TENSILE BEHAVIOR OF SUBBASE MATERIALS UNDER REPETITIVE LOADING

by

Raymond K. Moore
Thomas W. Kennedy

Research Report Number 98-12

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

October 1971

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Federal Highway Administration.

PREFACE

This is the twelfth report in the series dealing with research findings concerned with the evaluation of the tensile properties of stabilized subbase materials. This report summarizes the results of a study of the fatigue properties of asphalt-treated, lime-treated, and cement-treated materials subjected to repeated tensile stresses using the indirect tensile test. It was concluded that the indirect tensile test can be used to determine the fatigue properties of stabilized materials. The general nature of the relationships between tensile stress and fatigue life for all three materials is described In addition, the effects produced by certain mixture and compaction variables on the fatigue characteristics of asphalt-treated materials are summarized, and the results of an attempt to correlate fatigue life with other material properties and to develop predictive equations for estimating fatigue life for the asphalt-treated materials are included.

This report is a product of the combined efforts of many people. The assistance of the Texas Highway Department contact representative, Mr. Larry Buttler, is appreciated, and the support of Mr. George W. Ring of the Federal Highway Administration is gratefully acknowledged. Special appreciation is extended to Messrs. Pat Hardeman and James N. Anagnos for their assistance in the test program, and to Messrs. William O. Hadley and Joseph A. Kozuh for their suggestions concerning the design and analysis of the experimental data. Thanks are also due to the research and editorial staff of the Center for Highway Research.

Future reports will be concerned with

(1) a preliminary layered-system design method,

(2) a summary of previous work on lime-treated materials, including recommendations concerning the mixture design and construction of lime-treated materials and layers, and

(3) the final report for the project.

Raymond K. Moore
Thomas W. Kennedy

October 1971

LIST OF REPORTS

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

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

Report No. 98-3, "Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials," by Humberto J. Pendola, Thomas W. Kennedy, and W. Ronald Hudson, presents factors important in determining the strength of cement-treated materials.

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

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

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

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

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

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

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

ABSTRACT

Results of a study of the fatigue characteristics of asphalt-treated, cement-treated, and lime-treated subbase materials indicated that the indirect tensile test can be used satisfactorily to evaluate the fatigue properties of treated materials under repeated tensile stresses. In addition, the general nature of the relationship between applied tensile stress and fatigue life was determined along with the inherent variation associated with fatigue life of asphalt-treated materials. For the asphalt-treated materials, the relationships between tensile stress and log fatigue life were essentially linear, with failures occurring at tensile stresses ranging from 8 to 40 psi, which were approximately 6 to 30 percent of the static indirect tensile strength. Significant variation in fatigue life occurred, and it was found that the standard deviation varied linearly with the mean fatigue life, with the coefficient of variation ranging from 30 percent to more than 75 percent. Results concerning the fatigue life relationship for the cement-treated and lime-treated materials suggest that there is a critical stress level above which the fatigue life is very short and below which the fatigue life is very long.

The tensile fatigue characteristics of asphalt-treated materials were found to be affected by type of asphalt cement, asphalt content, compaction temperature, and mixing temperature. Within the range tested, it was found that 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, a simple predictive equation was developed which adequately described the fatigue life of the specimens tested. The fatigue life of the asphalt-treated materials was found to correlate with initial stiffness, initial tensile strain, and the ratio between tensile stress and strength, but these correlations were associated with a large amount of variation. No correlation was found between fatigue life and percent of air voids.

SUMMARY

This report summarizes the findings of an experimental program designed to evaluate the tensile and behavioral characteristics of asphalt-treated, cement-treated, and lime-treated materials subjected to repeated tensile stresses by means of the indirect tensile test. The objectives of the study were

(1) to determine whether the indirect tensile test can be used for the study of the behavior of treated materials subjected to repeated tensile stresses;

(2) to define the general nature of the relationship between applied tensile stress and fatigue life and to evaluate the effect on fatigue life of certain mixture and compaction variables; and

(3) to investigate the possibility of estimating the fatigue life of asphalt-treated, cement-treated, and lime-treated materials subjected to repeated applications of a tensile stress, either by developing a predictive equation or by establishing a correlation with other material characteristics.

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 studies of 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 it was found that the standard deviation varied linearly with the mean fatigue life, with the coefficient of variation ranging from 30 percent to more than 75 percent.

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 strains should be less than about 50 micro units in order to obtain a satisfactory, i.e., relatively long, fatigue life.

IMPLEMENTATION STATEMENT

Results from this study are preliminary in nature, and additional study is needed. Nevertheless, certain findings may have definite significance to construction using stabilized materials and the design of highway pavements.

The results from previous work conducted by this project indicated that compaction temperature had a significant effect on the behavioral characteristics of high-quality asphalt-treated mixtures, i.e., blackbase. It was found that both indirect tensile strength and modulus of elasticity were significantly larger when the mixture was compacted at a high temperature. The results obtained from the study of the fatigue properties of these materials also show that high compaction temperatures produce a material exhibiting a long fatigue life. Thus, consideration should be given to specifying a high compaction temperature and closely controlling the temperature of the mixtures during field compaction.

It was also found that a high viscosity asphalt cement and a high mixing temperature were important, and that there is apparently an optimum asphalt content for maximum fatigue life. This optimum may or may not correspond to the optimum asphalt content for maximum strength.

From the standpoint of pavement design, it was found that for the blackbase materials the relationship between tensile stress and the logarithm of fatigue life was linear, but that there was a considerable amount of variation associated with the data. The results also suggested that tensile stress should be less than about 10 percent of the tensile strength, and that the tensile strains produced by the first application of load should be less than about 50 micro units in order to have a relatively long fatigue life. In addition, it would appear that there is a fairly good correlation between fatigue life and the ratio of tensile stress and tensile strength. Thus, it may be possible to estimate fatigue life from the results of a static indirect tensile test.

TABLE OF CONTENTS

PREFACE iii

LIST OF REPORTS iv

ABSTRACT vi

SUMMARY vii

IMPLEMENTATION STATEMENT ix

CHAPTER 1. INTRODUCTION 1

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

Compacted Soil and Untreated Granular Materials 3
Asphalt-Treated Materials 4
Cement-Treated Materials 14
Lime-Treated Materials 20
Summary 22

CHAPTER 3. EXPERIMENTAL PROGRAM

Method of Test 24
Materials Investigated 26
Experiment Design 28
Specimen Preparation 29

CHAPTER 4. DISCUSSION OF RESULTS

Asphalt-Treated Materials 32
Cement-Treated Materials 48
Lime-Treated Materials 51

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Conclusions 56
Recommendations 57

REFERENCES 59

APPENDICES

Appendix 1. Batching and Mixing Procedures 66
Appendix 2. Compaction Procedures 69
Appendix 3. Curing Procedures 72

THE AUTHORS 73

CHAPTER 1. INTRODUCTION

The increased use of stabilized subbases as a part of rigid pavement structures has stimulated interest in developing a subbase design and analysis procedure. 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. As a part of this project the indirect tensile test was adopted and further developed to provide a test method which could be used to obtain estimates of tensile strength and tensile strain, modulus of elasticity, and Poisson's ratio for asphalt-treated, cement-treated, and lime-treated subbase materials. This test has been used and demonstrated to be applicable for the evaluation of the tensile characteristics of all three stabilized materials (Refs 3, 11-15, 17, 19, 20, 28, 38-40, 45, and 60).

Since any rational pavement design and analysis procedure must ultimately consider the fatigue characteristics of the materials utilized in the pavement structure, it was decided to gather such information by using the indirect tensile test. Thus, a preliminary investigation was designed to investigate 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.

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 relationship 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.

Chapter 2 contains a brief summary of the information currently available on the behavior of untreated soil and granular materials, asphalt and asphalt-treated materials, cement-treated materials including soil-cement, and lime-treated materials. Chapter 3 describes the experimental program in terms of the test, equipment, procedures, and experiment design. The findings of the study are discussed in Chapter 4 with emphasis placed on the evaluation of a high quality asphalt-treated subbase material similar to blackbase, which is used extensively in Texas. Conclusions and recommendations are summarized in Chapter 5.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

This chapter summarizes the current status of knowledge as obtained from the literature concerning the behavior of compacted soil and untreated granular materials under repetitive loading and the fatigue behavior of asphalt-treated aggregate mixtures, lime-stabilized materials, and cement-treated materials including soil cement.

COMPACTED SOIL AND UNTREATED GRANULAR MATERIALS

Although untreated soil and granular materials were not investigated as a part of this study, the findings from other investigations were evaluated and summarized in an attempt to gain a better understanding of the complex behavior of highway materials subjected to repetitive loading.

Compacted Soil

The majority of the available information concerning the behavior of compacted soil under repetitive loading was derived from studies conducted by Seed et al (Refs 37 and 47 through 55), in which compacted Vicksburg silty clay and other selected soils were subjected to repetitive triaxial loading. In addition, Lee (Ref 25) studied the behavior of pseudo-soil, which was oil-based modeling clay, under repetitive plate loadings; Lara-Thomas (Ref 22) studied the effect of repetitive loading on the viscoelastic properties of a Bedford shale derivative and two heavy Ohio clays; and Larew and Leonards (Ref 23) and Larew and Ahmed (Ref 2) used repetitive triaxial tests to study the deformational characteristics and strength moduli of selected cohesive soils.

These experimental studies revealed that the behavior of soil under repetitive loading is complex and is a function of many variables. The behavioral characteristics of compacted soil subjected to repetitive loading were dependent upon load magnitude, frequency of load application, duration of loading, interval between load application, moisture content, degree of saturation, test configuration, type of confining pressure (repetitive or static), and soil type. It was found that standard material tests do not always produce accurate estimates of the behavior of a soil subjected to repeated loading. In highly saturated clay soils, a time-dependent and strain-dependent strength gaining process, thixotropy, was noted which confounded test results and made analysis of data difficult. Thus, the study of the behavior of soil subjected to repetitive loading indicated that the characterization of soil properties was complex and that the difficulties encountered with these materials could be expected when other highway construction materials were investigated.

Untreated Granular Materials

Dunlap (Ref 9) studied the behavior of three different granular materials under repetitive triaxial loading, a caliche gravel, a crushed gravel from the same source, and a limestone material. Three different gradations were used for each aggregate type and test specimens were compacted with a gyratory shear compactor. The total strains occurring in the specimens were analyzed and the final results were presented as a set of design curves relating principal stresses and the number of repetitions required to produce a given total strain.

It was found that the Texas Triaxial classification was a valid indicator of performance for small numbers of repetitions, but that it was not a reliable indicator of performance as the number of repetitions increased. For example, an angular coarse material which had the highest Texas Triaxial classification was the best performing material after 100 load repetitions, but it had the poorest performance after 100,000 repetitions. On the other hand, a rounded medium aggregate which had a poor triaxial classification performed well after 100,000 repetitions. In general, the angular materials, which were best according to static triaxial tests, suffered the greatest loss in triaxial classification with an increased number of load applications. The rounded materials in all cases appeared to have smaller rebound strains than the other materials. The amount of degradation that occurred under repetitive triaxial loading was insignificant except for the soft materials.

ASPHALT-TREATED MATERIALS

A large amount of information is currently available concerning the fatigue behavior of asphalts and asphalt-treated materials. This section of the report summarizes the findings from previous studies concerned with the fatigue characteristics of asphalt-treated materials. The effects produced by factors associated with the mixture and construction procedures are discussed in detail, and the relationships between the fatigue characteristics and other properties of the mixtures are briefly summarized.

Test Methods

Monismith et al (Refs 8, 10, 29 through 34, and 36) utilized flexural beam tests to study the fatigue characteristics of asphalt-treated mixtures. The beams were tested on spring supports which represented subgrade support values of various magnitudes and on fixed supports with midpoint and thirdpoint loadings. Elastic beam theory was used to relate the observed behavior to the material properties.

Pell (Refs 42 through 44) utilized a torsional bending apparatus in which specimens with necked-down circular cross sections were clamped in a vertical position in the chuck of a rotating-type cantilever machine. The load was applied at the top of the specimen by a system of pulleys. This configuration produced equal and opposite loads on both ends of the specimen. When the specimen was rotated, the resulting loads created a sinusoidally varying bending stress of a constant magnitude. The frequency was controlled by adjusting the number of revolutions per unit time.

Kirk (Ref 21) used a four-point bending machine in which the specimens were clamped horizontally at the ends and loaded at the third points. Other tests include unconfined compression tests which were reported by Wood and Goetz (Refs 62 and 63), asphaltic concrete diaphragms which were used by Jimenez and Gallaway (Ref 18) and analyzed as circular plates fixed at the periphery with a uniform pressure acting on the bottom surface and a central load on the upper face, and trapezoidal specimens tested by Bazin and Saunier (Ref 4).

Monismith (Ref 32) recognized that the fatigue behavior of materials tested under constant stress would differ from that under constant strain and introduced a test mode factor in an attempt to account for this behavioral difference. A controlled stress test, in which nominal stress level is maintained constant for the duration of the test while the corresponding strains produced in the specimen are allowed to vary, and a controlled strain test, which allows the stress level to vary during the test while maintaining a constant applied strain, represent the extremes of the loading modes with an infinite number of intermediate modes possible. Hypothetical fatigue relationships for the different modes of loading are shown in Fig 1. As shown

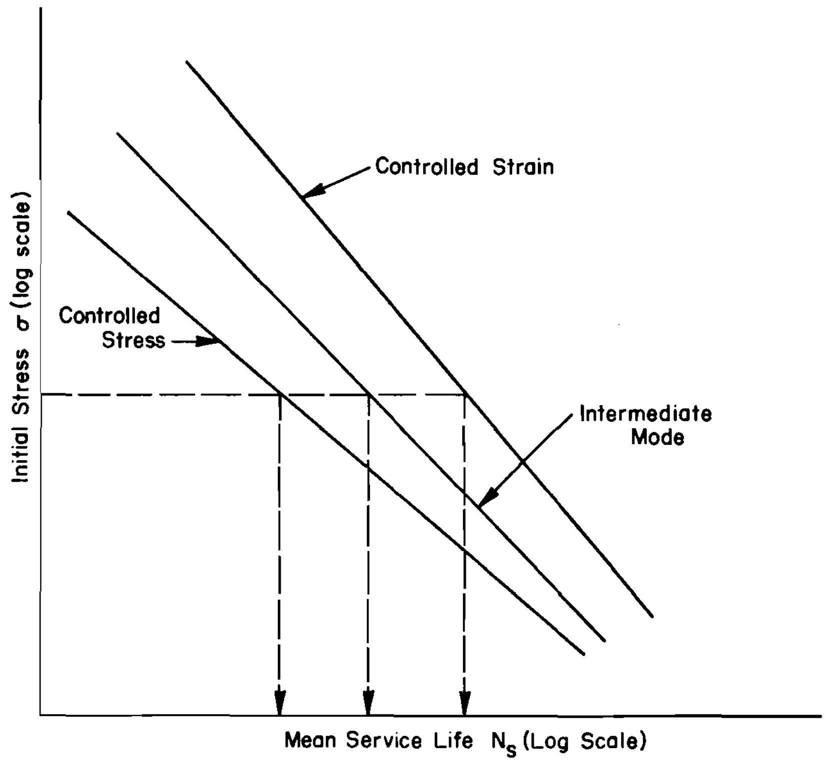


Fig 1. Hypothetical fatigue diagrams illustrating effect of mode of loading (Ref 32).

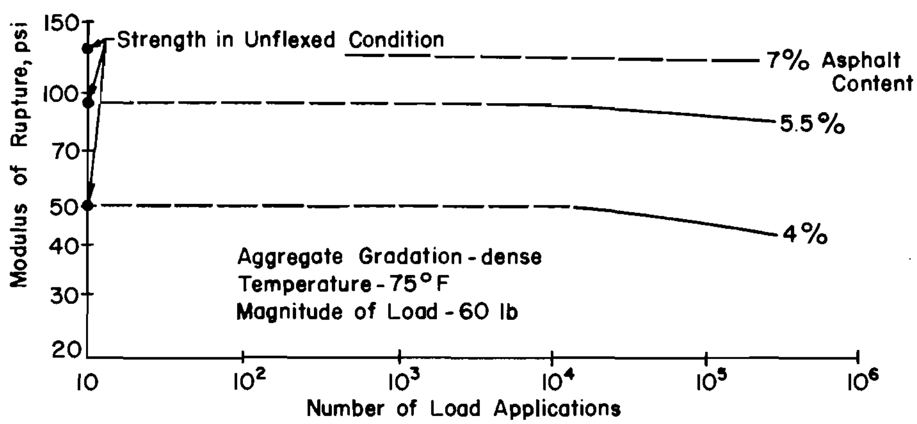


Fig 2. Effect of asphalt content on the behavior of dense graded mixtures (Ref 29).

in this figure, controlled stress tests are more severe, presumably because the strains are larger than those produced in the other test modes.

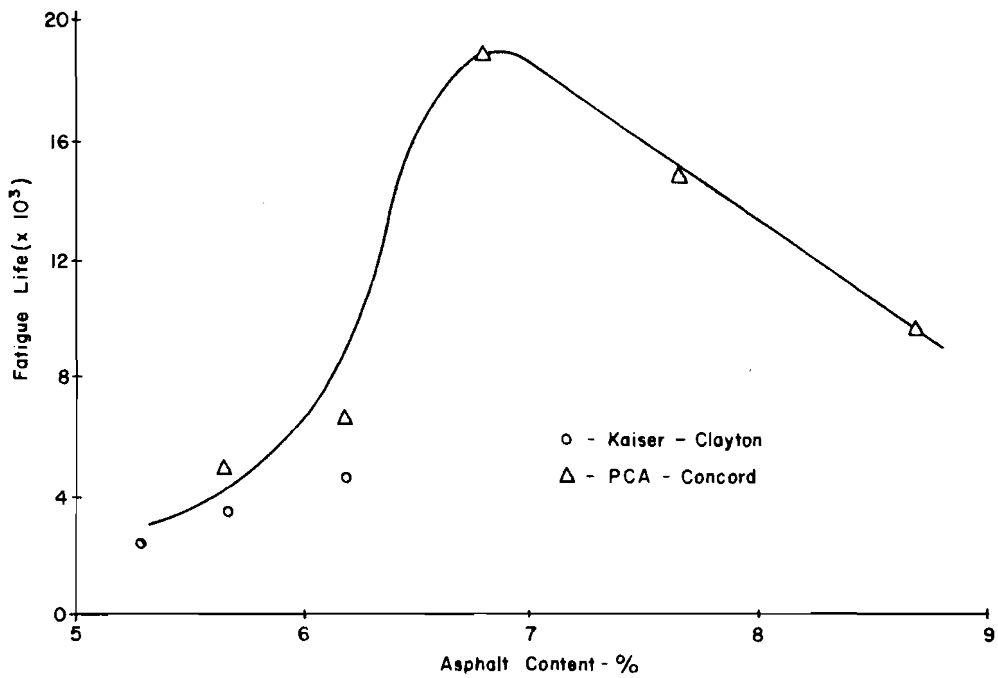
Asphalt Content

Monismith (Ref 29) postulated that high asphalt contents were best from the standpoint of fatigue resistance since thicker asphalt films were present in the asphalt mixture. The thicker films appeared to be less viscous and, therefore, provided more flexibility to the mixture. The increase in viscosity with thinning films was attributed in part to the polar nature of asphalt molecules which causes the molecule to be oriented on the surface of aggregate particles. The more oriented structure of the asphalt molecules in the thinner films produced a more viscous material and less flexibility of the mixture. Based on the data shown in Fig 2, Monismith suggested that for dense graded mixtures, the reduction in tensile strength due to repeated flexing is least for the specimens containing the largest amount of asphalt and that the reductions increase as the asphalt content is decreased.

