percent, and 8 percent should be used in preparing the supplementary specimens (step 1 below). However, if it should become necessary to use other materials, the cement contents contained in Table 9 are suggested as reasonable guidelines for initiating the supplemental procedure. The figures referred to in the following steps are hypothetical relationships which may serve to clarify the mix design procedure.

(1) Determine the optimum water content for maximum density for the material with 6 percent cement content. Optimum water contents for 4 and 8 percent may be estimated from the following relationship (Ref 14):

$$W = W_m + 0.25(C - C_m) \tag{1}$$

where

W = estimated optimum holding water content (percent) for either the high or low level of cement content;

W_m = the optimum moisture content (percent) for the middle level of cement content, determined from the moisture-density curve;

TABLE 9. CEMENT REQUIREMENTS OF AASHO SOIL GROUPS (Ref 22)

AASHO Soil Group	Physical Description	Usual Range in Cement Requirement		Estimated Cement Content and that used in Moisture-Density Test, Percent by Wt	Cement Contents for Wet-Dry and Freeze-Thaw Tests, Percent by Wt
		Percent by Vol	Percent by Wt		
A-1-a	Gravel and sand	5-7	3-5	5	3-5-7
A-1-b	Coarse sand	7-9	5-8	6	4-6-8*
A-2	Silty or clayey gravel and sand	7-10	5-9	7	5-7-9
A-3	Uniform sand, nonplastic	8-12	7-11	9	7-9-11
A-4	Sandy loam	8-12	7-12	10	8-10-12
A-5	Silt and clay loam	8-12	8-13	10	8-10-12
A-6	Lean clay	10-14	9-15	12	10-12-14
A-7	Fat clay	10-14	10-16	13	11-13-15

*These cement contents conform with those recommended by the Texas Highway Department (Ref 21).

C = the high or low level of cement content (percent); and

C_m = the middle level of cement content (percent).

(2) For each cement content, mold duplicate specimens at optimum water content and at water contents which are 1 percent, 2 percent, and 3 percent below the optimum value. Compaction and curing procedures are as outlined in test method Tex-120E (Ref 14). One of the duplicate specimens should be tested in compression (Tex-120E) and one in indirect tension.

(3) For each cement content, plot the relationships between unconfined compressive strength and molding water content (Fig 8a) and between indirect tensile strength and molding water content (Fig 8b).

(4) From the relationships between compressive strength and molding water content, estimate the cement content which provides an unconfined compressive strength of 650 psi (Fig 8a).

(5) Using the relationships between indirect tensile strength and molding water content, determine the water content which provides maximum tensile strength for the cement content determined in step 3 (Fig 8b).

(6) Insure that the water content determined in step 4 still provides for a minimum of 650 psi compressive strength at the cement content established in step 3. If the minimum compressive strength requirement has been met, then a mix design has been obtained which should give maximum tensile strength for the given cement and water content while meeting current specifications for minimum compressive strength. If the molding water content which gives maximum tensile strength appears to cause compressive strength to drop below 650 psi, then the cement content should be increased by one-half percentage point and the steps repeated, beginning with step 3. This iteration should be carried out until a mix design is obtained which gives maximum tensile strength and a minimum of 650 psi unconfined compressive strength.

SUMMARY OF RECOMMENDATIONS

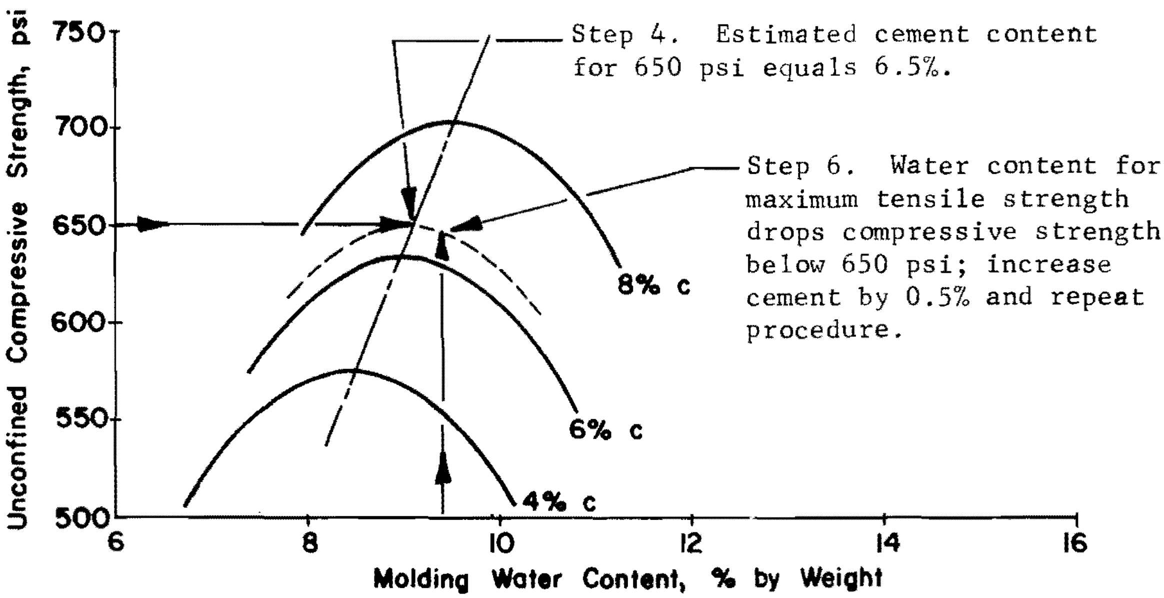
Materials

(1) A well-graded soil with a minimum of cohesive material should be used for cement-treated subbases whenever possible.