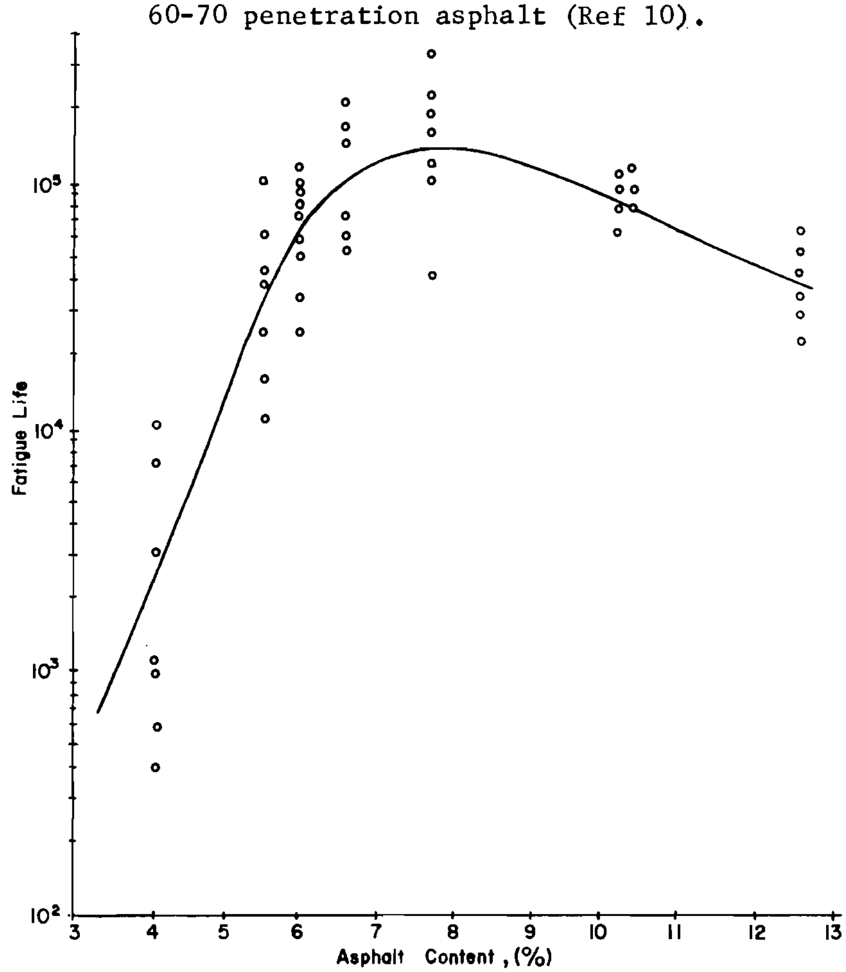
In later work Epps and Monismith (Ref 10) concluded that there is an optimum asphalt content for maximum fatigue life (Fig 3). Similarly, Pell (Ref 43) and Pell and Taylor (Ref 44) reported an optimum asphalt content with respect to maximum fatigue life, as shown in Fig 3. Jimenez and Gallaway (Ref 18) also indicated that an optimum asphalt content for fatigue life exists but that it is a function of aggregate type. Thus, fatigue life increases with increased asphalt content up to an optimum value and then decreases with the addition of more asphalt.

Aggregate Type

Pell (Ref 43), Kirk (Ref 21), and Epps and Monismith (Ref 10) reported that aggregate type had a negligible effect on fatigue life. Jimenez and Gallaway (Ref 18), however, concluded that aggregate type is important since it determines the amount of asphalt required in the mixture. Bazin and Saunier (Ref 4) stated that aggregate type is important for strain values less than 100 microunits, which is well within the range expected in flexible pavements under traffic. Epps and Monismith (Ref 10) presented data which showed a small interaction effect involving stress and aggregate type (Fig 4). Basalt had a longer fatigue life at stress levels above 150 psi, while granite performed better at lower stress levels. While it was suggested that aggregate



(a) California medium grading, Basalt aggregate, 60-70 penetration asphalt (Ref 10).



(b) Crushed rock base course mixture 40-50 penetration bitumen (Ref 44).

Fig 3. Effect of asphalt content on fatigue life.

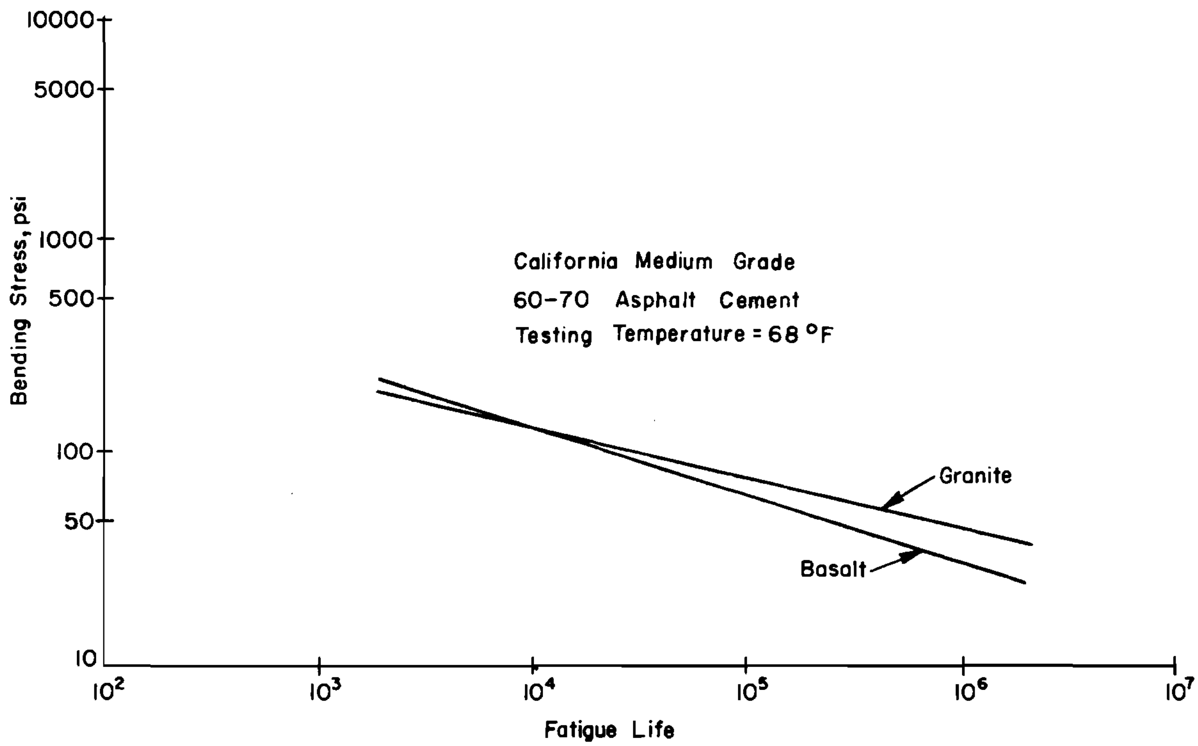


Fig 4. Effect of aggregate type on fatigue life (Ref 10).

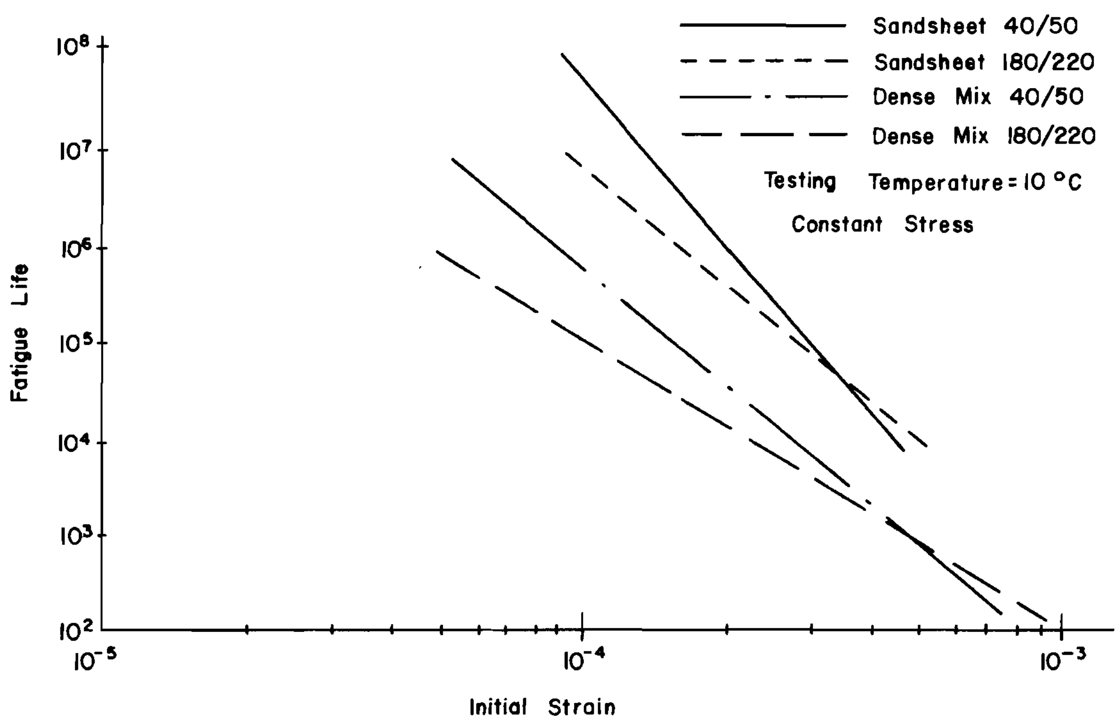


Fig 5. Effect of the grade of asphalt on fatigue life (Ref 4).

type had only a negligible effect when asphalt content was held constant, it was concluded that the effect of aggregate type on fatigue behavior is not clear. It was also noted that when mixtures containing different aggregates were compared at asphalt contents based on stability requirements, the differences in fatigue life could not be completely explained in terms of stiffness and air void differences.

Asphalt Viscosity

Bazin and Saunier (Ref 4) and Epps and Monismith (Ref 10) found that for small initial strains, a more viscous asphalt produced a mixture with a longer fatigue life (Figs 5 and 6). Epps and Monismith also concluded that the effect of asphalt viscosity is linear. As shown in Fig 7 the fatigue life at a given stress level increased as the penetration of the asphalt decreased.

Aggregate Gradation

The effect of aggregate gradation seems to be confounded with the effect of asphalt content and air void content. Epps and Monismith (Ref 10) concluded that data presented by Pell (Ref 43), Kirk (Ref 21), and Bazin and Saunier (Ref 4) could be explained by differences in the asphalt content and air void content of mixtures tested at temperatures below 50^{o} F. Epps and Monismith studied the fatigue behavior of asphalt mixtures using three different gradations. The results obtained for two of these mixtures are shown in Figs 8 and 9. These figures show that the mixtures with the medium gradation had the longer fatigue life for low bending stresses and low initial bending strains. It was also noted that this gradation had the highest stiffness.

Other Factors

Numerous other variables have been shown to be important to the fatigue life of asphalt-treated materials. The frequency of load applications was shown by Pell (Ref 43) and Pell and Taylor (Ref 44) to have a significant influence on the fatigue life with higher frequencies producing a longer fatigue life. Monismith (Ref 29), however, did not detect an effect due to frequency. Deacon and Monismith (Ref 8) studied the effect of compound loading on the fatigue properties of asphalt-treated materials. This type of multilevel loading better simulates the variation of vehicular stresses applied to pavements under traffic than previously used simple loading, i.e., one stress at one frequency for the duration of a given fatigue test. Monismith and

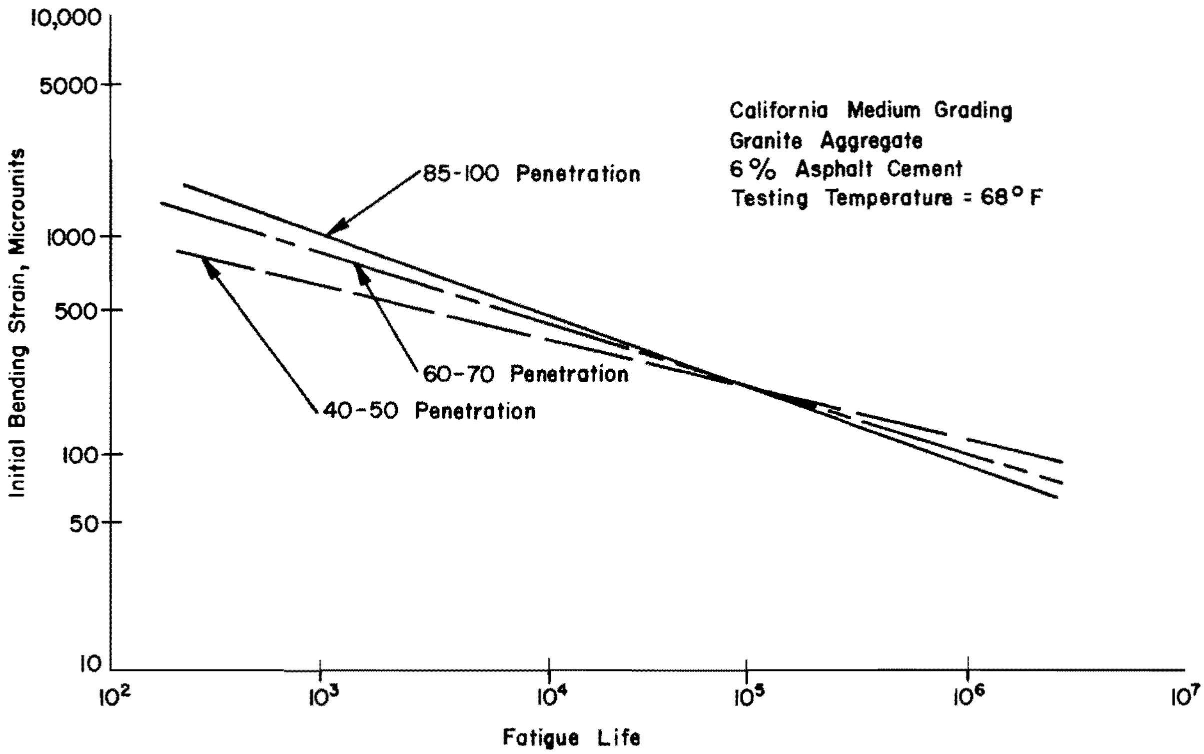


Fig 6. Effect of asphalt penetration on the initial bending strain versus applications to failure relationship (Ref 10).

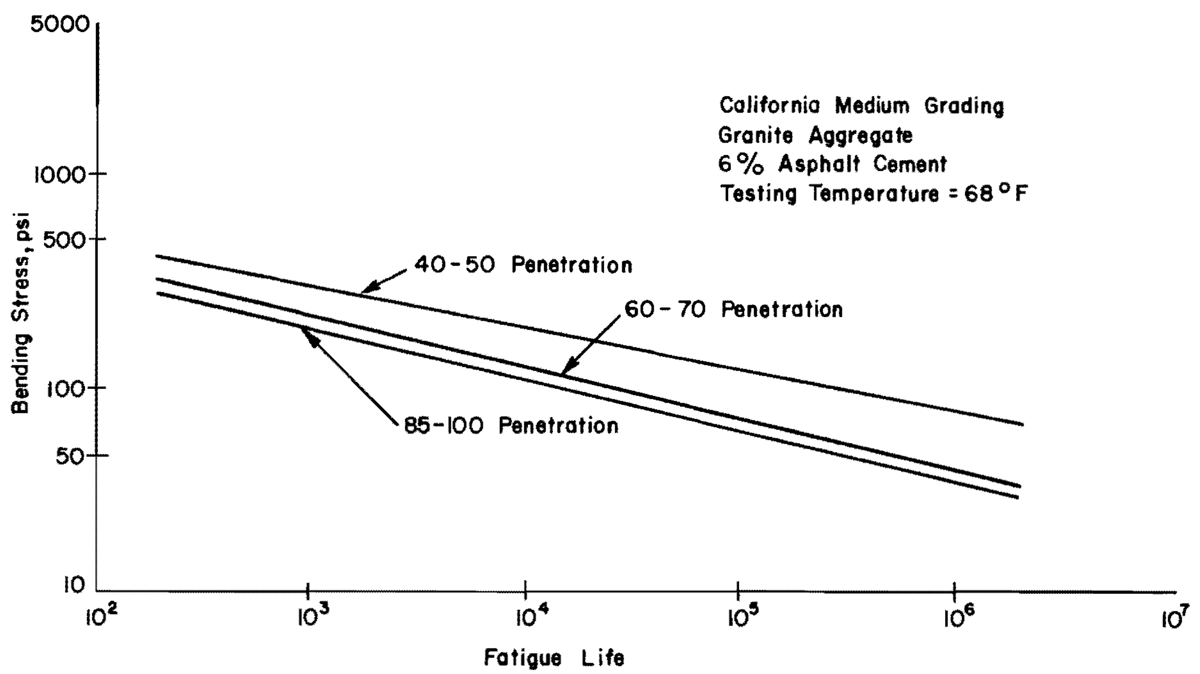


Fig 7. Effect of asphalt penetration on bending stress versus applications to failure relationship (Ref 10).

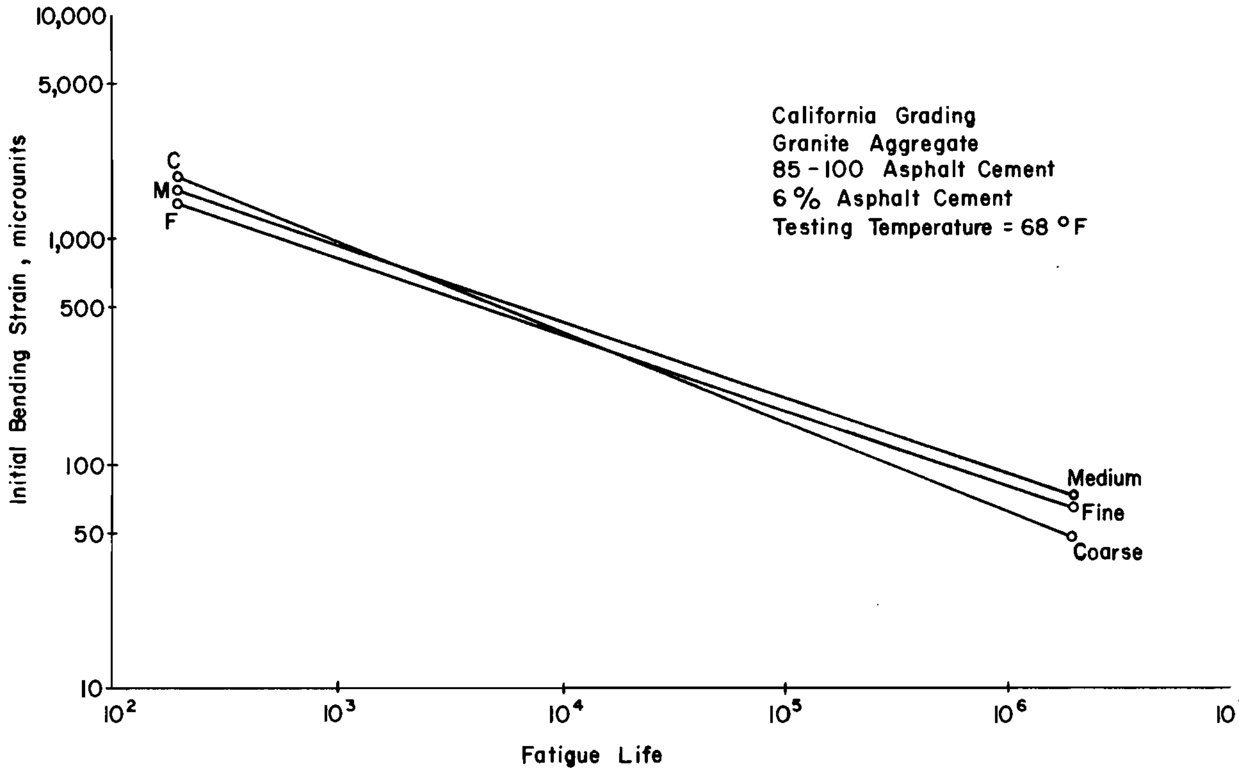


Fig 8. Effect of aggregate grading on the initial bending strain versus applications to failure relationship (Ref 10).

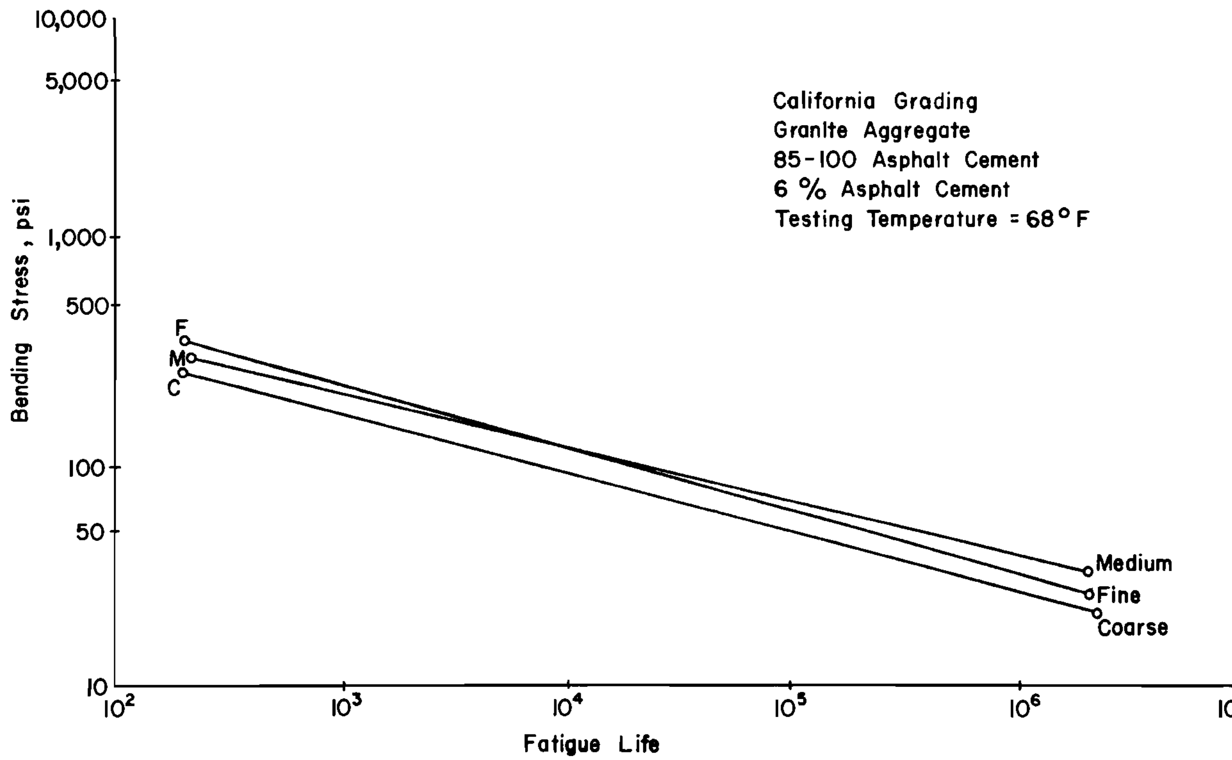


Fig 9. Effect of aggregate grading on the initial bending stress versus applications to failure relationship (Ref 10).

Secor (Ref 35) studied the effect of thixotropy on asphalts and concluded that changes in the properties of the asphalt-treated materials tested in flexure were not related to the thixotropic characteristics of the asphalts.

Testing temperature, which has been regarded as an environmental factor, has also been shown to influence the fatigue results (Refs 34 and 44), but the effects of compaction temperature and mixing temperature have not been studied to any extent. Usually these variables have been regarded as being related to stiffness, which could be used to explain their effects.

Correlation with Other Properties

Many attempts have been made to explain fatigue behavior in terms of other properties of the mixture such as stiffness, initial strain, or air void content, or to correlate these properties with fatigue behavior. The results from previous studies in which attempts have been made to establish such relationships are summarized below.

Stiffness or Modulus. From the fatigue standpoint, stiffness is an important material characteristic in flexible pavements since the stresses and strains produced by traffic are a function of the stiffness of the asphalt mixtures, which not only varies from mixture to mixture but also varies with temperature and loading rate (Ref 33).

Deacon and Monismith (Ref 8) stated that the stiffness of a mixture is important to the fatigue characteristics of asphalt-treated materials and that any factor that affects stiffness also affects the fatigue behavior. Deacon (Ref 7) also noted that stiffness is a function of the mode of loading. For controlled stress loading, a specimen with a high initial stiffness performed well as long as the mixture was not brittle and was reasonably well proportioned. However, the reverse seemed to be true for asphalt-treated materials subjected to controlled-strain loading.

Epps and Monismith (Ref 10) presented data which indicated that stiffness altered the slopes of the relationships between the logarithm of bending stress and the logarithm of the number of applications to failure (Fig 10) and showed that stiffer mixes have a longer fatigue life. The optimum asphalt content for maximum fatigue life also produced maximum stiffness.

Initial Strain. Saal and Pell (Ref 46) found that the relationship between the logarithm of the strain and the logarithm of the number of cycles to failure was linear for constant stress tests (Fig 11). Pell (Ref 43) stated that the relationship between the logarithm of strain and the logarithm of fatigue life seemed to be independent of temperature and speed of loading, and it was concluded that the fatigue life of a sandsheet mix within the ranges studied was primarily controlled by the magnitude of the applied strain and not by stress and that the effects of temperature and speed of loading could be explained in terms of stiffness.

Air Void Content. Many researchers have shown that void content has an influence on the fatigue life of a given asphalt mixture. As shown in Fig 12a, a change in void content from 10 percent to 4 percent resulted in a definite increase in fatigue life (Ref 46). Bazin and Saunier (Ref 4) concluded that void content could have an effect on the fatigue characteristics of asphalt-treated mixtures and that at a given level of strain an increase in voids resulted in shorter fatigue lives. Epps and Monismith (Ref 10) also found that as the void content decreased, the fatigue life increased (Fig 12b). Pell and Taylor (Ref 44) reported that the logarithm of the number of cycles to failure varied linearly with both the logarithm of strain and the void content.

CEMENT-TREATED MATERIALS

The literature which was reviewed with regard to the fatigue properties of cement-treated materials is limited and, thus, the number of general conclusions which can be made is limited.

Whittle and Larew (Ref 61) utilized repetitive triaxial tests to investigate the fatigue behavior of cement-treated materials and presented results which illustrate that sample deformation for a soil treated with 5 percent type III cement increased with an increase of the ratio of applied deviator stress to the ultimate compressive stress as determined in conventional triaxial tests. It was suggested that there is a level of $\Delta\sigma_r/\Delta\sigma_s$ below which the rate of deformation for a specimen decreases as the number of repetitions increases, and above which the rate of deformation increases as the number of repetitions is increased until failure.

Figure 13 illustrates the relative relationship between repeated and conventional triaxial test results. The stress-strain curve for a soil with 5 percent type III cement subjected to repeated loading indicates that for a given deviator stress, the strains observed for the repetitive triaxial tests

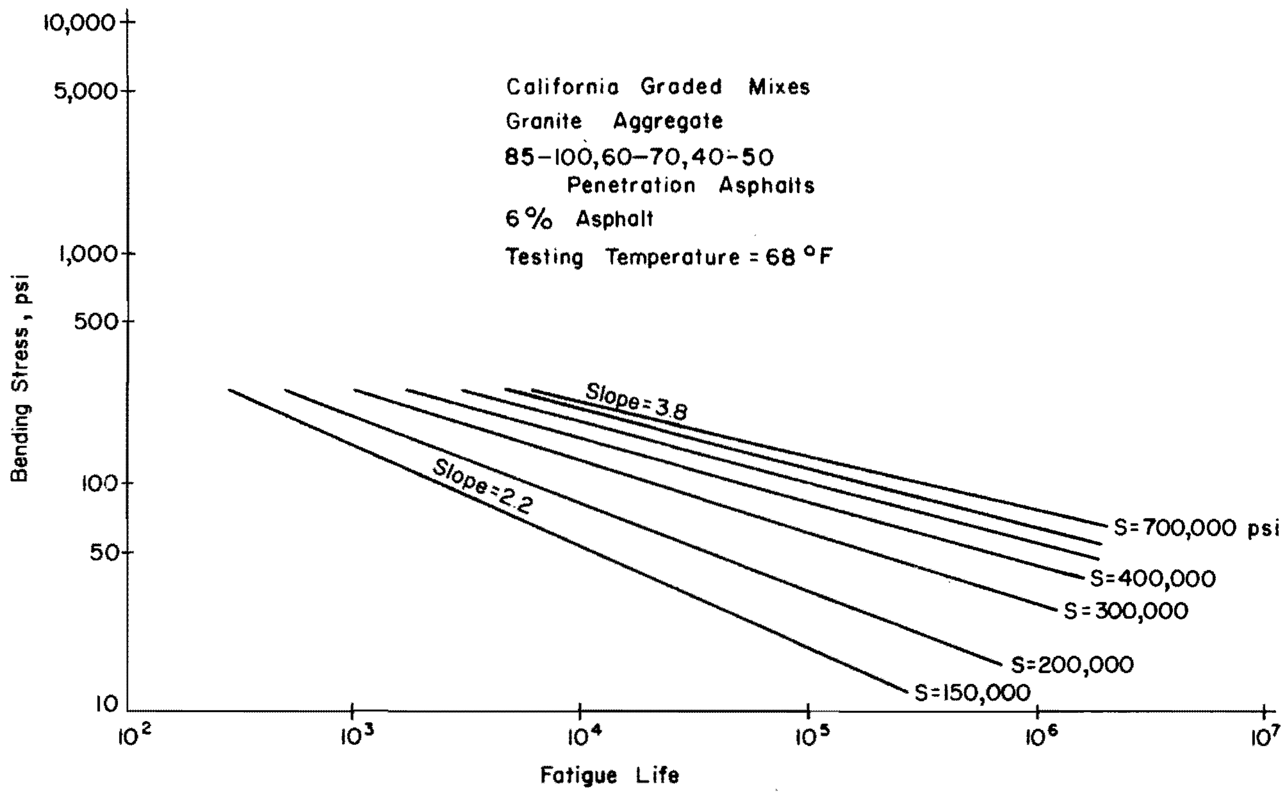


Fig 10. Bending stress versus application to failure, for mixes of different stiffness (Ref 10).

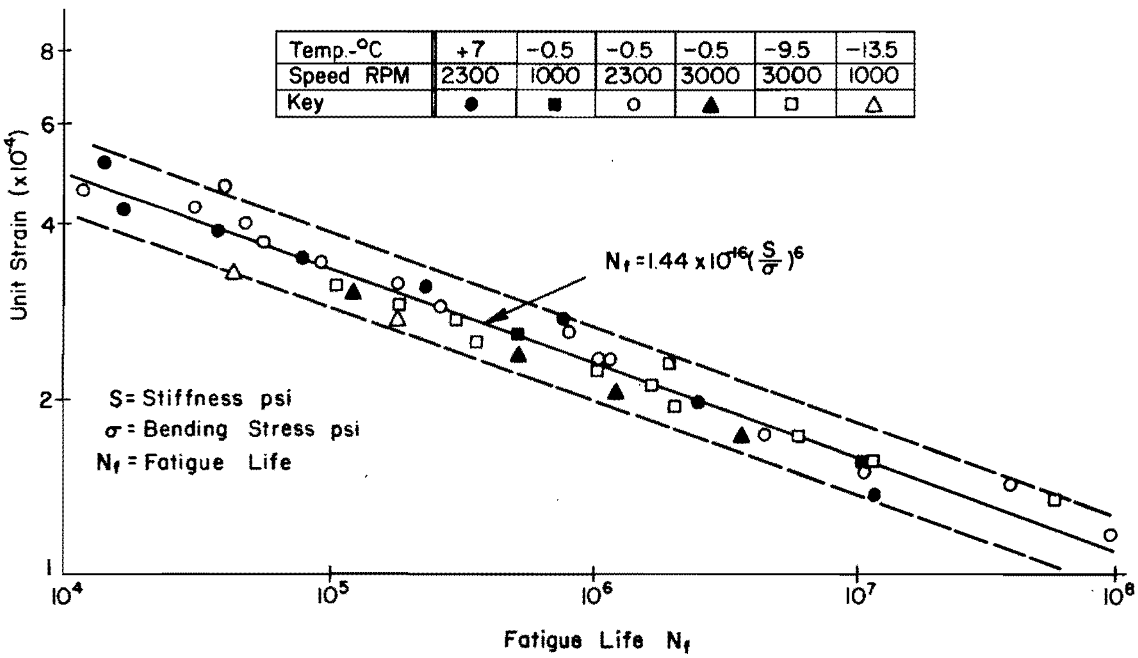
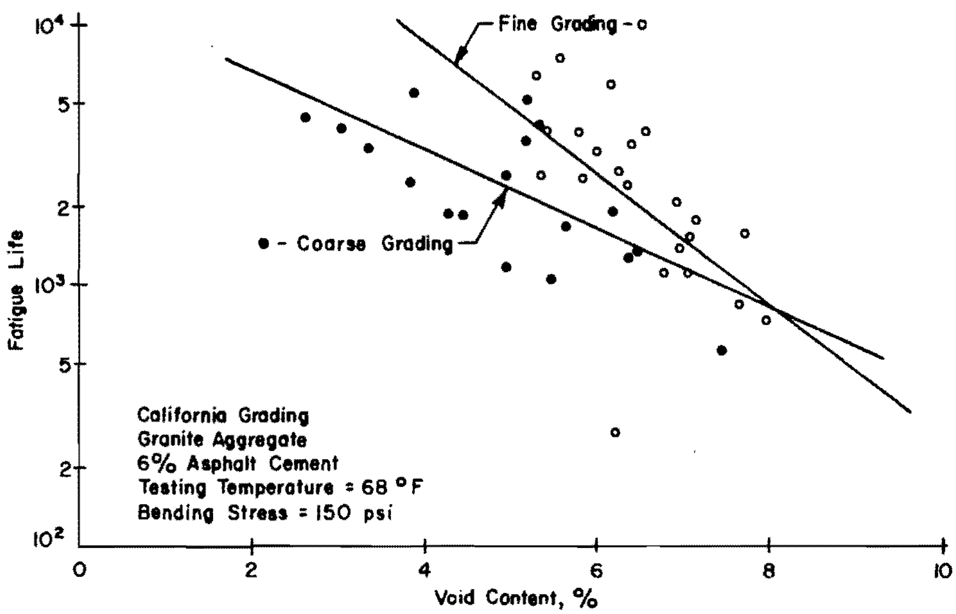
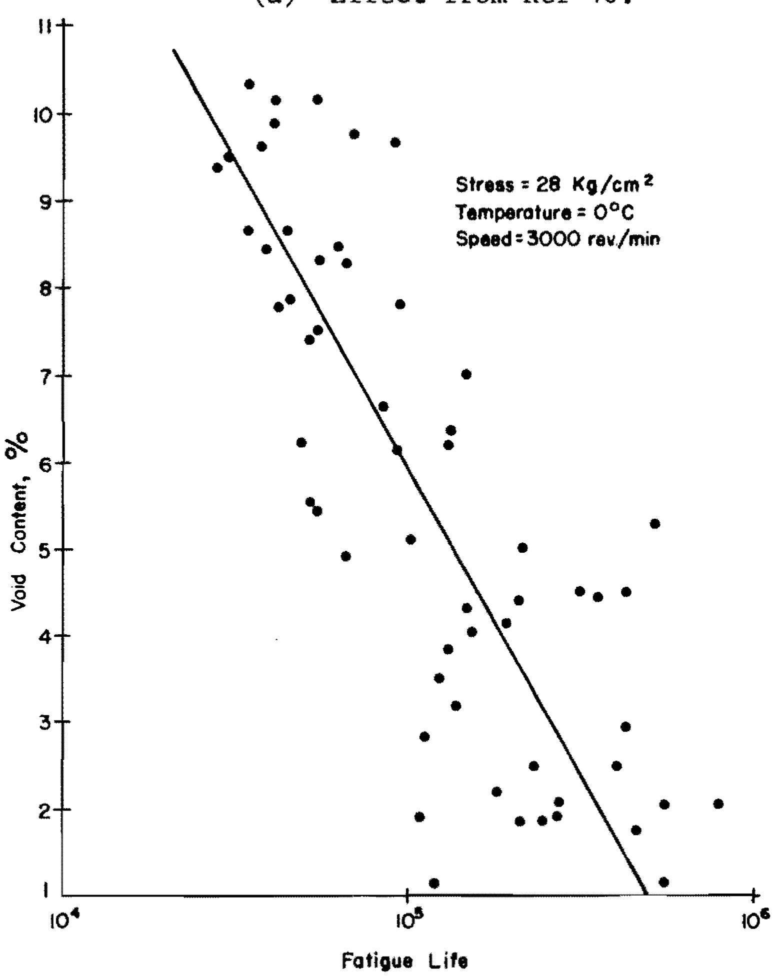


Fig 11. Results of fatigue tests at various temperatures and speeds (Ref 46).



(a) Effect from Ref 46.



(b) Effect from Ref 10.

Fig 12. Effects of air void content on fatigue life.

are larger. The strains at failure, however, were reported to be essentially equal. Cement-treated soils containing type III cement exhibited higher strength and stiffness characteristics under 100,000 applications of repeated deviator stress (Fig 14) than cement-treated soils containing type I cement. Both cement-treated soils showed marked improvement over the unstabilized soils.

The results from an investigation comparing the behavior of a Vicksburg silty clay-cement mixture and an Eliot sand-cement mixture in compression and flexure were reported by Shen and Mitchell (Ref 56). For the Vicksburg soil, the modulus of resilient deformation in compression varied with compaction conditions, applied stress intensity, curing period, and the number of load applications at high stress intensities. In flexural tests, however, the modulus varied little with respect to compaction conditions and the magnitude of the applied stress and the number of load applications up to 100,000 applications. The strains at failure in the flexure tests ranged from 3 to 14 percent of the strains for the compression tests, with the greatest difference being observed at optimum moisture content. A study of the comparative data of the Eliot sand revealed that the moduli of resilient deformation in both compression and flexure increased with increasing dry density. The strain at failure was 5 percent of the values in compression.