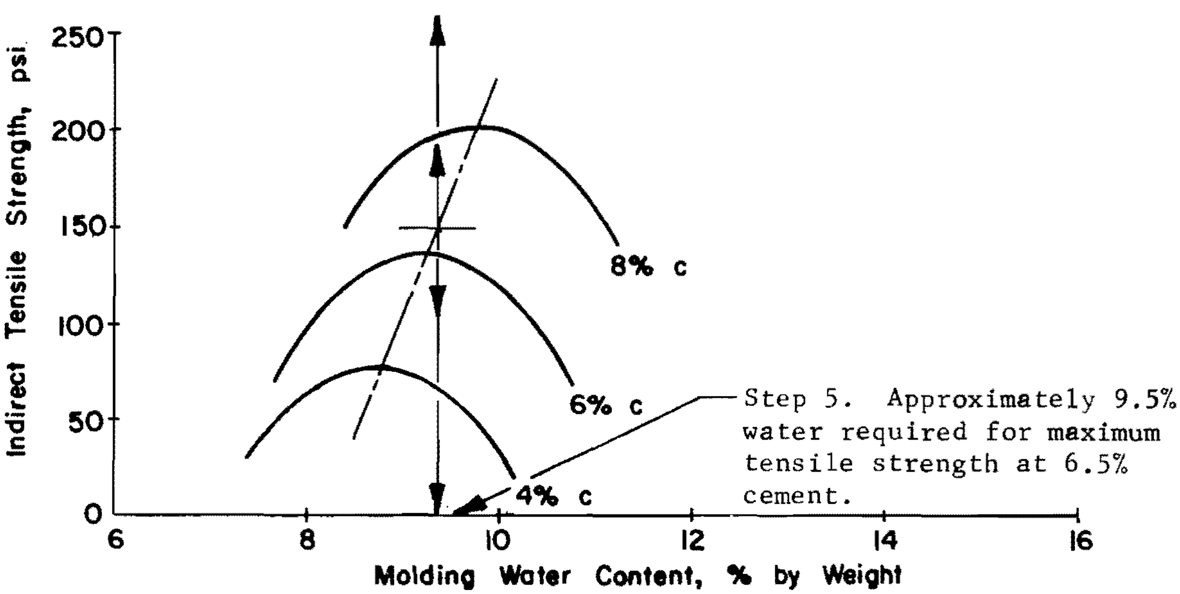
(2) If it is necessary to use a soil containing cohesive material, it is recommended that the clay content be limited to 8 percent for montmorillonite, 15 percent for kaolinite, and appropriately interpolated amounts of each if the soil contains both clay types.

(3) The soil should not contain aggregate larger than 1 inch nominal size.

(4) Type II cement should be used rather than Type I for the purpose of minimizing shrinkage cracking.



(a) Compressive strength versus molding water content.



(b) Tensile strength versus molding water content.

Note: Step 1. For illustrative purposes, assume that the optimum moisture content for maximum density was 10% for material with 6% cement. Equation 1 then gives estimated water contents of 9.5 and 10.5% for 4 and 8% cement, respectively. C = cement content.

Fig 8. Hypothetical relationships between compressive and tensile strengths and molding water content.

(5) Depending upon the clay content of the soil, it may be desirable to replace 1 or 2 percent cement with lime to minimize shrinkage.

Mix Design

It is recommended that the mix design procedure outlined in the preceding chapter be used to establish the required water and cement content for a cement-treated base or subbase. The procedure involves compaction on the dry side of optimum moisture for maximum density and results in minimum compressive strength of 650 psi and maximum tensile strength for the given water and cement content.

Construction and Curing

(1) Expected delays in compaction of the subbase should be taken into consideration when the moisture content of a cement-treated mixture is specified. The recommendation is that 2 to 4 percent excess compaction moisture be added if the time between mixing and compaction is greater than two hours and the soil is granular and if the delay is less than two hours and the soil is fine-grained.

(2) Cement-treated bases and subbases should be compacted to 95 to 100 percent of the density specified in test method Tex-113E (Ref 14).

(3) The cement-treated subbase should be sealed immediately after compaction and cured under sealed conditions for at least seven days in order to reduce the possibility of damage due to construction traffic and to reduce shrinkage cracking.

(4) A cement-treated subbase should not be constructed under extremely cold weather conditions. Current guidelines, which specify that the subbase not be mixed or placed when the air temperature is below 40° F and falling but may be mixed or placed when the air temperature is above 35° F and rising, appear to be satisfactory. Also, the subbase should be protected to prevent its freezing for a period of seven days after placement and until it has hardened.

FATIGUE OF STABILIZED MATERIALS

Since any rational pavement design and analysis procedure must ultimately consider the fatigue characteristics of the materials utilized in the pavement structure, a preliminary investigation was designed to study the use of the indirect tensile test to obtain fatigue information and to determine the general nature of the tensile-fatigue characteristics of asphalt-treated, cement-treated, and lime-treated materials (Ref 12).

The general objectives of this study were

(1) to determine whether or not the indirect tensile test can be used to study and evaluate the fatigue behavior of stabilized materials;

(2) to define the general nature of the relationships between applied tensile stress and the number of applications to failure, i.e., fatigue life, and to evaluate the inherent variations associated with the relationship;

(3) to evaluate the effect on fatigue life of certain mixture and compaction variables; and

(4) to investigate the possibility of estimating the fatigue life of stabilized materials subjected to repeated applications of a tensile stress, either by developing a predictive equation or establishing a correlation with other material characteristics.

Experimental Program

The factors and the levels of these factors, which were selected on the basis of the results from previous experiments concerned with the tensile characteristics of the three materials, are shown in Table 10.

The basic indirect tensile testing apparatus was a closed-loop electrohydraulic loading system. The actual loading device was a modified, commercially available die set with upper and lower platens constrained to remain parallel during the test. The load was controlled with a strain-gage type load cell and was alternately applied and released at a sinusoidal frequency of one cycle per second. All tests were conducted at a temperature of approximately 75° F. The basic parameter evaluated in this experiment was fatigue life, i.e., the number of applications of a given tensile stress required to cause a specimen to fail.