Larsen and Nussbaum (Ref 24) presented findings from research designed to study the flexural fatigue behavior of soil-cement and to determine the effects produced by (1) soil type and general physical properties, (2) depth of layer, and (3) reaction modulus of the supporting subgrade. Figure 15 illustrates typical fatigue relationships in the form of regression equations fitted to the data points in the range between 10 and 1,000,000 applications of load. Specimens which did not fail were not used in the derivation of the regression equation. The general form of this equation is

$$\frac{R_c}{R} = aN_f^{-b} \tag{2.1}$$

where

R_c = the critical radius of curvature,

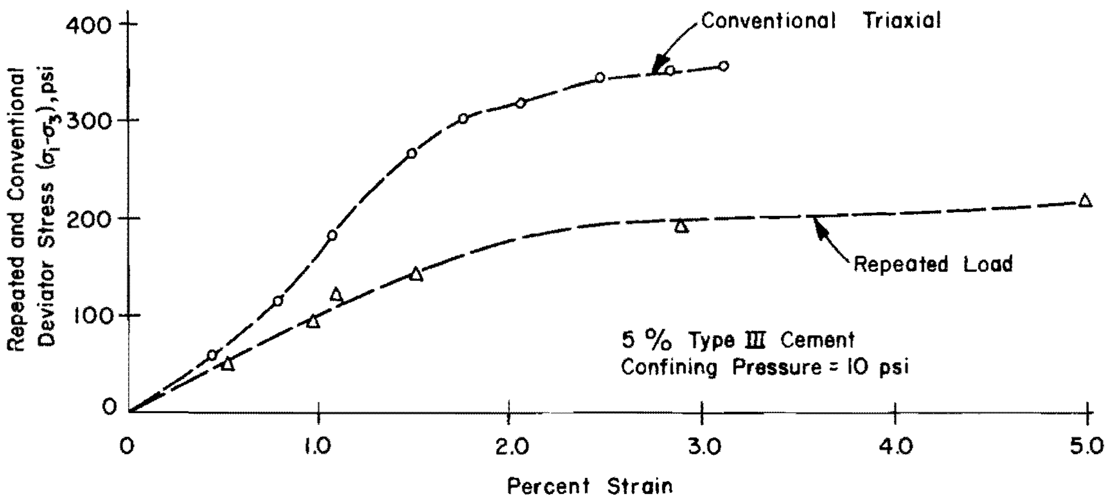


Fig 13. Repeated load and conventional stress versus strain curves for cement-stabilized soil (Ref 62).

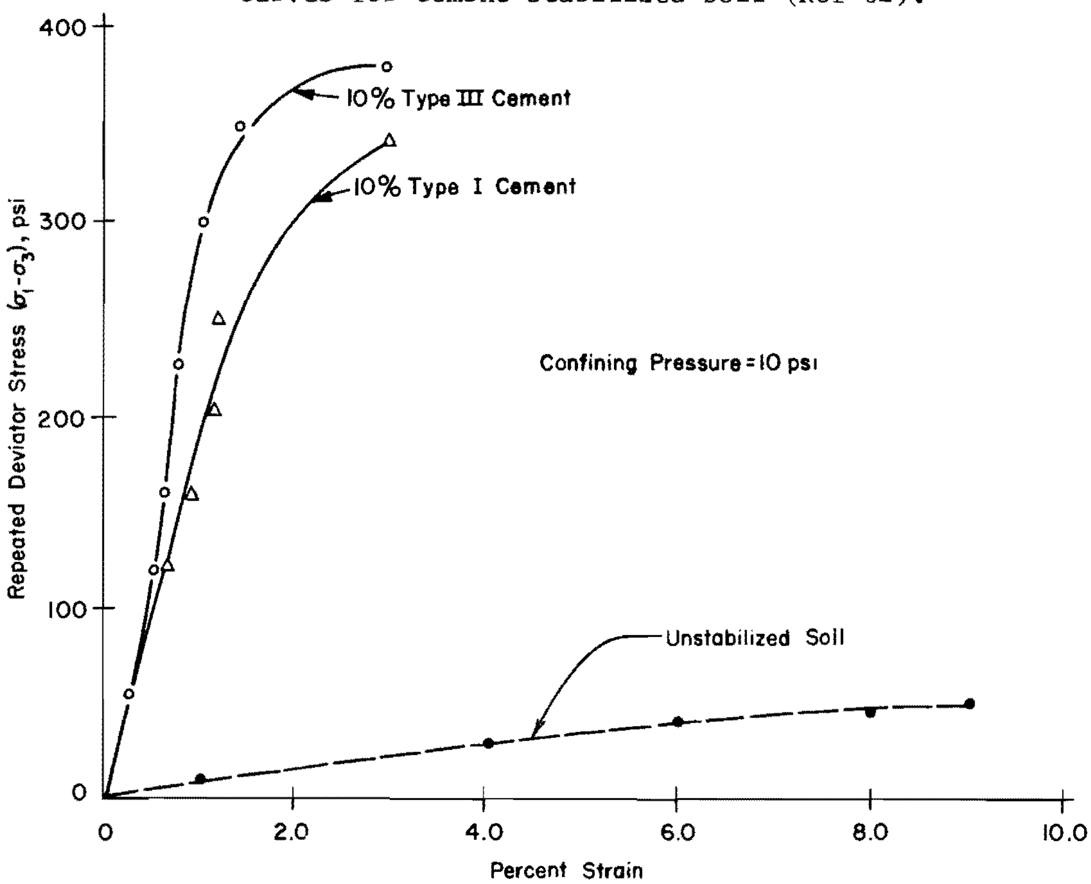


Fig 14. Comparison of repeated stress versus strain curves for unstabilized and cement-stabilized soil (Ref 62).

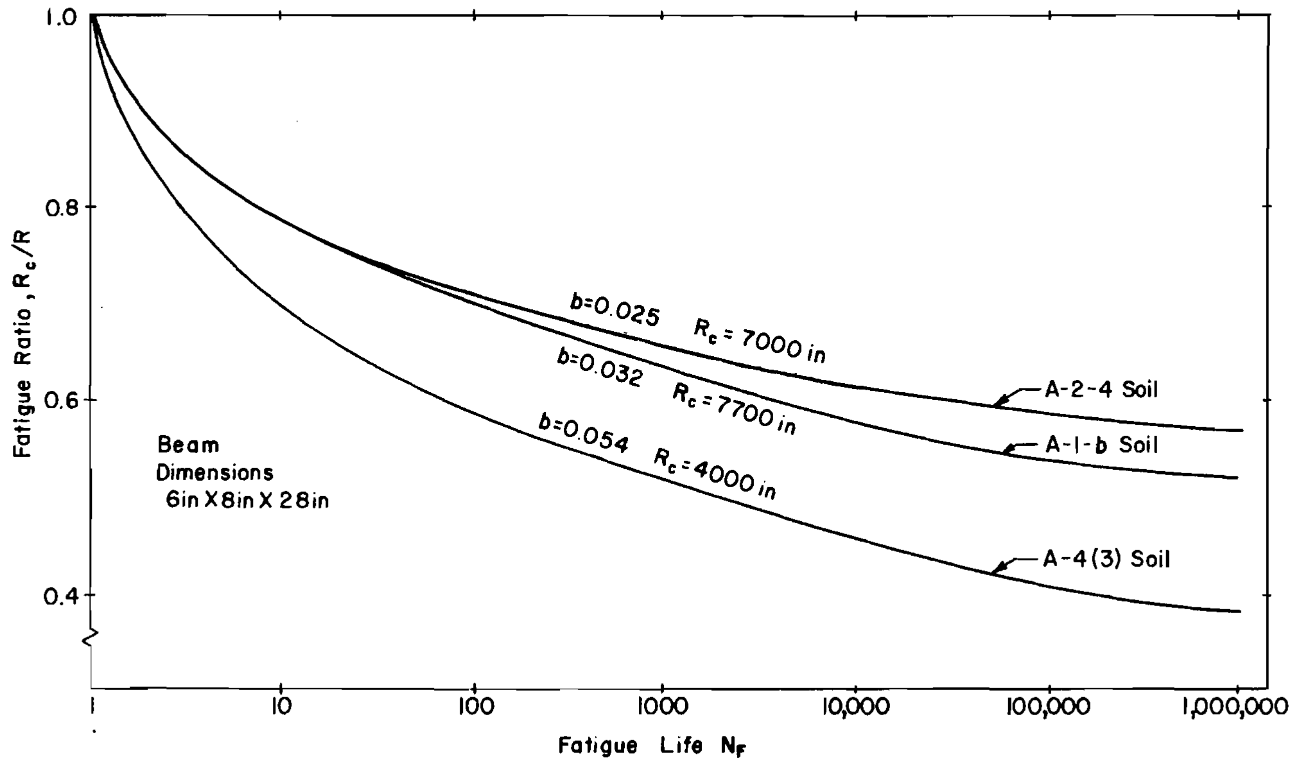


Fig 15. Influence of soil type on fatigue life of soil-cement (Ref 24).

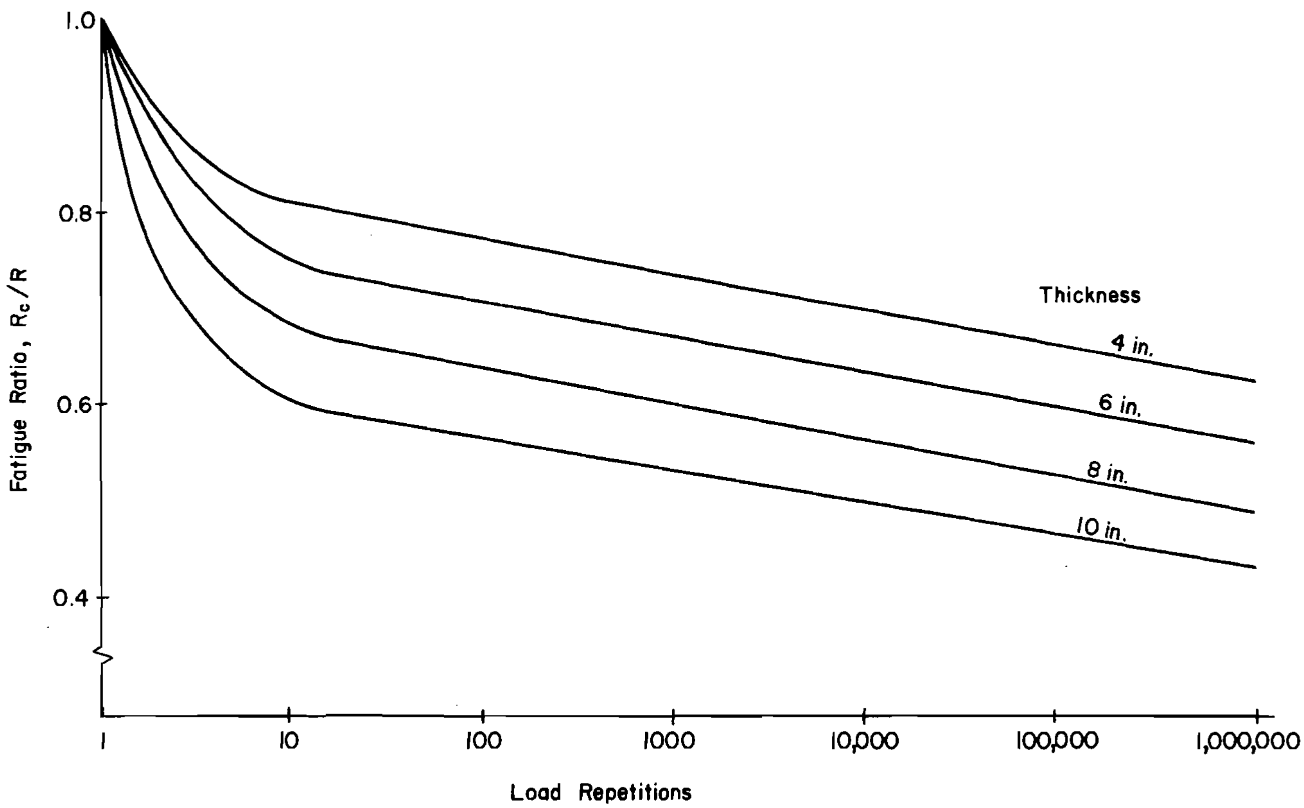


Fig 16. Influence of beam thickness on fatigue life of soil-cement (Ref 24).

R = the radius of curvature produced by the applied load in a given test,

N_f = fatigue life, and

a and b = fatigue parameters.

Figure 15 shows the effect of soil type on the fatigue test data. Values of the critical radius, i.e., the radius of curvature at which the first crack appears, and the fatigue parameter b for the three soils are shown. The values of the fatigue coefficient differed for each soil with the largest value occurring for the A-4(3) soil. Therefore, it was concluded that b was a function of soil type. Figure 16 illustrates the influence of beam thickness on the fatigue life of soil-cement specimens. The curves are separate but approximately parallel; hence, it was concluded that thickness influences the parameter a of the regression model, while parameter b was independent of thickness. It was also noted that the effect of subgrade support on the fatigue life of the soil-cement beams was insignificant.

LIME-TREATED MATERIALS

The information concerned with the fatigue characteristics of lime-treated materials is limited. To date, no large, comprehensive programs have been reported in the literature. Each of the references reviewed was independent in scope and purpose; thus, overall conclusions are limited in number.

Ahlberg and McVinnie (Ref 1) measured the number of cycles to failure for flexural beams composed of 82 percent aggregate, 14 percent fly ash, and 4 percent lime. Figure 17 illustrates typical results which relate maximum bending stress in the beam, the estimated modulus of rupture, and the number of cycles to failure. In general, it was concluded that the repeated loads caused the mixtures of lime, fly ash, and aggregate to fracture at stress levels considerably below the static strength of the material.

Swanson and Thompson (Ref 58) studied the flexural fatigue of four lime-soil mixtures. Optimum lime contents and moistures were used for all mixtures. Specimens were tested at stress levels ranging from 40 to 95 percent of their ultimate strength. Typical results, shown in Fig 18, illustrate the random variation of data which is characteristic of fatigue testing of lime-treated materials.

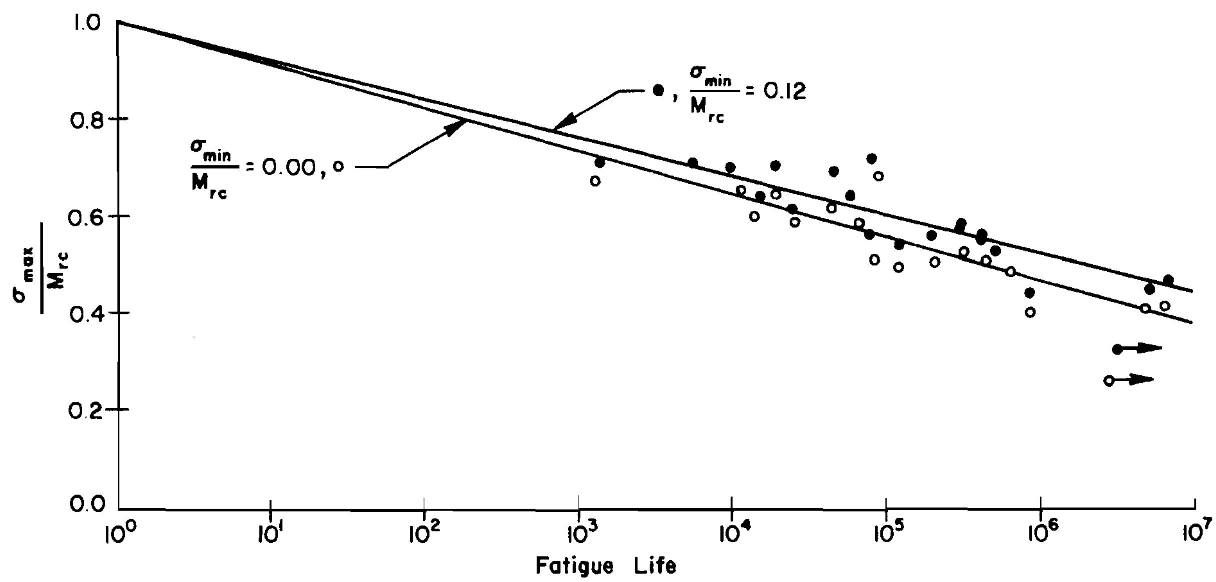


Fig 17. Relationship between maximum bending stress and logarithm of number of cycles to failure for lime-fly ash treated materials (Ref 1).

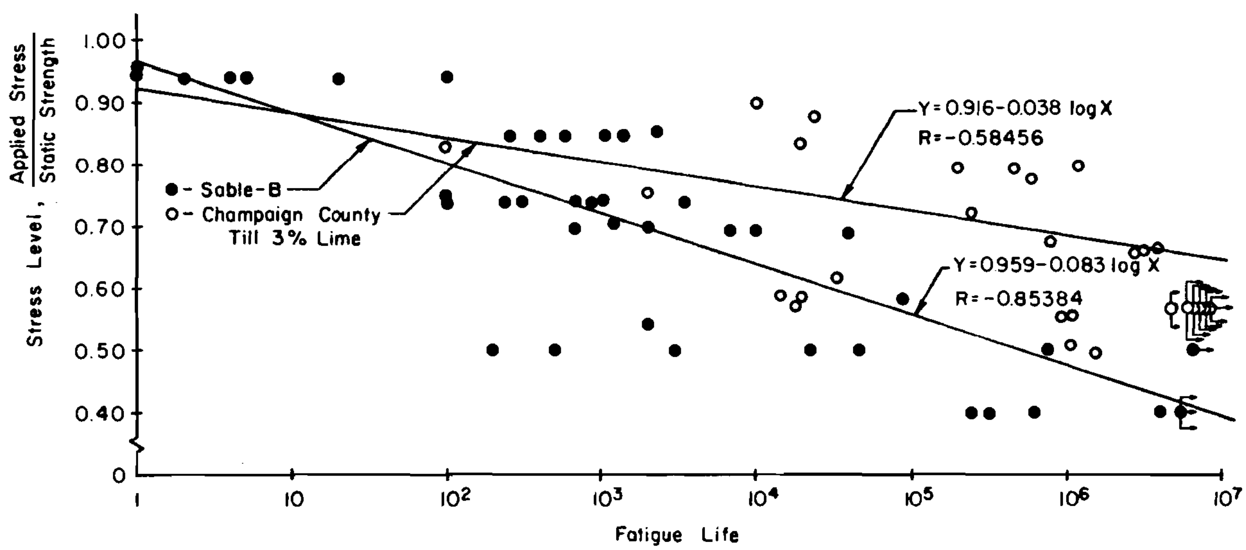


Fig 18. Typical fatigue results for lime-treated materials (Ref 58).

Nguyen (Ref 41) utilized repetitive-loading, unconfined compressive tests to study the behavior of lime-stabilized clay and concluded that the reduction in compressive strength varied with the magnitude of the load applied and the number of applications. The decrease in strength ranged from 1.3 to 18.1 percent of the ultimate static strength of the lime-stabilized Taylor Marl clay. A small reduction in the magnitude of the applied repeated load greatly increased the number of cycles required to fracture the specimen. The ratios of the split-tensile strength to the unconfined compressive strength averaged 0.145 for specimens subjected to static loading conditions and 0.151 for specimens subjected to 10,000 and 20,000 repetitions of an unconfined compressive loading prior to testing.

Previous investigators have not studied the influence of the mixture variables, e.g., lime content, moisture content, and curing temperature, on fatigue life. Tests have been conducted on specimens which are usually compacted at optimum lime contents and moisture contents. Notable random scatter of results is inherent in all previous studies; the presence of this stochastic variation suggests that statistical experiment design and regression analysis techniques should be utilized in future work in order to distinguish random variation from variation caused by changing the mixture variables. The indirect tensile test has not been used in previous fatigue studies but flexural fatigue studies have been reported. Because of the limited information available, a need exists for additional information concerning mixture variables with regard to the fatigue characteristics of lime-treated materials subjected to repeated tensile stresses.