Findings from Fatigue Study

In Report 98-12 it was concluded that the indirect tensile test can be used to evaluate the fatigue properties of stabilized materials, and the general nature of the relationship between tensile stress and fatigue life was determined. It was found that the relationship between tensile stress and the logarithm of fatigue life was essentially linear for the asphalt-treated materials, increasing with decreasing tensile stress. However, the results for the cement-treated and lime-treated materials suggested that a critical stress level may exist, above which relatively short fatigue lives would occur and below which long fatigue lives would result.

Significant variation in fatigue life occurred for all three materials, and for the asphalt-treated materials the standard deviation varied linearly with the mean fatigue life, with the coefficient of variation ranging from 30 to more than 75 percent.

TABLE 10. FACTORS AND LEVELS SELECTED FOR EVALUATION

	Factor	Levels: Low (-1)	Medium (0)	High (+1)
Asphalt-treated	Aggregate type	Gravel		Limestone
	Asphalt cement type*	AC-5 (8.5)	AC-10 (9.1)	AC-20 (9.6)
	Asphalt content, % by wt. of total mixture	5.5	7.0	8.5
	Mixing temperature, °F	250	300	350
	Compaction temperature, °F	200	250	300
	Tensile stress, psi	16		32
Cement-treated	Aggregate type (stress levels)	Gravel (150 psi)		Limestone (300 psi)
	Cement content, % by wt. of aggregate	4	6	8
	Molding water content, % by wt. of aggregate and cement	5.25	6.5	7.75
	Compactive effort	85	110	135
	Curing temperature, °F	75	100	125
Lime-treated	Clay content, % by wt. of aggregate	37.5	50.0	62.5
	Lime content, % by wt. of aggregate and clay	1.5	3.0	4.5
	Molding water content, % by wt. of aggregate, clay, and lime	10.5	13.0	15.5
	Compactive effort	100	125	150
	Curing temperature, °F	75	100	125

*The asphalt cements are designated by the slopes of their logarithm temperature-logarithm viscosity relationships between 140° F and 275° F, which were constant in this temperature range.

The study of asphalt-treated materials indicated that fatigue life was affected by type of asphalt cement, asphalt content, compaction temperature, and mixing temperature. Within the range tested, fatigue life was increased by using a more viscous asphalt cement, higher compaction temperature, and higher mixing temperature. It was also concluded that there is an optimum asphalt content for maximum fatigue life. In addition, fatigue life was found to correlate with initial stiffness, initial tensile strain, and the tensile stress-strength ratio. No correlation was found between fatigue life and percent air voids, although such a correlation may exist for a given mixture. Even though associated with a large amount of variation, these correlations suggest that the tensile stress should be less than 10 percent of the static indirect tensile strength and that the initial strain should be less than about 50 microunits in order to obtain a satisfactory, i.e., relatively long, fatigue life.

Recommendations for Future Fatigue Studies

Research Report 98-2 is the only report concerned with the fatigue properties of stabilized subbase materials programmed within this research project. Although preliminary in nature, the conclusions reached in it on the basis of the analysis of the fatigue data collected clearly illustrate the need for conducting additional research within this area. Additional information on the fatigue characteristics of cement-treated and lime-treated materials is critically needed, and special emphasis should be placed on further investigation of what appeared to be critical stress levels. Other areas which need further research include the effects of frequency; environmental variables, i.e., those found under field conditions; controlled strain loading; and compound loading.

Because (1) information on the fatigue characteristics of stabilized materials is urgently needed to develop and improve rational design procedures, and (2) fatigue testing is time-consuming and expensive and a well-planned research effort requires a significant period of time, it is further recommended that additional tensile testing of stabilized materials be initiated immediately.

CHAPTER 4. DEVELOPMENT OF A DESIGN SYSTEM FOR STABILIZED PAVEMENT LAYERS

Although in recent years there has been an increase in the use of pavement involving one or more layers of stabilized materials, most pavement design methods do not provide for the structural design of stabilized layers, and, in fact, the thicknesses of these layers in some methods are 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 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. Therefore, a study was conducted to develop a design method for selecting the necessary thickness of each layer in a pavement structure to insure adequate tensile resistance to a large number of applications of vehicle loads (Ref 4).

The design system, which is based on the prevention of tensile failures in the surface and subbase layers of a pavement structure, 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 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, including a method for selection of a critical design thickness and practical solutions of the design equations through the use of nomographs.

DEVELOPMENT OF SYSTEM

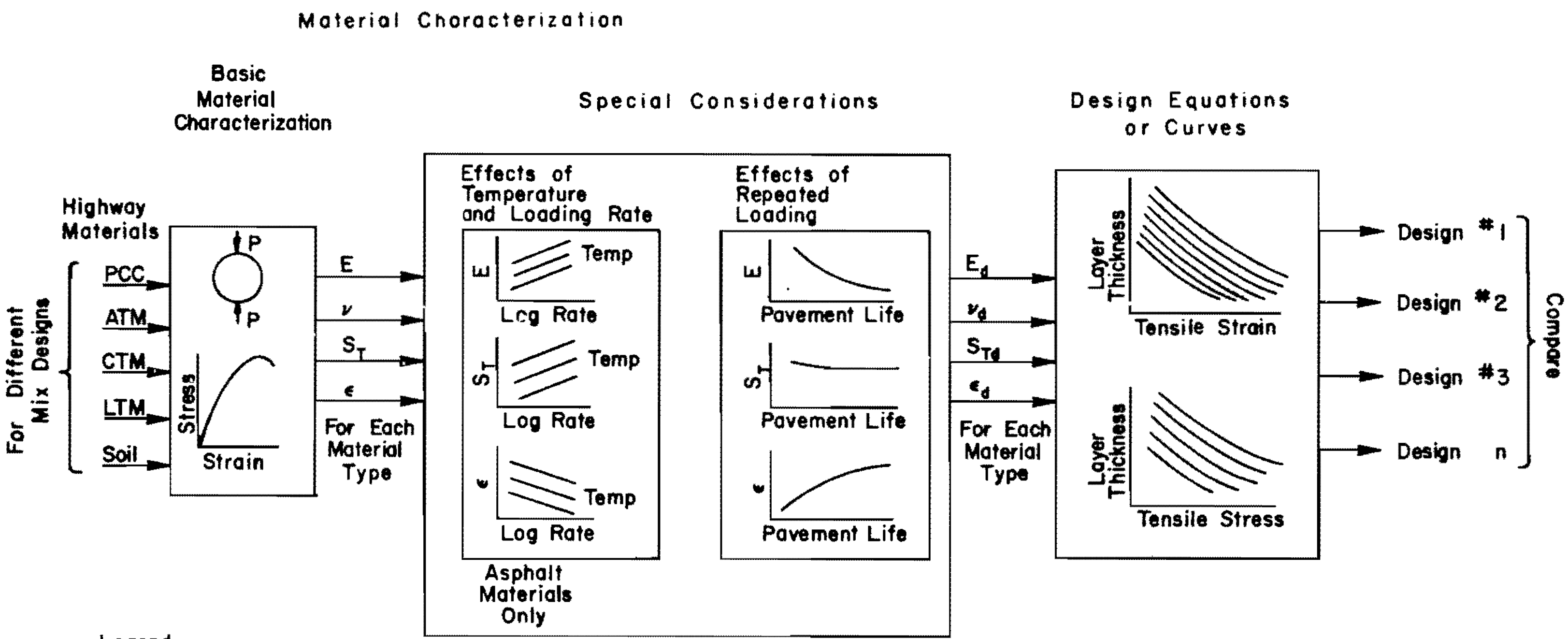
The design system described in Research Report 98-13 and outlined in the following paragraphs was developed for use in the design of stabilized pavement layers and is based on prevention of tensile failures.

The formalized design system is presented in Fig 9 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 in which 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.

Linear elastic layered theory was selected as the basic design theory in this design system. The hypothetical pavement design section adopted for this design system, illustrated in Fig 10, consists of three layers, i.e., a surface course, a subbase course, and the subgrade. The pavement is assumed



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

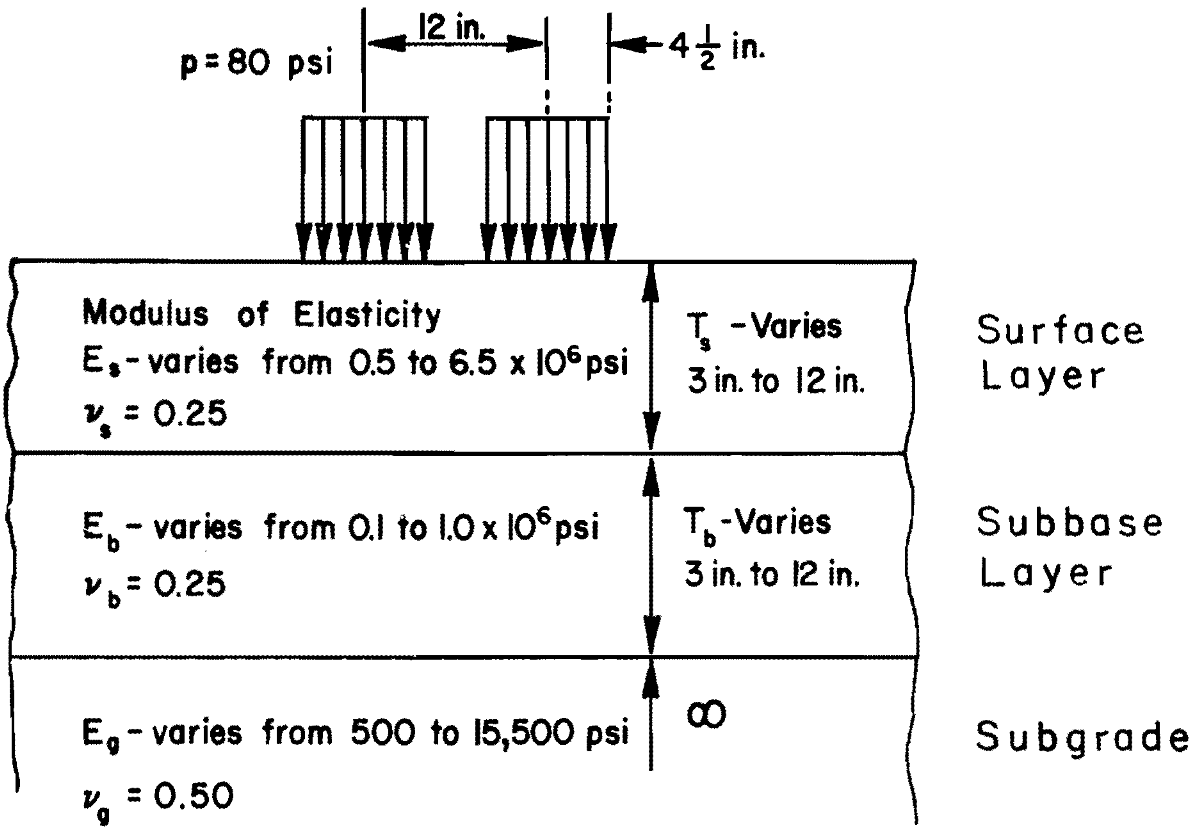


Fig 10. Hypothetical pavement section.

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.

Layered theory provides a deterministic model for predicting stresses, strains, and deflections in a given pavement system; however, it cannot be used directly for the structural design of the individual layers of a pavement system without time consuming and costly iterative solutions since the thicknesses of the layers are required as inputs. To overcome this shortcoming a simple mathematical model or algorithm 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 for various levels of the design variables. A stepwise regression technique was used to relate specific stresses and strains obtained from the computer program to the design variables listed in Table 11.