SUMMARY

Comprehensive testing programs concerning the fatigue characteristic of asphaltic materials have been conducted using flexural and torsional shear tests. The mixture variables which have been studied for their effect on fatigue life include asphalt content, aggregate type, asphalt viscosity, and aggregate gradation. The effects of mixing temperature and compaction temperature have not been studied. In addition, the effect of interactions which may exist between these factors have not been evaluated to any extent. Additional emphasis has been placed on establishing relationships between fatigue behavior and other dependent characteristics, e.g., stiffness, initial strain, stress-strength ratio, and air void content, all of which are dependent on the mixture variables and construction procedures. While a great deal of research concerned with the fatigue behavior of asphalt-treated materials has been conducted, additional work is needed to broaden the technology which is vital to rational pavement design.

Work concerned with the fatigue characteristics of cement-treated materials is limited in quantity and scope. Previous investigators have not studied the effect of mixture variables on fatigue life. Thus, there exists a definite need for additional information concerned with the fatigue properties of these materials and the effect of mixture and curing variables, e.g., cement content, water content, and curing temperature, on the fatigue life. Although flexural fatigue tests have been reported, a need still exists for additional information on the tensile behavior of cement-treated materials under repetitive loading.

Fatigue work on lime-treated soils is practically nonexistent. In the few studies which have been conducted a great deal of random variation was evident. Because of the limited information available, a need exists for additional information concerning the fatigue characteristics of lime-treated materials.

CHAPTER 3. EXPERIMENTAL PROGRAM

This chapter describes the indirect tensile test, the method of test, the design of the experiment, and the techniques used to prepare and test the specimens. The basic parameter evaluated in this experiment was fatigue life, i.e., the number of applications of a given stress required to fail the specimen.

METHOD OF TEST

The indirect tensile test involves loading a right circular cylindrical element or specimen with compressive line loads acting along two opposite generators (Fig 19). To distribute the load and maintain a constant loading area, the compressive force was applied through half-inch-wide rigid stainless steel loading strips which had a radius of curvature of 2 inches at the interface with the specimens.

This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane through the center of the loading strips. Specimens fail by splitting or rupturing along the vertical diameter. Hondros (Ref 16) analyzed a circular specimen subjected to loading through a narrow strip, assuming that the body forces were negligible, and developed equations for the resulting stresses. Based on these equations, the tensile stress in the center of the specimen is

$$\sigma_T = \frac{2P}{\pi a h} \left(\sin 2\alpha - \frac{a}{2R}\right) \qquad (3.1)$$

where

σ_T = indirect tensile stress, in psi;

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

a = width of loading strip, in inches;

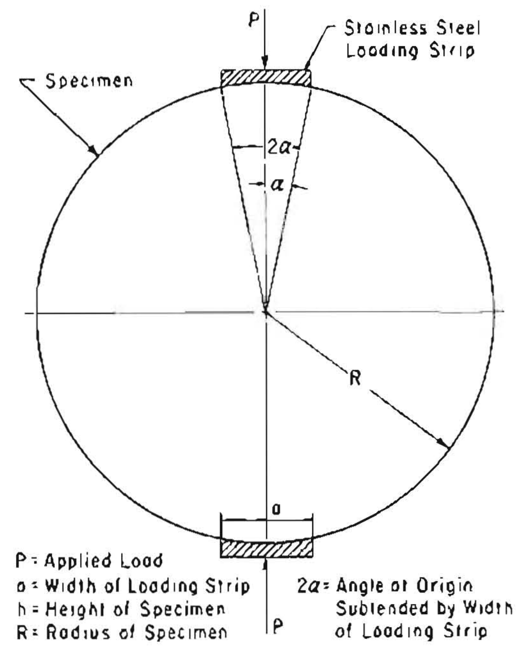


Fig 19. Indirect tensile test.

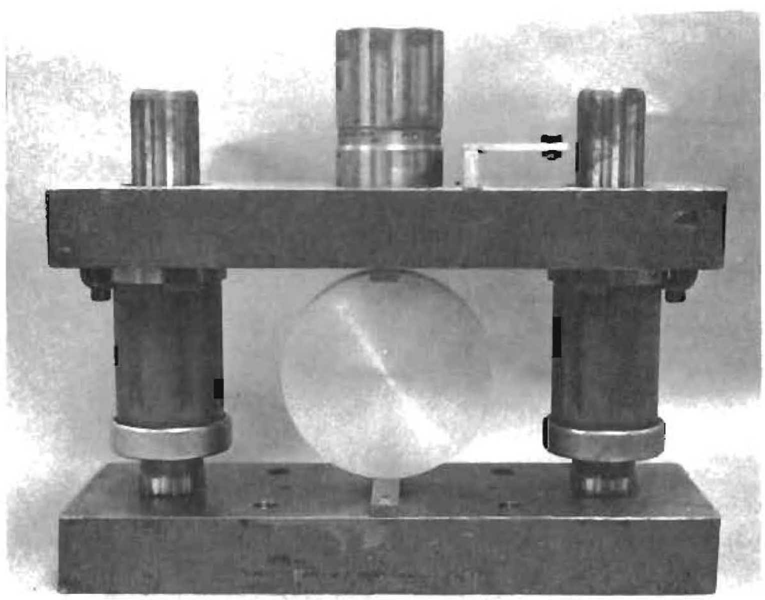


Fig 20. Loading device.

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

2α = angle at center of specimen subtended by width of loading strip;

R = radius of specimen, in inches.

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

The basic 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 (Fig 20). Load-deformation data were recorded with a light-beam oscillograph.

The load was controlled with a strain gage type load cell and was varied in magnitude sinusoidally with respect to time at a frequency of one cycle per second. This moderately high frequency was selected to insure that the specimen would fail within a reasonable period of time and because it closely approximates the load frequency experienced by urban freeway pavements with heavy traffic volumes (Ref 36). All tests were conducted at a temperature of approximately 75° F.

MATERIALS INVESTIGATED

Two different aggregate types were used, a crushed limestone which was angular and relatively porous and a rounded and smooth river gravel which was relatively nonporous. Each material was separated and recombined to produce the appropriate grain size distribution shown in Fig 21. For the lime-treated materials, the aggregates were combined with various percentages of Taylor Marl clay which was composed of approximately 30 to 35 percent calcium montmorillonite, 50 to 60 percent illite, and 10 to 15 percent kaolinite and exhibited a liquid limit, plastic limit, and plasticity index of 59, 18, and 41, respectively. The grain size distribution for the clay is shown in Fig 21.

The three grades of asphalt cement used (AC-5, AC-10, and AC-20) were produced by the Cosden Refinery, Big Spring, Texas. The temperature-viscosity relationships for the three asphalt cements are shown in Fig 22. Since asphalt is susceptible to viscosity changes with time, this effect was evaluated by conducting sliding plate microviscometer tests in which plates were prepared and allowed to remain undisturbed for 0, 7, or 14 days prior to testing (Fig 23). The type I portland cement was manufactured by Centex Cement

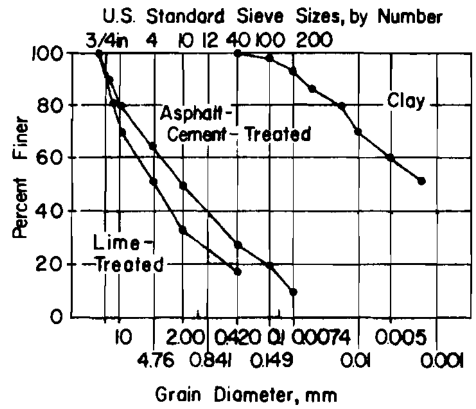


Fig 21. Grain size distribution curves for aggregates and clay.

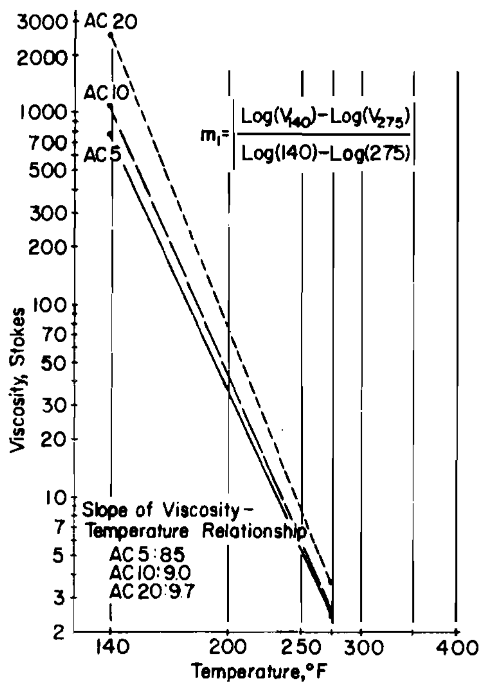


Fig 22. Temperature viscosity relationships for asphalt cements (Ref 14).

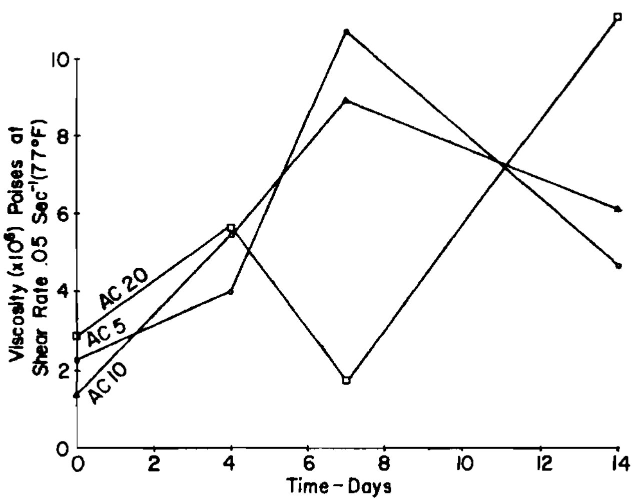


Fig 23. Microviscometer results for asphaltic cements.

Corporation, Corpus Christi, Texas, and the hydrated calcitic lime was manufactured by Austin White Lime Company, Austin, Texas.

The chemical composition of the lime is as follows:

Chemical	Percent by Weight
$Ca(OH)_2$	93.67
CaO	0.0
Free Water content, H_2O	1.38
$CaCO_3$	3.75
Inert Matter (SiO_2, etc.)	1.20
Residue retained on No. 30 (590 micron) sieve	0.0

EXPERIMENT DESIGN

The factors and levels chosen for the fatigue studies are shown in Table 1 for the three types of stabilization. The selection of the factors and levels was based primarily on the results of previous experiments concerned with the tensile characteristics of the three treated materials (Refs 3, 11-15, 17, 19, 20, 28, 38-40, 45, and 60). In order to achieve the objectives of the study, the experiment and analysis were divided into three phases:

(1) development of the relationship between tensile stress and fatigue life;

(2) determination of mixture and compaction factors which affect tensile fatigue life; and

(3) correlation of material properties and fatigue life, and development of prediction equations based on stress levels and material factors.

Phase One

The first phase of the investigation involved testing specimens at several stress levels to define the relationship between applied stress and the number of applications to failure. The asphalt-treated and cement-treated specimens were prepared using the medium levels for all factors investigated except aggregate type, which was studied at two levels. The lime-treated materials were prepared using the medium level of all five factors studied. The variation in fatigue life for each aggregate type at the various stress levels was evaluated in order to provide a quantitative measure of the amount of variation which must be considered in stochastic analyses required for pavement design. In addition, this phase provided an estimate of experimental error for use in the analysis of variance used in Phase Two.

Phase Two

The purpose of the second phase was to evaluate the effects of selected mixture, compaction, and curing variables on the fatigue life of the asphalt-treated materials. The experiment consisted of a half-fractional factorial in which all factors were varied and only the low and high levels were used. Figure 24 graphically presents the designs and indicates the specimens which were actually tested. This design allowed all factors and all two-factor interactions at a given stress level to be evaluated by analysis of variance, assuming that all higher-order interactions are negligible. The estimate of experimental error at each stress level was obtained from the results of tests in Phase One.

Phase Three

The last phase included the investigation for possible correlations between fatigue life and material properties such as modulus of elasticity, initial tensile strain, and stress-strength ratio, all obtained from the static indirect tensile test, as well as between fatigue life and percentage of air voids in the mixture. In addition, a prediction equation for estimating fatigue life in terms of stress level and the material factors studied was developed by combining all the data from Phases One and Two and conducting a regression analysis.

SPECIMEN PREPARATION

Aggregate mixtures were batched by dry weight to meet the gradation requirements and the necessary quantity of the appropriate stabilizing agent was added. The aggregate and stabilizing agent were mixed in an automatic, 12-quart-capacity Hobart mixer.

The mixture was then compacted using the Texas gyratory shear compactor as specified in test method Tex-206-F (Ref 27). Following compaction, the specimens were extruded from the compaction mold, weighed, and measured and then cured for a designated period of time at a designated temperature. All

Mixing Temp. °F	Compaction Temp. °F	Rounded Gravel				Crushed Limestone			
Asphalt Cement Type		AC-5		AC-20		AC-5		AC-20	
Asphalt Content, %		5.5	8.5	5.5	8.5	5.5	8.5	5.5	8.5
300	350		TEST	TEST		TEST			TEST
	250	TEST			TEST		TEST	TEST	
200	350	TEST			TEST		TEST	TEST	
	250		TEST	TEST		TEST			TEST

(a) Asphalt-treated.

Curing Temperature, °F	Compactive Effort, psi *	Rounded Gravel				Crushed Limestone			
Cement Content, %		4		8		4		8	
Molding Water Content, %		5.25	7.75	5.25	7.75	5.25	7.75	5.25	7.75
125	135		TEST	TEST		TEST			TEST
	85	TEST			TEST		TEST	TEST	
75	135	TEST			TEST		TEST	TEST	
	85		TEST	TEST		TEST			TEST

(b) Cement-treated.

Curing Temperature, °F	Compactive Effort, psi *	Lime Content, % 1.5				4.5			
Clay Content, %		37.5		62.5		37.5		62.5	
Molding Water Content, %		10.5	15.5	10.5	15.5	10.5	15.5	10.5	15.5
125	150		TEST	TEST		TEST			TEST
	100	TEST			TEST		TEST	TEST	
75	150	TEST			TEST		TEST	TEST	
	100		TEST	TEST		TEST			TEST

(c) Lime-treated.

Fig 24. Graphical representation of factorial experiment designs and test specimens.

specimens were nominally 4 inches in diameter and 2 inches high. A detailed description of the specimen preparation procedure is contained in Appendices 1, 2, and 3.

CHAPTER 4. DISCUSSION OF RESULTS

This chapter contains the findings and discussion related to the behavior of asphalt-treated, lime-treated, and cement-treated subbase materials subjected to repetitive tensile stresses. The fatigue results for each material are considered separately and are discussed in subsections concerned with (1) the development of the relationship between tensile stress and the logarithm of the fatigue life and the determination of the inherent variation, (2) the determination and discussion of the factors affecting fatigue life, and (3) the development of methods for estimating fatigue life, either by prediction equations or by relating to various other dependent variables such as modulus of elasticity, initial strains produced by the first stress application, stress-strength ratio, and air void content.

ASPHALT-TREATED MATERIALS

Stress-Fatigue Life Relationship

For each aggregate type, duplicate specimens were prepared using the middle or zero levels of the other factors investigated (Table 1) and were subjected to five stress levels in order to define the stress-fatigue life relationship of each aggregate type and to measure the inherent variation in fatigue life which could be expected for identical specimens. The fatigue life data for each specimen are given in Table 2 and are shown graphically in Fig 25 in terms of tensile stress and the logarithm of fatigue life. As seen in Fig 25, there was an apparent linear trend in the relationship between tensile stress and the logarithm of fatigue life, with fatigue life decreasing with increasing stress.

The specimens containing gravel generally exhibited a longer fatigue life than the specimens containing crushed limestone, even though the limestone specimens probably had higher indirect tensile strengths than the gravel specimens (Refs 11, 14, and 15). The limestone specimens failed soon after the first tensile crack began to form; however, the gravel specimens did not fail

TABLE 1. 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 (Fig 22), which were constant in this temperature range.

**See Appendix 3 for procedure utilized to produce different compactive efforts with the gyratory shear compactor.

TABLE 2. FATIGUE LIFE DATA FOR DUPLICATE ASPHALT-TREATED SPECIMENS

Tensile Stress, psi	Aggregate*	Fatigue Life Measured	Average	Variance	Standard Deviation	Variance of Log
8	Gravel	323,519 1,102,353** 476,396 1,042,639**	737,000	---	---	---
	Limestone	359,726 196,109	278,000	---	---	---
16	Gravel	10,912*** 221,686 79,784 264,061 340,460	186,103 (226,500)	$19,000 \times 10^6$ $(12,000 \times 10^6)$	138×10^3 (109×10^3)	0.37594 (0.07641)
	Limestone	12,138 12,126 20,793 11,379 13,610	14,000	15×10^6	3.9×10^3	0.01164
24	Gravel	909 5,210 1,260 1,243 37,006***	9,100 (2,150)	250×10^6 (4.0×10^6)	15.8×10^3 (2.0×10^3)	0.45119 (0.11508)
	Limestone	3,370 7,143 2,121 2,322 2,981	3,600	4.2×10^6	2.05×10^3	0.04426
32	Gravel	1,090 873 1,690 5,055 1,290	2,000	3.0×10^6	1.7×10^3	0.08912
	Limestone	285 785 1,524 1,240 888	944	0.22×10^6	$.47 \times 10^3$	0.07921
40	Gravel	315 286 209 1,623 819	650	0.35×10^6	$.59 \times 10^3$	0.13705
	Limestone	275 290 261 252 1,070	430	0.13×10^6	$.36 \times 10^3$	0.08158

* Medium or zero levels from Table 2 were used with each aggregate.

** Specimen did not fail.

*** Numbers in parentheses were calculated excluding fatigue life for these specimens.

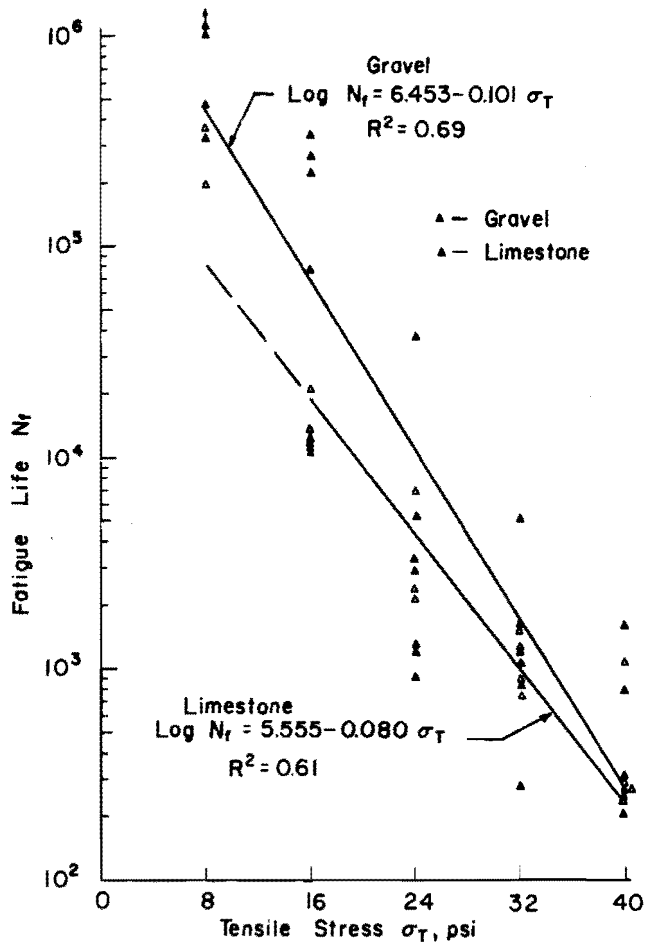


Fig 25. Relationships between logarithm of fatigue life and tensile stress.

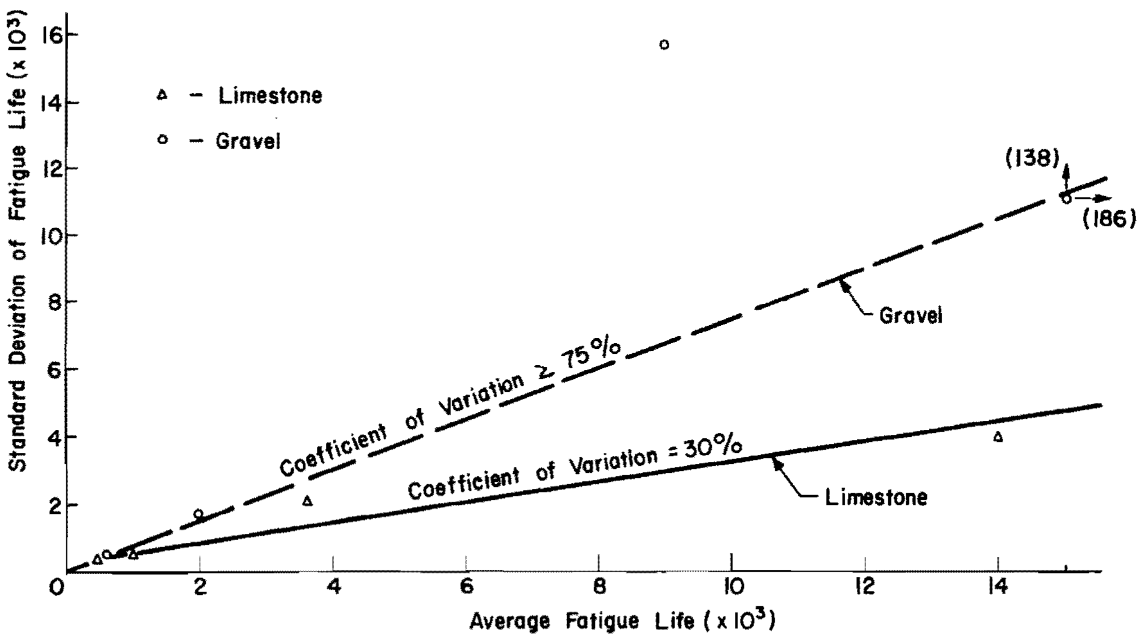


Fig 26. Relationships between the average and the standard deviation of fatigue life.

immediately and often required additional stress applications before rupture occurred.

Visual inspection of the specimens after failure revealed that the gravel specimens absorbed less asphalt than the limestone and that thicker films surrounded the gravel particles. These thicker films possibly retarded the propagation of cracks through the gravel specimens and thus prevented the immediate rupture of the specimen. Another possible explanation is that, if failure is related to strain, for a given stress the strain would be less in the thicker films than in the thinner ones.

Variation in Fatigue Life

As shown in Fig 25, there was a great deal of scatter in the fatigue life at any given stress level. Table 2 lists the variance of fatigue life and the variance of the logarithm of fatigue life estimated for each aggregate type at each stress level except 8 psi, for which there were insufficient data to obtain an adequate estimate of variance. Figure 26 illustrates the relationship between the standard deviation and the mean value of fatigue life at various stress levels. The relationship for both aggregate types was approximately linear, and the standard deviation was essentially proportional to the mean value. Based on the slope of these relationships, it was estimated that the coefficient of variation for the fatigue data obtained for the limestone specimens was approximately 30 percent while that obtained for the gravel specimen was in excess of 75 percent, although the relationship was not well defined. However, when the two outlier data points obtained at stresses of 16 and 24 psi (Table 2) were eliminated, the relationship was better defined.

Factors Affecting Fatigue Life

Since fatigue life can be affected by factors other than stress, an analysis was conducted to ascertain whether the other factors under investigation had an effect and to determine the nature of any such effects. Because of the significant amount of variation which was associated with the fatigue life data, analysis of variance techniques were used to determine whether certain factors were important.

Only two stress levels, 32 and 16 psi, were used, in order to minimize the number of test specimens required. Since the relationship between tensile stress and the logarithm of fatigue life was essentially linear, two levels of stress not only established which factors were important but also allowed the relationship between stress and the logarithm of fatigue life for each mixture to be estimated. The decision to use these particular stress levels was based on the need to provide a stress difference large enough to determine whether different factors affect fatigue life at different stress levels and at the same time to be able to subject all the mixtures to the same two stress levels.

Since the variances were nonhomogeneous, i.e., unequal with respect to stress and aggregate type, and since the standard deviation was essentially proportional to the mean fatigue life, a logarithmic transformation of the data was used. This transformation would be expected to produce homogeneous variance with respect to stress, which is required if analysis of variance techniques are to be used to analyze the effects of the various mixture and compaction factors at the two stress levels (Refs 5, 6, and 57). A review of the variances of the logarithm of the fatigue life (Table 2) indicated that these values were essentially equal.

The fatigue data for the factorial arrangement of treatments tested at 16 and 32 psi stress levels are shown in Table 3 and the summary of the analysis of variance is shown in Table 4. As expected, stress was the most important factor; however, the results of the analysis of variance indicated that there were also four mixture and compaction factors, i.e., asphalt cement type, asphalt content, compaction temperature, and mixing temperature, and one two-factor interaction, involving asphalt content and mixing temperature, which had a significant effect on fatigue life at a probability level of one percent.

The two-factor interaction indicated that the increased mixing temperature had essentially no effect on fatigue life at an asphalt content of 5.5 percent, but that at an asphalt content of 8.5 percent, the increased mixing temperature produced a substantial increase in fatigue life. Nevertheless, in terms of pavement behavior, it was felt that the effect of the two-factor interaction had little practical significance and it was not considered.

The nature of the effects produced by asphalt cement type, asphalt content, compaction temperature, and mixing temperature are shown in the form of tensile stress and logarithm of fatigue life relationships in Figs 27 through 30 and are discussed below. These fatigue relationships were developed using all the data in Table 3; thus, each point represents the average of eight specimens. Although normally it would not be adequate to connect two points with a straight line, the portion of this study in which five stress levels were used suggested that the relationship was essentially linear.

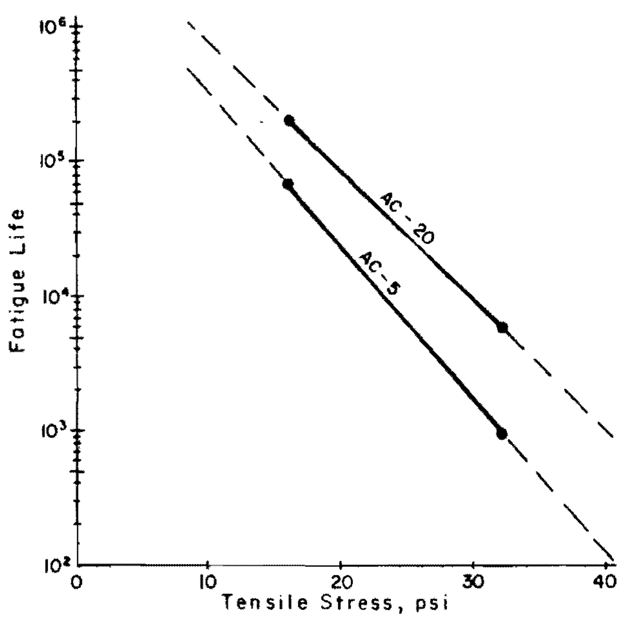


Fig 27. Effect of type of asphalt cement on fatigue life.

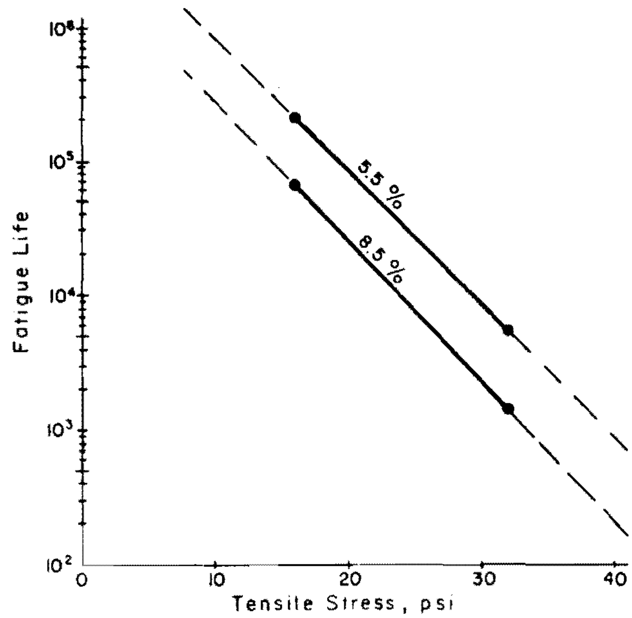


Fig 28. Effect of asphalt content on fatigue life.

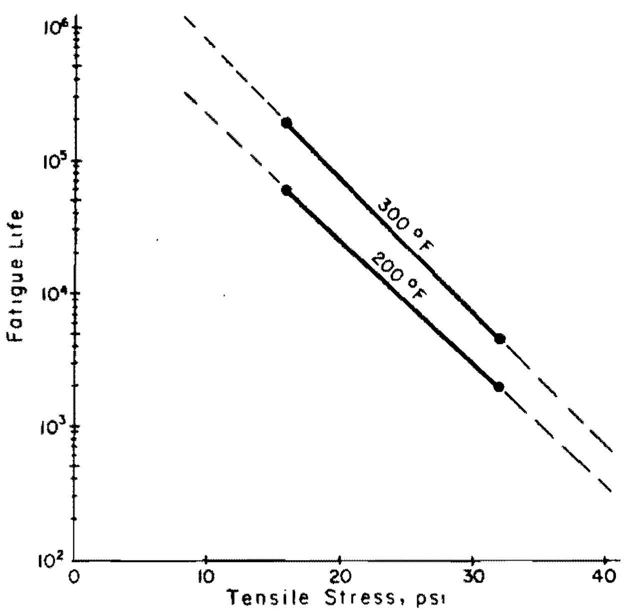


Fig 29. Effect of compaction temperature on fatigue life.

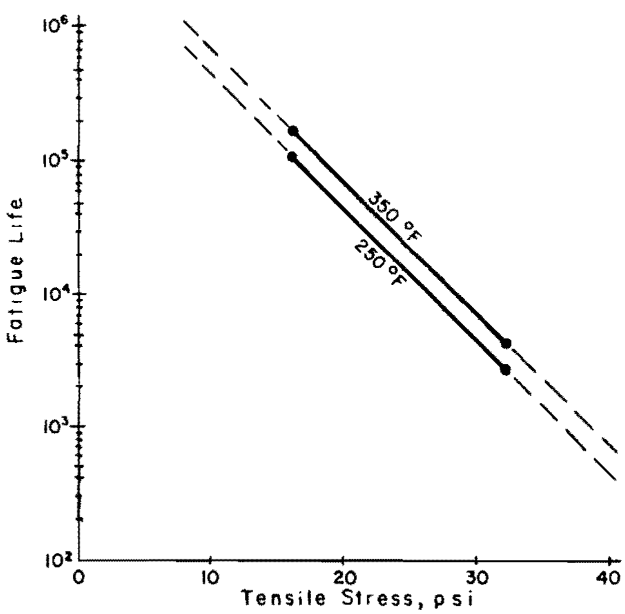


Fig 30. Effect of mixing temperature on fatigue life.

TABLE 3. FATIGUE LIFE FOR ASPHALT-TREATED SPECIMENS AT 16 AND 32 PSI

Tensile Stess, psi	Compaction Temp, °F	Mixing Temp, °F	Rounded Gravel				Crushed Limestone			
Aggregate Type			Rounded Gravel				Crushed Limestone			
Asphalt Cement Type			AC 5		AC 20		AC 5		AC 20	
Asphalt Content, %			5.5	8.5	5.5	8.5	5.5	8.5	5.5	8.5
32	300	350		1641	14,611		4022			4275
		250	1065			1238		88	12,346	
	200	350	408			3369		85	5577	
		250		76	6150		262			262
16	300	350		261,492	500,000*		212,189			166,214
		250	66,781			13,870		901	500,000*	
	200	350	5068			66,041		3416	160,888	
		250		838	298,066		7874			4555

* Specimen did not Fail

TABLE 4. ANALYSIS OF VARIANCE OF LOG FATIGUE LIFE FOR ASPHALT-TREATED SPECIMENS

Factor	dF	Mean Square	F Ratio	Significance Level, %
Tensile stress	1	17.12	271	1
Asphalt cement type	1	7.19	114	1
Asphalt content	1	5.26	83.2	1
Compaction temperature	1	3.46	54.7	1
Mixing temperature	1	2.60	41.1	1
Asphalt content × mixing temperature	1	1.73	27.3	1
Aggregate × asphalt content	1	0.61	9.67	5
Asphalt cement type × compaction temperature	1	0.58	9.21	5
Mixing temperature × compaction temperature	1	0.47	7.45	5
Residual	22	0.063		
Error*	15	0.063		

*Pooled error from specimens tested at 32 and 16 psi excluding outliers (Table 2).

Asphalt Cement Type. The fatigue life for the asphalt-treated mixtures containing an AC-20 asphalt cement was greater than for mixtures containing an AC-5 asphalt cement (Fig 27). This can be explained by the fact that the films bonding the aggregate together were more viscous for the mixtures containing the AC-20 and therefore provided a greater resistance to deformation under repeated tensile stresses. Epps and Monismith (Ref 10) and Bazin and Saunier (Ref 4) have reported findings which are substantially the same. The more viscous asphalts tend to resist the effect of repetitive stresses better and thus are associated with increased fatigue life. Studies concerning changes in asphalt consistency as evaluated by the sliding plate microviscometer indicated that the viscosity of the AC-20 asphalt cement increased more with time than did the viscosity of the AC-5 asphalt cement. For long-term fatigue tests, this increase in viscosity with time could provide additional fatigue resistance if the repeated strains were small (Ref 26).

Asphalt Content. The effect of asphalt content on fatigue life at the 32 psi and 16 psi stress levels is shown in Fig 28. At both stress levels, the mean fatigue life for a mixture containing 8.5 percent asphalt was less than that for a mixture containing 5.5 percent. Based on the previous findings reported by Epps and Monismith (Ref 10), Pell and Taylor (Ref 44), and Jimenez and Gallaway (Ref 18), this effect is interpreted to mean that there was an optimum asphalt content which would provide maximum fatigue life and that 8.5 percent asphalt was well above this optimum. In support of this, the 8.5 percent was above the optimum asphalt content of this mixture as determined by the Texas Highway Department method for selecting optimum asphalt contents (Ref 59).

Compaction Temperature. As shown in Fig 29, the mean fatigue life for the asphalt-treated mixtures compacted at 300° F was greater than for mixtures compacted at 200° F. It is postulated that the increased compaction temperature decreased the viscosity of the asphalt, allowing it to flow more readily over the surface of the aggregate during compaction and thus producing a stronger asphalt bond and aggregate matrix which in turn produced greater resistance to the repeated tensile stresses. Although there is apparently no information available on the effect of compaction temperature on fatigue life, Hadley et al (Refs 11 and 14) found that compaction temperature was very important to the tensile strength of asphalt-treated materials and that as the compaction temperature was increased from 200° F to 300° F, the tensile strength was significantly increased. Thus, compaction temperature has an important effect on the tensile behavior of asphalt-treated mixtures, and it is suggested that the temperature of the mixture at the time of compaction should be more closely controlled.

Mixing Temperature. As illustrated in Fig 30, the fatigue life was greater for asphalt-treated materials mixed at 350° F than for materials mixed at 250° F; however, the magnitude of the effect was not as large as that produced by the other factors. The increased mixing temperatures allowed the asphalt to more fully coat the limestone particles and provided a more uniform distribution of the asphalt, all of which increased the strength of the aggregate-asphalt matrix and the resistance to repetitive tensile stresses. It is also possible that the viscosity could have changed as the result of the higher mixing temperatures. No previous information on this variable and its effect on fatigue life is available, although related work (Refs 11 and 14) has shown that mixing temperature did not significantly affect the tensile strength of the same types of asphalt-treated materials.

Estimation of Fatigue Behavior

It would be desirable to estimate fatigue life or the relationships between stress and logarithm of fatigue life for various mixtures without conducting long-term fatigue tests for each material. One approach to making such estimates is to develop prediction equations which express fatigue life in terms of stress level and the important mixture and construction factors. A second approach is to relate fatigue life to other properties, e.g., modulus of elasticity, initial strain, stress-strength ratio, and air void content.

Prediction Equations. Simple prediction equations which provided satisfactory estimates of the fatigue behavior of the specimens and materials tested were developed. These were based on the findings from the analyses of variance, which showed that asphalt cement type, asphalt content, compaction temperature, and mixing temperature were important but, with one exception, did not interact to produce significant effects. All of the data from this experiment were combined, and a multiple regression analysis was conducted to develop equations for gravel and limestone mixtures treated with asphalt cement:

Gravel-asphalt cement mixtures

$$\text{Log } \hat{N}_f = 3.98060 - 0.26723A + 0.4405B + 0.25031C$$

$$+ 0.30331D - 0.78362E + 0.36732AC \qquad (4.1)$$

Limestone-asphalt cement mixtures

$$\text{Log } \hat{N}_f = 3.67579 - 0.54366A + 0.50400B + 0.31985C$$

$$+ 0.35408D - 0.66805E + 0.09747AC \qquad (4.2)$$

where

$\text{Log } \hat{N}_f$ = the predicted logarithm of fatigue life;

A = the coded level of asphalt content (-1, 0, +1);

B = the coded level of asphalt cement type (-1, 0, +1);

C = the coded level of mixing temperature (-1, 0, +1);

D = the coded level of compaction temperature (-1, 0, +1); and

E = the coded level of stress (-2, -1, 0, +1, +2, tensile stresses for 8, 16, 24, 32, 40 psi, respectively).

The coefficients of determination were 0.86 and 0.94 and the standard errors for the residuals were 0.48 and 0.32, respectively. Table 1 indicates the proper coded level which corresponds to a given factor level.

The measured values of fatigue life and those predicted by these two multiple regression equations are shown in Fig 31. The equations are both conservative; i.e., between 10^5 to 10^6 applications, the predicted fatigue life was less than the observed life. Since the regression equations were based on orthogonal coded data, trends indicated as significant in the regression analysis were essentially the same as those found to be important in the analyses of variance. These equations are very simple, with all effects linear; however, no attempt was made to evaluate the nonlinear effects. In addition, all the main effects were positive; i.e., by changing from a low level of a factor to a higher level, the fatigue life was increased, except

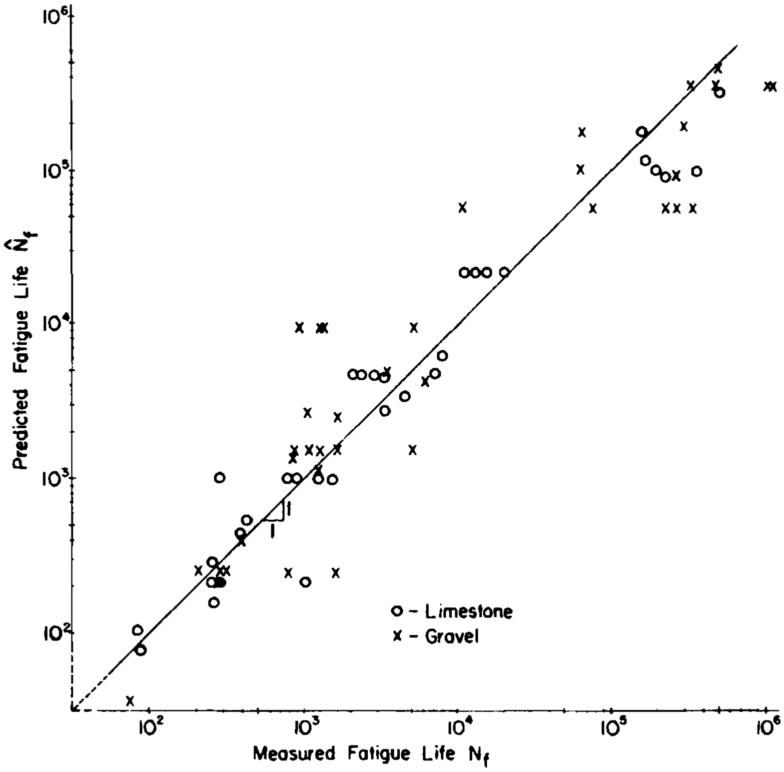


Fig 31. Comparison of measured and predicted fatigue life.