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 10 and Table 11. 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 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 80 psi. However, since the location of the maximum values varied from one design section to another, a survey of 28 different computer solutions was made to find the most likely location for each of the maximum stress and strain values. These locations were designated as shown in Fig 11 and Table 12 and were

TABLE 11. FACTORS AND LEVELS USED IN DEVELOPMENT OF DESIGN EQUATIONS

	Levels				
Variables	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	-

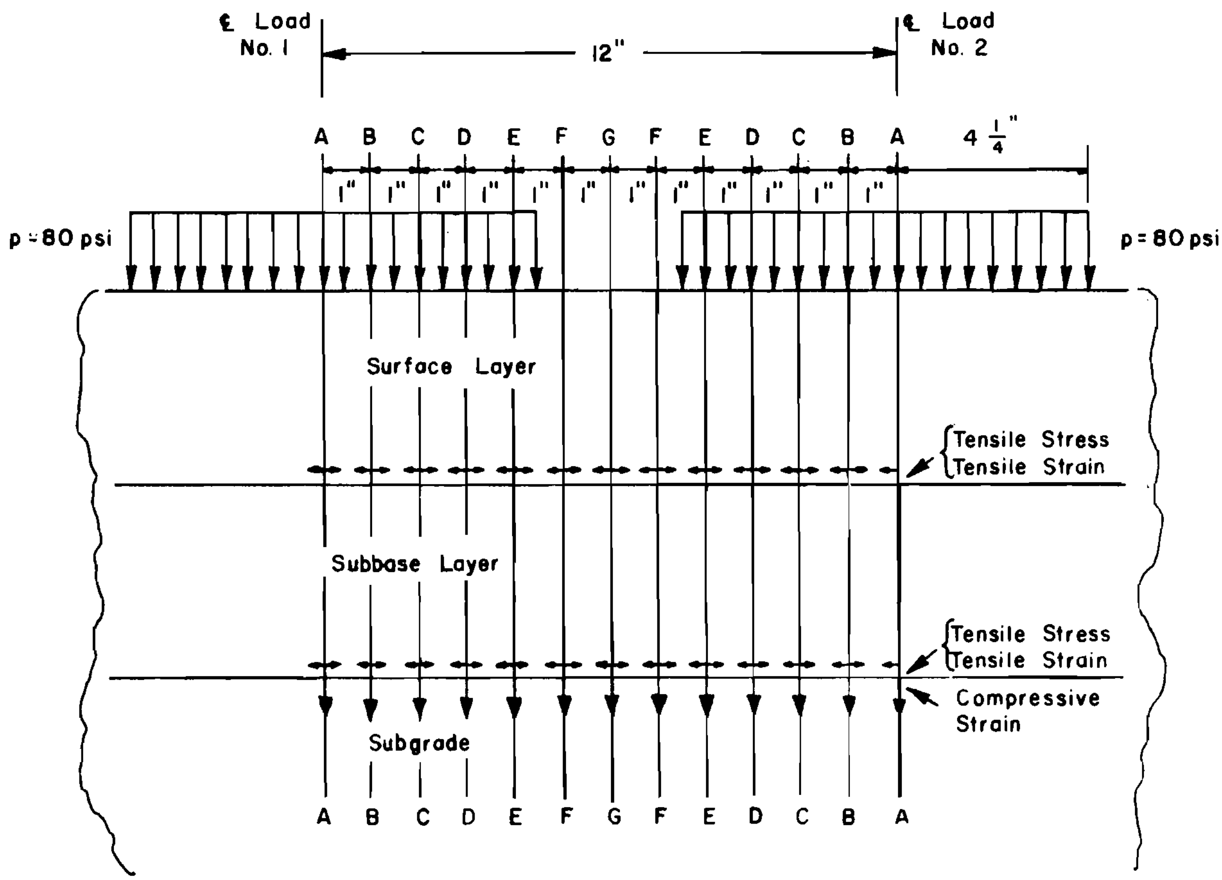


Fig 11. Scheme for selection of most likely location for maximum stresses and strains in the pavement layers.

TABLE 12. DESIGNATED LOCATIONS FOR SURVEY OF MAXIMUM STRESS AND STRAIN VALUES

Designated Location	Distance in Inches From Center Line of Load No. 1	Distance in Inches From Center Line 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

(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 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. Separate equations were obtained for low and high modulus layers, as indicated in Table 11, 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 6.5×10^6 psi are

<u>Tensile Stress in Bottom of Base Layer σ_b .</u>

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

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

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

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

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

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

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

<u>Tensile Strain in Bottom of Base Layer ϵ_b .</u>

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

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

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

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

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

$$+ 3.9517(E_b - 5.5)(T_s - 7.5) + 2.7973(T_s - 7.5)^2 \qquad (3)$$

Similar equations were developed for compressive strain in subgrade (ε_c), tensile stress in bottom of surface layer (σ_s), and tensile strain in bottom of surface layer (ε_s).

Design of Low Modulus Surface Layers

In order to simplify the overall procedure, a second set of similar equations was developed for low modulus materials. The regression equations for pavement structures with surface layers exhibiting modulus of elasticity values in the range of 0.5 to 3.5 x 10^6 psi are illustrated below for tensile stress and strain in the bottom of the base layer. Similar equations and criteria were developed for compressive strain in the subgrade and tensile stress and strain in the surface.

Tensile Stress in Bottom of Base Layer σ_b .

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

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

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

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

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

$$(T_s - 7.5) - 21.341(E_g - 8.0) + 1.7005(E_g - 8.0)^2 \qquad (4)$$

Tensile Strain in Bottom of Base Layer ϵ_b .

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

$$1614.23 - 60.373(T_s - 7.5) - 30.108(T_b - 7.5)$$

$$+ 3.1786(T_s - 7.5)(T_b - 7.5) - 81.580(E_s - 2.0)$$

$$- 8.9055(E_s - 2.0)(T_s - 7.5) - 50.011(E_b - 4.9)$$

$$+ 3.7758(E_b - 4.9)^2 + 2.7682(E_b - 4.9)(T_s - 7.5)$$

$$- 21.619(E_g - 8.0) + 1.7407(E_g - 8.0)^2 \qquad (5)$$

APPLICATIONS TO PAVEMENT DESIGN

Application of Design Equations

Because of the number of terms involved, each of the equations presented in this study (Ref 4) can best be solved using 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 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. 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.

Thickness Selection Procedure

The procedure for selecting a subbase thickness is illustrated in Fig 12 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 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.

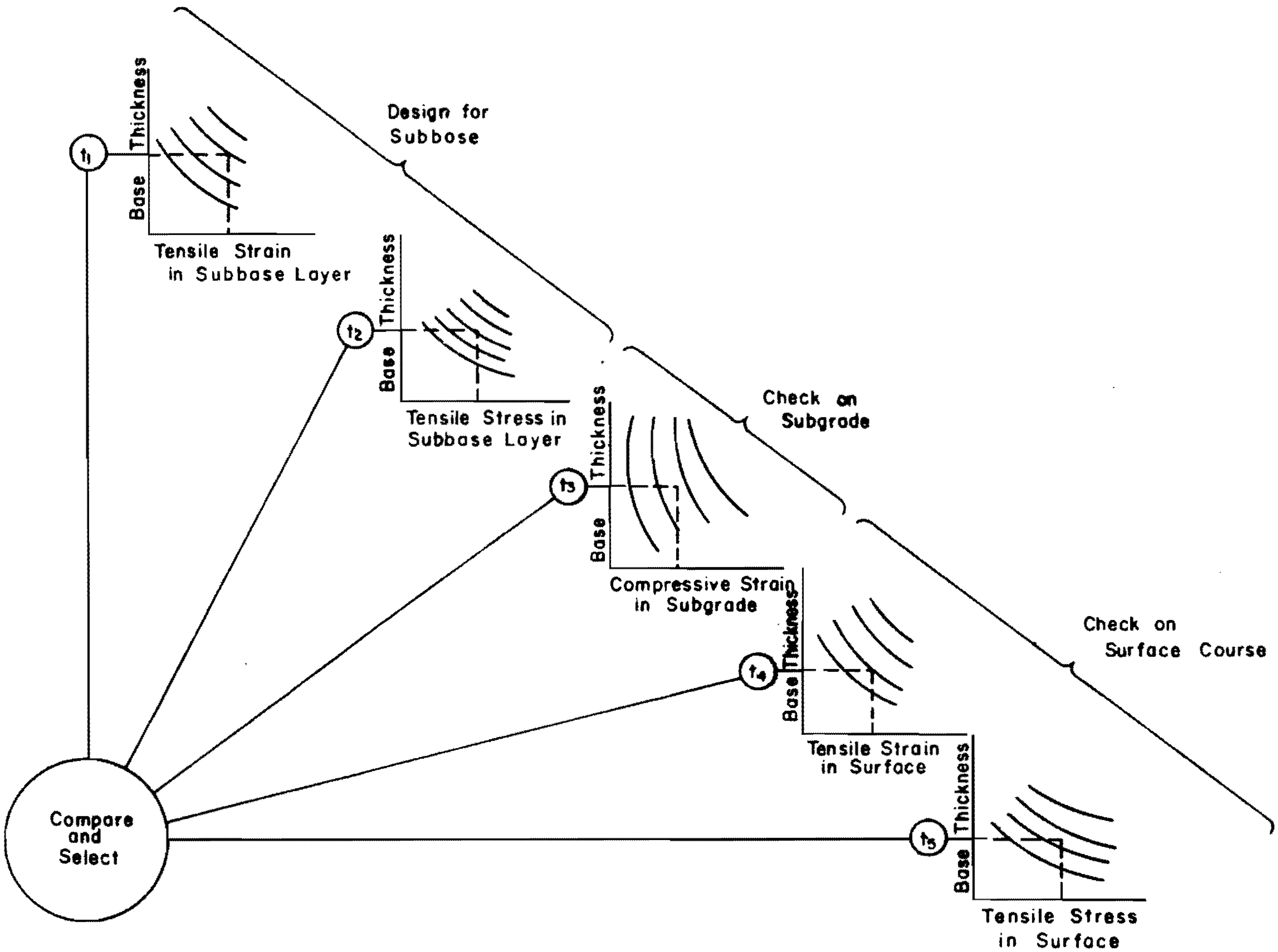


Fig 12. Process for selecting final base or subbase thickness.

SUMMARY OF THE PROPOSED DESIGN METHOD

In this chapter a formalized design system to prevent 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.

CHAPTER 5. SUMMARY

It is difficult to summarize six years of work on a complex research project such as this. In the next few pages, only the high spots related to the work in the project can be included. If detailed information is of interest, it can be obtained from the 13 other project reports (Refs 1-8, 10-13, and 15). An attempt is made in this chapter to summarize the major findings of the project and to state the general recommendations which have evolved as the work progressed. It is not possible in the space available to present a detailed summary of all the work accomplished.

FINDINGS

The findings of this project are numerous and complex. They are drawn from work conducted over a six-year period and dealing with a variety of test methods, materials, and other factors.

This chapter can only highlight the major findings of the project. The individual project reports should be consulted for more details on a particular aspect of a problem under consideration. Each of the general findings shown below is referenced to the particular research report where the work is reported and documented.

One of the early findings of the project indicated that the indirect tensile test was the most practical and useful method of obtaining or evaluating tensile properties of paving materials. A series of experiments conducted on other available tests supported this early evaluation.

In general, a methodology for using the indirect tensile test to evaluate tensile properties of stabilized materials has been developed in this project. Also, a method for estimating elastic properties of materials from the test has been developed, making the test even more useful to the pavement designer.

With the background developed early in the project, a series of evaluation experiments was run on asphalt-treated, lime-treated, and cement-treated materials, and a number of useful findings were uncovered which related the tensile properties of the stabilized materials to the physical characteristics of the component elements of the mix.

A large portion of the project activity was related to investigating the tensile properties of asphaltic cement and lime-treated materials, described in more detail in Chapter 3.

Another important finding of the project was that the indirect tensile test was simple enough for practical field utilization. As a result, methodology and equipment which were developed for the test could be easily adapted for use by the District laboratories (Ref 2).