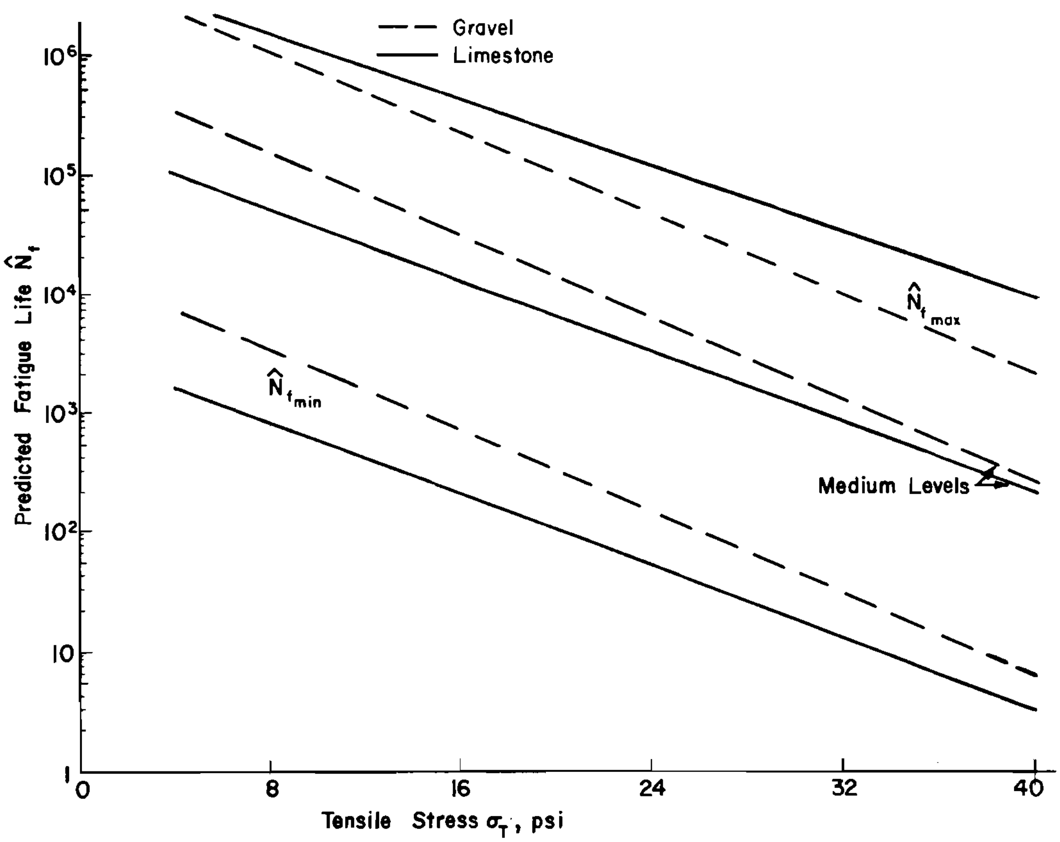


Fig 32. Predicted fatigue life relationships.

for asphalt content and stress level. For asphalt content, this has been interpreted, in view of previous information, to mean that the asphalt contents used in the development of the regression equation were probably higher than the optimum asphalt content for maximum fatigue life.

Caution must be exercised when attempting to apply these equations for conditions other than those directly associated with the data used in their development. It is recommended that these equations not be used at stress levels lower than 8 psi, since errors associated with the estimates may increase as the extrapolation moves further from the conditions of the investigation for which the data were obtained.

Figure 32 illustrates relationships between stress and predicted logarithm of fatigue life developed by using the two equations. The mixtures with the combination of mixture and compaction factors which produce the shortest fatigue life are noted by $\hat{N}_{f\ min}$. Mixtures composed of the levels of the mixture and compaction variables most likely to produce maximum fatigue life based on the experimental data are shown as the curves marked $\hat{N}_{f\ max}$. The effect of aggregate type is pronounced; the limestone is associated with the longest fatigue life. This results from the best combination of 5.5 percent asphalt content, AC-5 asphalt cement, 350° F mixing temperature, and 300° F compaction temperature, but the gravel performed better for other combinations of factors. It appears that properly proportioned limestone-asphalt cement mixtures might perform better than gravel-asphalt cement mixtures.

Correlation with Dependent Properties. As previously reported, attempts have been made to establish correlations between fatigue life and other material properties such as modulus of elasticity, initial strain, the stress-strength ratio, and air void content. Except for air void content, these parameters were not measured in this study; however, it was possible to estimate them utilizing relationships developed from indirect tensile test results for the same type of asphalt-treated materials.

Modulus of Elasticity. Hadley et al (Refs 13 and 15) developed a method for estimating the modulus of elasticity or stiffness in terms of the mixture and construction variables by using the total vertical and lateral deformations obtained from the indirect tensile test and a regression equation. Utilizing this equation, modulus values were estimated for the mixtures tested in repetitive loading. Figure 33 illustrates the relationships between the

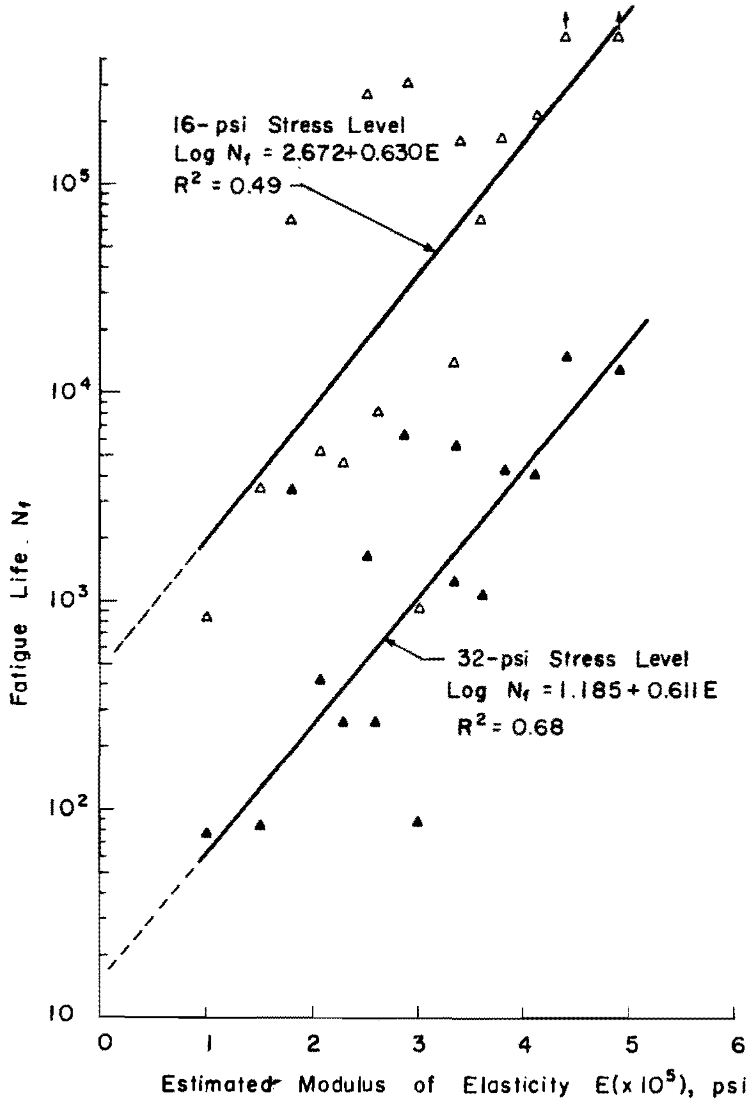


Fig 33. Effect of initial stiffness on fatigue life.

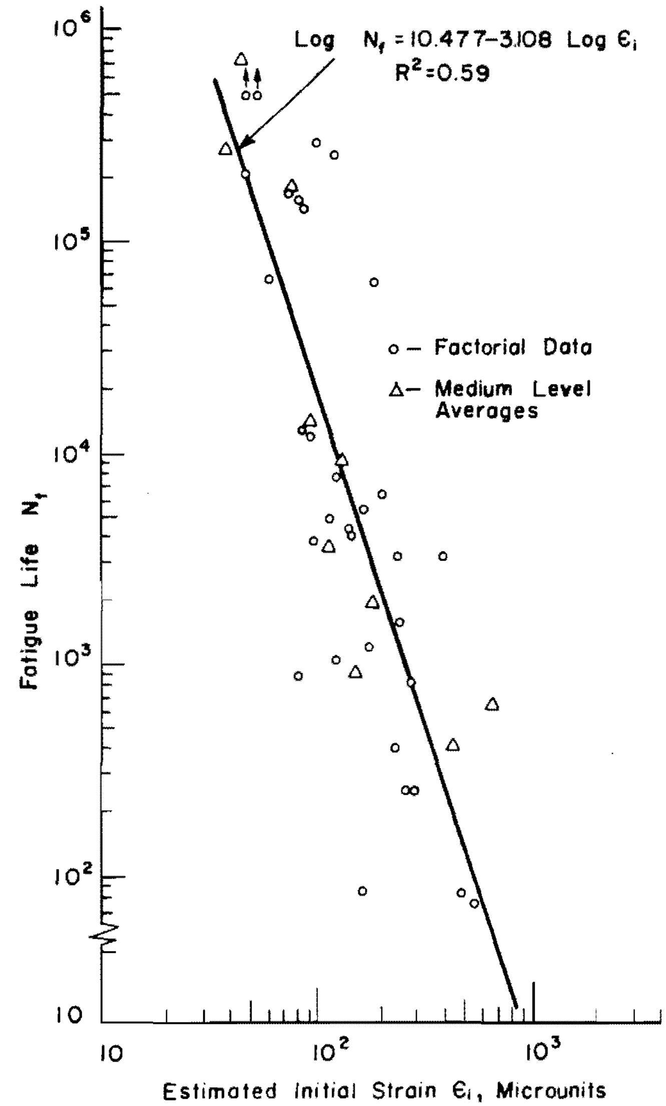


Fig 34. Relationship between the logarithms of fatigue life and initial strain under first repetition of load.

estimated modulus value and the logarithm of fatigue life for each tensile stress. These correlations are essentially linear and parallel, but the increase in fatigue life with an increase in modulus is probably slightly less for the higher tensile stress since it appears that the relationship for the 16-psi tensile stress would be steeper if the two specimens had been allowed to fail.

Both correlations had relatively low coefficients of determination (0.49 and 0.68) and, therefore, probably would not provide a satisfactory estimate of fatigue life for design use.

Initial Strain. Estimates of the initial tensile strains of the asphalt-treated specimens under the first application of stress were made based on the work reported by Hadley et al (Refs 14 and 15). The relationship between the logarithm of the estimated initial strain and the logarithm of fatigue life is shown in Fig 34. The mean values for the medium level data (Table 2) are also shown on the figure. The coefficient of determination was 0.59, indicating that these relationships would not be very satisfactory for estimation purposes. The trend indicated by this relationship suggests that if the tensile strains were less than 50 microunits, a satisfactory fatigue life, i.e. a relatively long fatigue life, would probably result.

Stress-Strength Ratio. The stress-strength ratio is defined as the ratio of the repeated stress to the estimated tensile strength of the material. The tensile strengths of the mixtures in this study were estimated from previously developed regression equations (Refs 14 and 15). The correlation between the logarithm of the estimated stress-strength ratio and the logarithm of fatigue life is shown in Fig 35. The coefficient of determination was 0.76, and it is felt that the stress-strength ratio can be used to estimate fatigue life of asphalt-treated materials since the relationship is relatively good for the variety of asphalt-treated mixture tested. The trend indicated by this relationship suggests that the applied tensile stress should be less than about 10 percent of the static indirect tensile strength in order to obtain a satisfactory fatigue life.

Air Void Content. Figure 36 illustrates the relationships between air void content and the logarithm of fatigue life for both a 16 and 32 psi stress level. This figure and a correlation analysis indicated that there was little relationship between fatigue life and void content for the asphalt mixtures in

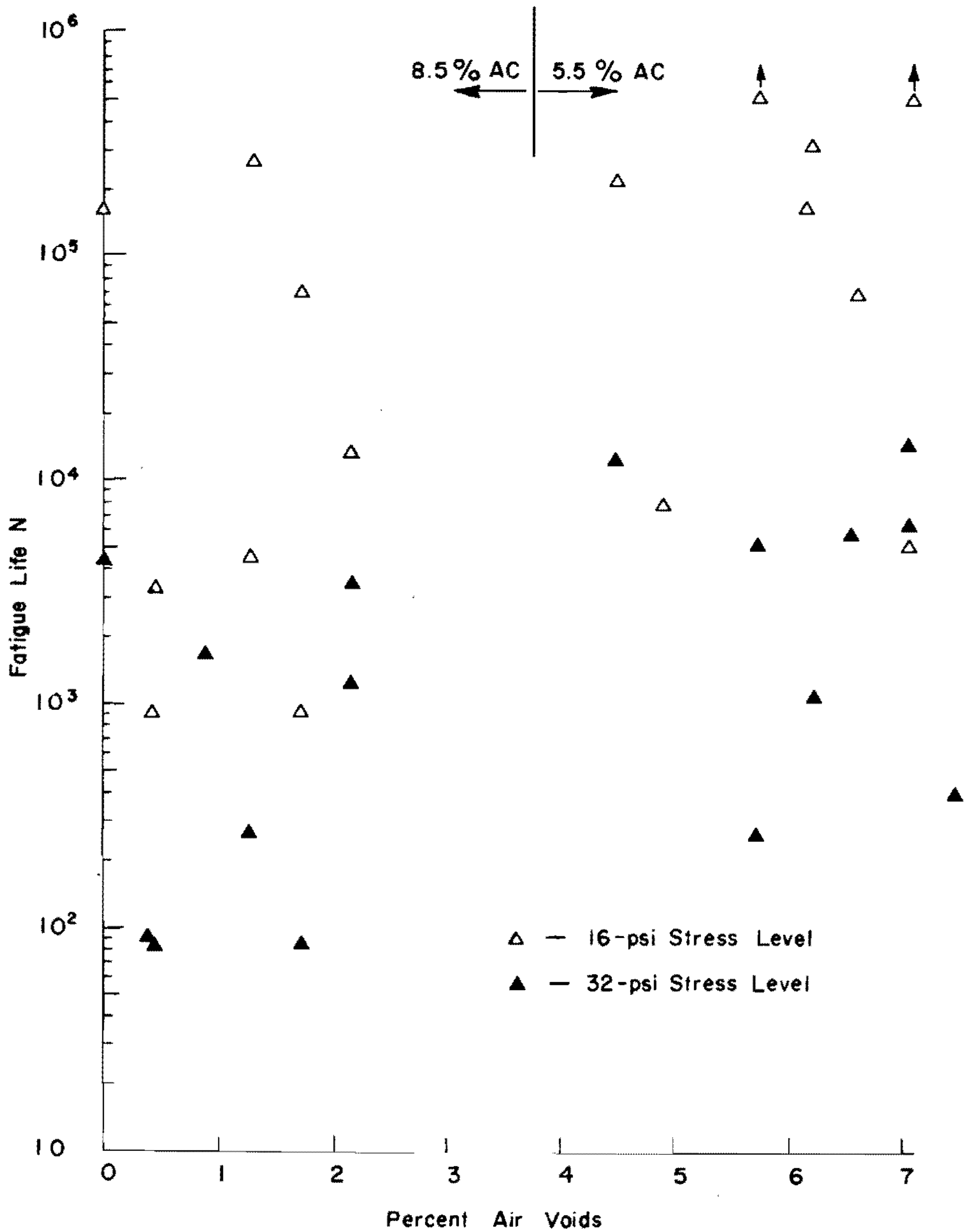


Fig 35. Relationship between logarithm of fatigue life and air void content.

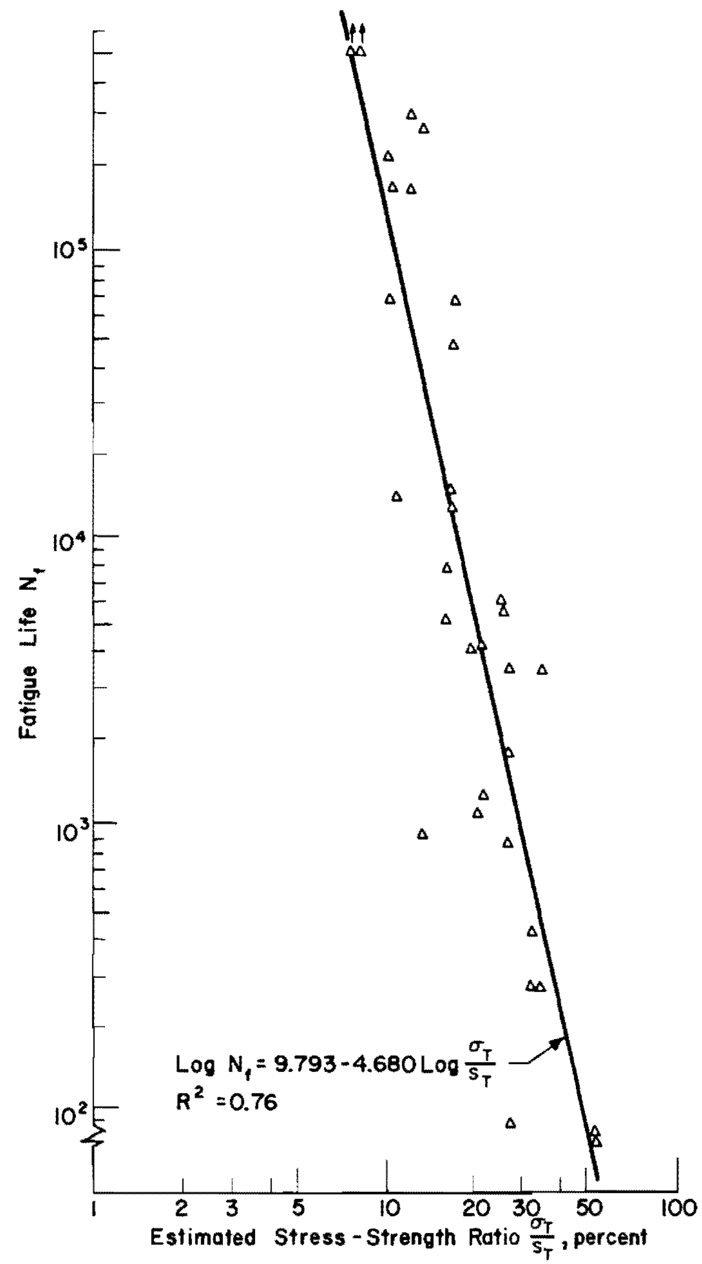


Fig 36. Relationship between logarithm of fatigue life and air void content.

this investigation. The coefficients of determination for both correlations were approximately 0.20, and as seen in the figure, fatigue life tended to increase slightly although not significantly with increased air void content. Data presented by Hadley et al (Ref 14) indicated that there was no general correlation between air void content and tensile strength. Nevertheless, for a given single mixture, such a correlation could exist, as documented by Epps and Monismith (Ref 10), Pell and Taylor (Ref 44), Bazin and Saunier (Ref 4), and Saal and Pell (Ref 46), all of whom used other test configurations. Thus, it seems that air void content is not directly related to laboratory tensile fatigue life but may relate to the fatigue properties of a given basic mixture if the voids are allowed to vary. In addition, void content may have a more definite influence on the performance of an actual in-service pavement due to age hardening or other environmental influences.