A major outgrowth of the project has been the generalized design procedure for stabilized pavement layers presented in Ref 4. This design method was the major original objective of the project and fulfills that goal.

A major side-benefit of this project has been the findings related to the application of statistical methods to complex 13 and 14-factor problems. Three and four-factor interactions were often significant in the study, and physical evaluation seemed to support the validity of these interactions. As a result of this work, it is possible in civil engineering problems to utilize complex statistical methods to reduce the work load involved in making large complex experiments without sacrificing the information which comes from factorial analysis and random experimentation.

Future rational pavement design methods must take into account some aspects of fatigue or repeated loading of materials. Reference 12 presents the findings of a preliminary study of fatigue characteristics under the indirect tensile test for stabilized materials. While the findings to date are not broad or complete, they have generated followup work to answer more specific questions in Project 3-9-72-183, "Tensile Characterization of Highway Pavement Materials," being conducted at the Center for Highway Research under the auspices of the Texas Highway Department and the Federal Highway Administration.

From this general background of findings on Project 98, it is possible to develop the following specific findings which relate to the problems of the project.

<u>Indirect Tensile Test</u>

(1) The indirect tensile test is the best test currently available for determining the tensile properties of highway materials (Ref 10).

(2) While there are a number of approximations appropriate to the test as it is used for stabilized materials, none of these approximations seems to limit the utility of the method for stabilized materials (Ref 10).

(3) It was determined that estimates of the modulus of elasticity and Poisson's ratio could be obtained from the results of the indirect tensile test, either by evaluating overall deformations in the x and y directions or by evaluating center strains in the x and y directions on the specimen (Ref 5).

(4) Although, from an engineering viewpoint, the loading rate used in one indirect test had no practical significant effect on modulus values, the loading rate did have significant effect on the Poisson's ratio of the material. Some type of coordination of these test evaluations is needed (Ref 5).

(5) The modulus of elasticity and Poisson's ratio of stabilized materials can be estimated from the loads and deformations obtained from the indirect tensile test. Evaluation of these results seems to indicate that the measured properties are reasonably reliable (Ref 5).

(6) For the conditions of the experiments to date among the different mixtures, no precise correlation between density and modulus of elasticity or tensile strength of the asphalt-treated material was detected. Therefore, density differences alone cannot be used as a measure of expected change in tensile properties of the mix but must be accompanied by careful consideration of other factors involved in the mixture (Ref 8).

(7) A practical methodology for instrumenting and conducting the indirect tensile test by District laboratories of the Texas Highway Department was developed in this project (Ref 2).

(8) Although loading rate generally affects asphaltic materials, it was found that for the materials and test conditions used that from an engineering standpoint the loading rate had no practical effect on the test results (Refs 5 and 10).

<u>Asphalt-Treated Materials</u>

(9) Early work on asphalt-treated materials indicated complex relationships between the tensile strength and material properties, as outlined in Ref 6; more details of these findings are presented in subsequent reports.

(10) A series of tests on asphalt-treated materials indicated good correlations existed between indirect tensile test values such as modulus of elasticity, tensile strength, and tensile strain and values from the cohesiometer and stability tests (Ref 7).

(11) Five major factors were shown to affect the tensile properties of asphalt-treated materials (Ref 8). These factors which should be considered were

(a) compaction temperature,

(b) asphalt content,

(c) aggregate type,

(d) asphalt cement type, and

(e) aggregate gradation.

Cement-Treated Materials

(12) The large number of statistical interactions significant at a probability level of 0.01 percent in early tests on cement-treated materials indicate the complexity of the relationship between tensile strength and the material characteristics involved (Ref 13).

(13) Molding water content was the most important factor affecting the strength of cement-treated materials in the early experiments; it was a highly significant main effect and was involved in six of the eleven highly significant two-way interaction effects (Ref 13).

(14) In general, it was found that the tensile strength of cement-treated materials was increased by

(a) increasing the cement content,

(b) using crushed aggregate,

(c) increasing the water content up to optimum, and

(d) increasing the curing temperature.

A number of significant two and three-factor interactions were present in the experiment (Ref 1).

(15) Comparison of the relationship between the indirect tensile strength and the cohesiometer value indicated a good correlation between these two methods of evaluating tensile strength of cement-treated materials. The correlation between tensile strength and unconfined compressive strength was only fair, as would be expected (Ref 1).

(16) A small series of tests comparing the tensile properties of 4 and 6-inch-diameter specimens of cement-treated materials which otherwise had equivalent properties indicated no effect of specimen diameter on the test results (Ref 1).

Lime-Treated Materials

(17) Early experiments with lime-treated materials indicated an extremely large number of significant main effects and interactions. Since there are a large number of interacting effects, it is not adequate to consider only the main effects when evaluating properties of lime-treated materials (Ref 11).

(18) In second-stage testing of lime-treated materials, indirect tensile strength was found to be increased by

(a) increasing the curing temperature,

(b) increasing the lime content, and

(c) increasing the compactive effort.

Probably the most important factor affecting the indirect tensile strength was curing temperature. It produced the largest main effect, as shown by the analysis of variance. It also was found to produce a significant quadratic effect and appeared in three of the four significant two-factor interactions (Ref 15).

(19) It was found that specimen size does not have a significant effect on indirect tensile strength of lime-treated materials. This finding is in general agreement with previous theoretical and experimental evaluations of size effects (Ref 15).

Fatigue Behavior

(20) In general, the indirect tensile test was shown to be quite applicable to the study of the fatigue characteristics of asphalt-treated, cement-treated, and lime-treated materials subjected to repeated applications of tensile stress (Ref 12).

(21) The relationship between tensile stress and the logarithm of fatigue life was essentially linear, as expected. Fatigue failures occurred at indirect tensile stresses ranging from 8 to 40 psi. These were approximately 6 to 30 percent of the static indirect tensile strengths of the materials (Ref 12).

(22) There was significant random variation in the fatigue life tests; however, this was not unexpected since fatigue life for even homogeneous materials often varies significantly (Ref 12).

(23) The tensile fatigue life characteristics of asphaltic materials were found to be affected by the

(a) type of asphaltic cement,

(b) asphalt contents,

(c) compaction temperature, and

(d) mixing temperature.

It was concluded from the test that there is an optimum asphalt content for maximum fatigue life for any particular set of material characteristics (Ref 12).

(24) For both cement-treated and lime-treated materials, the relationship between tensile stress and the logarithm of fatigue life appeared to exhibit a critical stress level, above which the fatigue life was very short and below which the fatigue life was very long (Ref 12).

(25) A number of difficulties in the experiment were associated with the fatigue testing of both lime-treated and cement-treated materials. This makes it highly desirable to conduct additional tests before further conclusions can be made (Ref 12).

Subbase Design System

(26) Based on the findings of the project to date, it has been possible to develop a generalized design method for all types of stabilized layers for use with both portland cement concrete and asphaltic concrete pavements. This method has been adapted for computer design and nomographic design methods in order that it may be more generally applied by field design personnel (Ref 4).

PROJECT RECOMMENDATIONS

Throughout this project, a number of specific recommendations have been included in the individual reports (Refs 1-8, 10-13, and 15) and in the project proposals submitted to the Texas Highway Department and the Federal Highway Administration each year. Many of these recommendations are related to subsequent work within the project and most of them have been subsequently accomplished. The following recommendations made at this time, at the end of the project, are limited to general recommendations concerning the indirect tensile test and its implementation for use by the Texas Highway Department.

(1) It is recommended that the Texas Highway Department continue the development of practical methods for utilizing the indirect tensile test in each of its field laboratories. This will make it possible to evaluate the tensile properties of pavement materials, particularly stabilized materials, for better utilization of these properties in pavement design.

(2) It is recommended that material specifications for pavement materials contain a tensile strain requirement and that the test to be used for evaluation of this tensile strength be the indirect tensile test.

(3) It is recommended that a series of fatigue or repeated-load tests be conducted on pavement materials in a subsequent research project in order to develop relationships between fatigue life as a measure of performance and tensile strength as a measure of predicted behavior of materials.

(4) It is recommended that the tentative stabilized layer design procedure developed in Report 98-13 be implemented by one or more user agencies to provide a method for evaluating the technique. It is then recommended that the method be revised as necessary and implemented into the flexible pavement design system (FPS) which is currently being evaluated for use by the Texas Highway Department.

(5) It is recommended that the Texas Highway Department Materials Testing Laboratories begin to utilize tensile strength as the criterion for selecting mix design characteristics of paving materials of all types. Test procedures can be provided with the indirect tensile test.

(6) Finally, it is recommended that whenever practical, additional verification of the relationships between the indirect tensile test and various materials properties be sought as a part of routine laboratory tests or subsequent research projects, in order to reinforce or modify the findings of this project to get better pavement design and performance for the Texas Highway Department and the Federal Highway Administration.

CHAPTER 6. IMPLEMENTATION

Implementation is an important part of any worthwhile research effort. Throughout this project, the need for implementation has been kept in mind by the research staff. Implementation has ranged from the immediate application of the tensile testing technique to field problems for the Abilene District in 1969 to the development of a practical method of applying the indirect tensile test for use in the District laboratories, as reported in Report 98-10. This testing method is currently being implemented in a number of the District laboratories by the staff of Research Project 183.

Specifically, important aspects of implementation of the results of Project 98 involve three major areas:

(1) implementation of findings from this project,

(2) utilization of the indirect tensile test in design and construction of pavements, and

(3) utilization of the test techniques for further research on material behavior and performance.

Specific items which should be considered for immediate implementation include the following:

(1) This project has developed a relatively simple, inexpensive method for evaluating the tensile properties of stabilized materials of all types. All materials testing elements of the Highway Department should be encouraged to obtain the necessary equipment to perform the test in order that other important aspects may be subsequently implemented.

(2) Tensile strength and material properties should be utilized in mix design procedures for stabilized materials. This should include evaluation of the behavior of the material, its cost, and optimum combinations of stabilizing components.

(3) Given available mix designs, the elastic properties of the material should be obtained from the indirect tensile test and should be used in the design of stabilized layer thickness and configuration for use in portland cement concrete and asphalt concrete pavements. The method outlined in Research Report 98-13 should be implemented as a part of FPS and RPS pavement design methods (Refs 16-20).

(4) Through use of the indirect tensile test for design, material specifications should be revised to require adequate tensile strength in appropriate pavement layers.

(5) Construction control methods should be developed utilizing the rapid and simple indirect tensile test to provide construction control parameters to insure that adequate tensile strength, as specified, is obtained within reasonable statistical limits.

(6) The indirect tensile test can be used as a tool for evaluating materials on in-service pavements where evaluation of these pavement systems is desirable for upgrading or prediction of future performance. Such feedback data can assist in the improvement of pavement design methods for the Highway Department.

(7) Use of the tensile test as a research tool should continue where needed. In particular, a series of fatigue tests on various types of stabilized materials should be inaugurated as soon as possible to develop the information needed relating material design properties to the fatigue or performance characteristics observed.

(8) Finally, a series of findings related to various aspects of the properties of stabilized materials has been developed in the various research reports produced on this project. These reports should be made available to laboratory and design engineers through a series of conferences, schools, or short courses to familiarize them with the aspects of tensile testing as applied to mix design, construction, and control. A number of the general findings could be immediately useful. As an illustration, it was found that the compaction temperature was very critical in determining the tensile strength of asphalt mixes. At the present time, there is no control exercise in the field on the temperature of the asphaltic concrete for the bituminous stabilized materials at the time of compaction. Due to this lack of temperature control, there is undoubtedly a wide variation in the tensile strength properties of the material in place. The strength variations will result in decreased pavement life. With little additional expense, the compaction temperature could be monitored by construction inspectors to insure that adequate tensile strength is obtained from the compacted mixture. This same type of relationship is found with the amount of mixing water available to cement-treated and lime-treated materials and, likewise, inadequate control is often provided.

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