CEMENT-TREATED MATERIALS

Detailed findings with regard to the fatigue characteristics of the cement-treated materials were very limited due to difficulties associated with establishing a stress level which was compatible with the wide range of strengths exhibited by the various mixtures. Nevertheless, it was found that the indirect tensile test could be used for the study of the fatigue behavior of the cement-treated materials.

Stress-Fatigue Life Relationship

The duplicate specimens were mixtures which combined 6.5 percent molding water, 6 percent cement, and two aggregate types, a rounded gravel and a crushed limestone. The specimens were compacted using the gyratory shear compactor at a compactive effort of 110 psi* and were cured at 100° F. Two aggregates were used during the center point testing since previous work (Refs 45 and 3) indicated higher tensile strengths for the limestone aggregate than for the rounded gravel. The fatigue results for the center point specimens tested are listed in Table 5 and shown graphically as a tensile stress and logarithm of fatigue life relationship in Fig 37. As previous work indicated, fatigue life of specimens containing limestone aggregate was greater

*See Appendix 2 for a description of the procedure utilized for compaction.

TABLE 5. FATIGUE LIFE DATA FOR DUPLICATE CEMENT-TREATED SPECIMENS

Tensile Stress, psi	Aggregate	Fatigue Life: Measured	Average	Variance	Standard Deviation
130	Gravel	16,816	--	--	--
145	Gravel	1,520 4 16,949 98 9,246 11 500,000*	75,404	$35{,}100 \times 10^6$	187.3×10^3
150	Gravel	3 17	10	--	--
160	Gravel	4 2	3	--	--
170	Gravel	1	--	--	--
188	Gravel	2	--	--	--
200	Gravel	1			
	Limestone	500,000*	--	--	--
260	Limestone	92,828 500,000*	296,414	--	--
300	Limestone	1 1 8 96 6	22.4	1,735	41.65
320	Limestone	248 1 12	87	--	--
400	Limestone	1	--	--	--
450	Limestone	1 1	1	--	--

* Specimen did not fail.

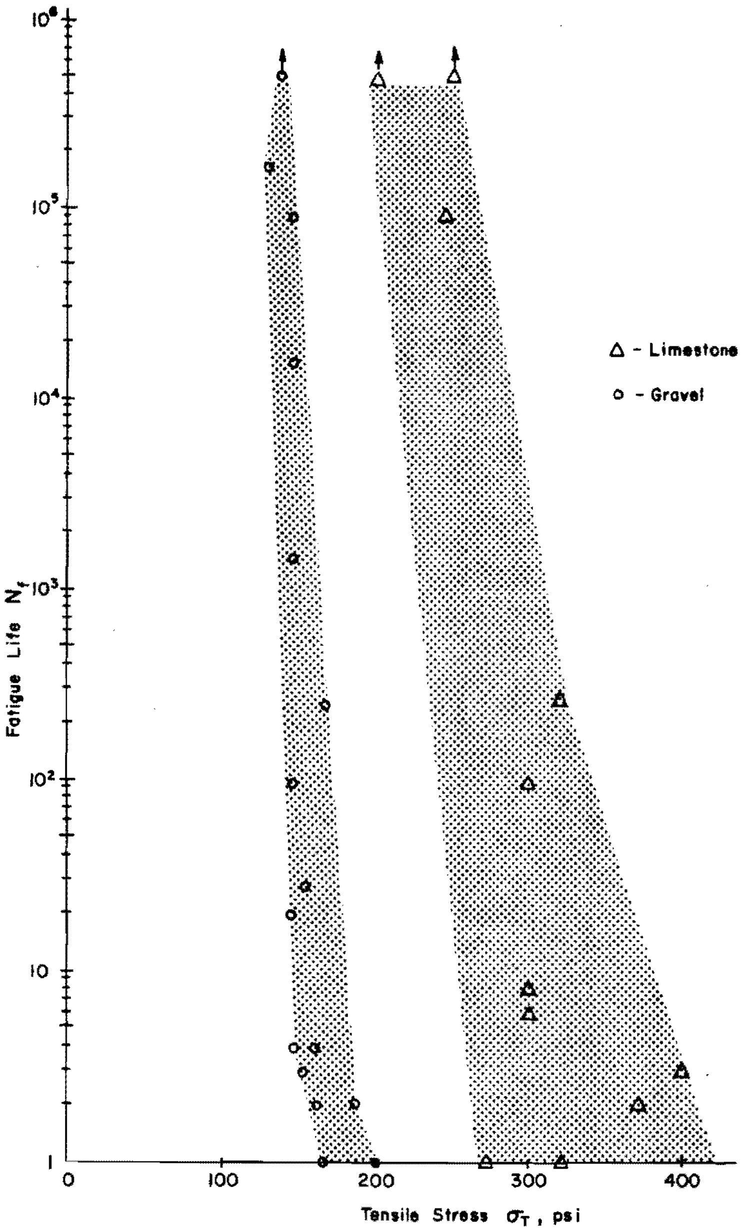


Fig 37. Relationships between logarithm of fatigue life and tensile stress for cement-treated materials.

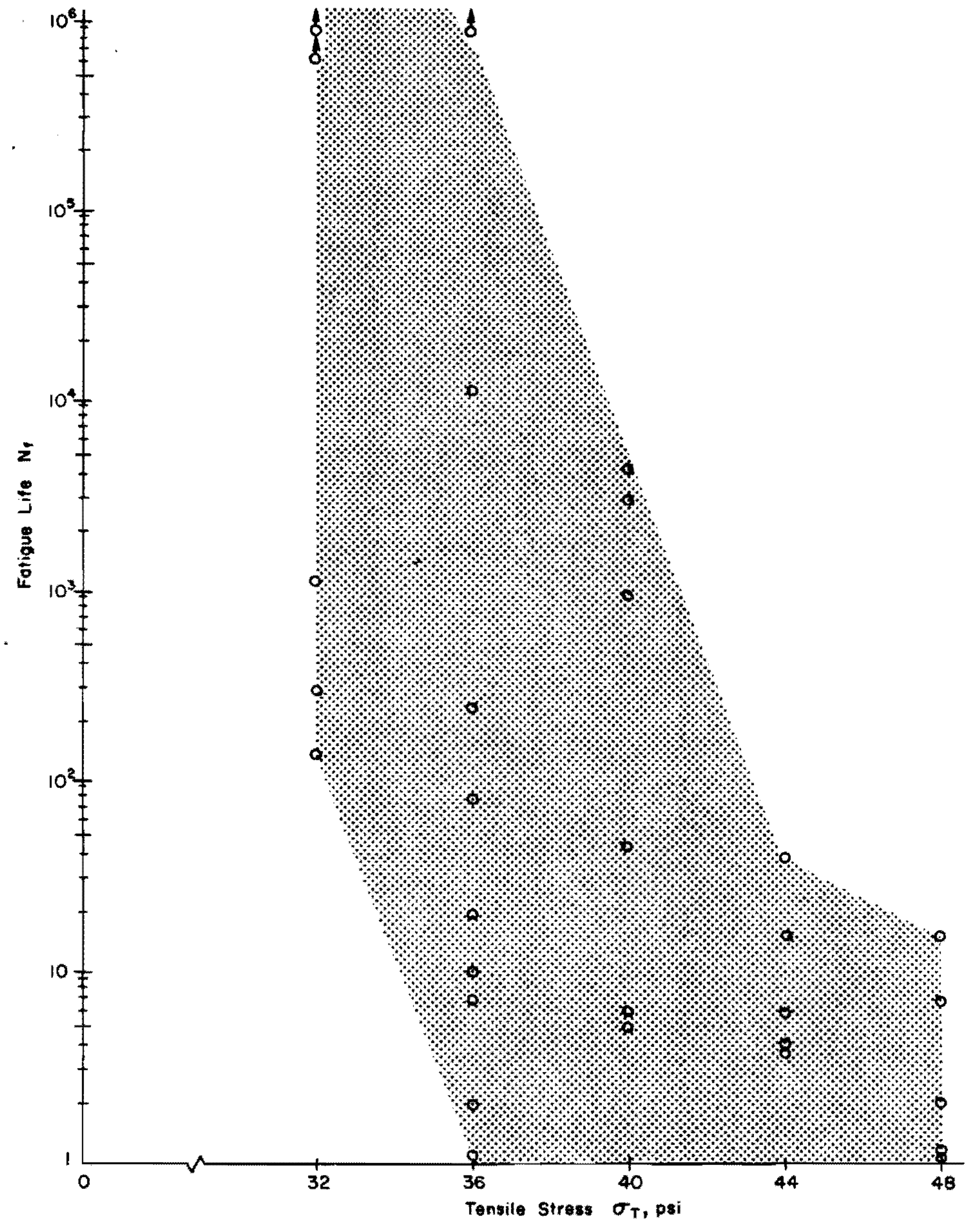


Fig 38. Relationships between logarithm of fatigue life and tensile stress for lime-treated materials.

than for specimens containing gravel aggregate. There also appeared to be a critical stress level above which the fatigue life was very short and below which the fatigue life was very long. For the specimens containing limestone, this critical stress level was approximately 300 psi, while for the gravel specimens, it was much lower, about 150 psi.

Limitations in Experiment Design

In the factorial experiment two stress levels were used to test the limestone and gravel specimens, 300 psi and 150 psi, respectively. All specimens failed at less than ten applications of stress. Thus, the strength range for the various mixtures and conditions included in this experiment was too large to allow testing of all of the mixtures at a given stress level. For example, the range of estimated tensile strengths for the cement-treated materials varied from 176 psi to 423 psi (Ref 3). A stress level which would cause fatigue failure to occur for the high strength specimens would cause the low strength specimens to fail on the first application of stress. On the other hand, a stress level which would cause the low strength specimens to fail in fatigue would not be severe enough to produce a fatigue failure of the high strength specimens.

Conclusions

It appears that the indirect tensile test has potential for the further investigation of cement-treated materials. The specimens composed of limestone aggregate were stronger and had a longer fatigue life than specimens composed of rounded gravel, although both have similar stress-fatigue life relationships. As with previous research, there was significant variation in the fatigue life of duplicate specimens subjected to the same stress level. The results suggest that there may be a critical stress level below which the number of applications of tensile stress required to cause failure would increase substantially.

LIME-TREATED MATERIALS

The results from the fatigue testing of lime-treated materials using the indirect tensile test also were limited due to difficulties in establishing a stress range applicable to the strength range of the materials included in the experiment. Nevertheless, the test was shown to be applicable to the study of the fatigue behavior of lime-treated materials and some information was obtained with respect to the general nature of the stress-fatigue life relationship, the variation associated with fatigue life, and factors affecting the fatigue life.

Stress-Fatigue Life Relationship

Specimens composed of 13 percent molding water, 3 percent lime content, and 50 percent clay content, compacted with a compactive effort designated as 125 psi on the gyratory shear compactor, and cured at 100° F, were tested at several stress levels. The number of stress applications required to produce failure of these duplicate specimens when subjected to different stress levels is listed in Table 6, and the relationship between tensile stress and the logarithm of fatigue is shown in Fig 38. Considerable variation is noted as the stress level approaches 32 psi, but the general trend was that the fatigue life increased as the stress level decreased. However, as with the cement-treated specimens, the tensile stress-logarithm fatigue life relationship did not indicate a gradual increase of fatigue life with decreased stress level. Figure 38 suggests that the fatigue life was very short until the stress dropped below some critical value, at which point the fatigue life became very large. This change was very abrupt and occurred within a small stress range, less than 10 psi.

Factors Affecting Fatigue Life

A tensile stress of 36 psi was used to test the half-fractional arrangement of treatments. It was felt that this stress level would be high enough to collect fatigue data for the specimens cured at 125° F and also be low enough to enable fatigue results to be obtained from some specimens cured at 75° F.

As shown in Table 7, the 36 psi stress level was too severe for the specimens cured at 75° F and all specimens failed in one to two cycles. As expected, the analysis of variance for the data at both temperature levels indicated that curing temperature was the only factor which had a significant effect on fatigue life. Moisture content at the time of test was confounded with the curing temperatures since the 75° F specimens had moisture contents in the 8 to 10 percent range and the 125° F specimens had moisture contents of less than 2 percent. The higher temperatures, which would be expected to accelerate the lime reaction, also caused an apparent moisture loss even though the specimens were sealed.

TABLE 6. FATIGUE LIFE DATA FOR DUPLICATE LIME-TREATED SPECIMENS

Tensile Stress, psi	Fatigue Life			
	Measured	Average	Variance	Standard Deviation
32	410,000* 259,640* 135 295 1,162	134,246	$36,350 \times 10^6$	191×10^3
36	10 245 173,000* 1,199 92 19 1 2 7	19,397	$3,318 \times 10^6$	57.6×10^3
40	2,935 4,382 5 46 6 924	1,383	3.44×10^6	1.86×10^3
44	16 3 39 3 6	13	234	15.3
48	8 7 2 1 1	4	11.8	3.43

* Specimen did not fail.

TABLE 7. FATIGUE LIFE FOR LIME-TREATED SPECIMENS TESTED AT 36 PSI

Curing Temperature, °F	Compact Effort, Psi	Clay 37.5 / Water 10.5 / Lime 1.5	Clay 37.5 / Water 10.5 / Lime 4.5	Clay 37.5 / Water 15.5 / Lime 1.5	Clay 37.5 / Water 15.5 / Lime 4.5	Clay 62.5 / Water 10.5 / Lime 1.5	Clay 62.5 / Water 10.5 / Lime 4.5	Clay 62.5 / Water 15.5 / Lime 1.5	Clay 62.5 / Water 15.5 / Lime 4.5
125	150		500,000*	2		500,000*			500,000*
	100	345			2		147,595	60	
75	150	1			1		1	2	
	100		1	1		2			1

* Specimen Did Not Fail

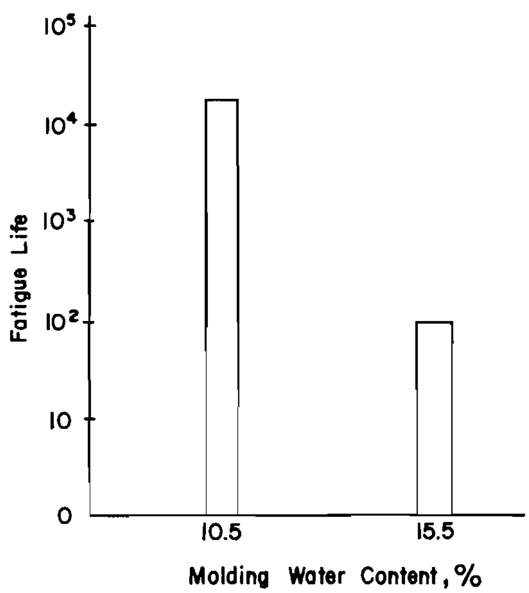


Fig 39. Effect of molding water content on fatigue life of lime-treated materials cured at 125° F.

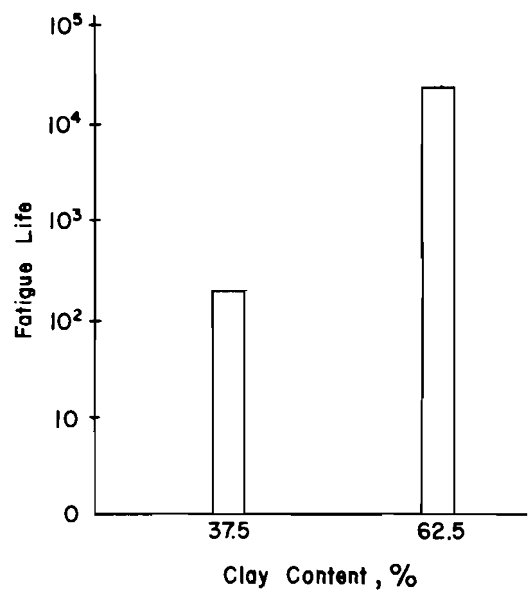


Fig 40. Effect of clay content on fatigue life of lime-treated materials cured at 125° F.

The data were reanalyzed using only the 125^{o} F specimens to determine if any factors were significant within this curing temperature. The analysis of variance summary showed that water content during compaction and clay content influenced fatigue life.

Water Content During Compaction. The fatigue life of specimens compacted at 15.5 percent water content was higher than that for specimens compacted at 10.5 percent (Fig 39). Tulloch et al (Ref 60) found a similar effect for static tensile strength over a range of curing temperatures from 50^{o} F to 150^{o} F which was interpreted to mean that the moisture contents were all on the wet side of an optimum water content for strength.

Clay Content. As the clay content was increased from 37.5 percent to 62.5 percent, the fatigue life increased (Fig 40). Tulloch et al (Ref 60) found that clay content did not have a direct effect on tensile strength but did significantly influence the effect produced by other factors and was, therefore, very important.

Conclusions

These results are from a limited investigation, and additional work must be done before adequate conclusions concerning the factors which affect the fatigue life of lime-treated materials can be made. The factor levels selected were not compatible for the testing of the entire design at a single stress level. A better experiment can be developed after additional indirect tensile test data are obtained. Nevertheless, it was concluded that the indirect tensile test can be used to obtain information on the fatigue behavior of lime-treated materials subjected to repeated tensile stresses, and it is felt that meaningful fatigue results can be obtained. In addition, the data indicated that there might be some critical stress level below which a long fatigue life might be expected.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the findings from a study in which asphalt-treated, cement-treated, and lime-treated materials were subjected to repeated tensile stresses by means of the indirect tensile test. The conclusions and recommendations based on these findings are stated below.

CONCLUSIONS

General

(1) The indirect tensile test can be used to study the fatigue characteristics of asphalt-treated, cement-treated, and lime-treated materials subjected to repeated applications of tensile stress.

(2) There was significant random variation associated with the fatigue life data for all three basic types of materials studied.

Asphalt-Treated Materials

(1) The relationship between tensile stress and the logarithm of fatigue life was essentially linear, as previously reported from studies utilizing other test configurations. Fatigue failures occurred at indirect tensile stresses ranging from 8 to 40 psi, which were approximately 6 to 30 percent of the static indirect tensile strengths.

(2) Significant random variation in fatigue life occurred. It was found that the standard deviation of fatigue life varied linearly with the mean of fatigue life and that the variation was aggregate dependent. The variation of fatigue life for the asphalt-gravel mixtures was much larger than for the limestone-asphalt mixtures. The coefficient of variation for the limestone was 30 percent while the coefficient of variation for the gravel was more than 75 percent.

(3) The tensile fatigue life characteristics were found to be affected by the type of asphalt cement, asphalt content, compaction temperature, and mixing temperature. Within the range tested, it was found that fatigue life was increased by using a more viscous asphalt cement, higher compaction temperatures, and higher mixing temperatures. It was also concluded that there is an optimum asphalt content for maximum fatigue life.

(4) A simple predictive equation developed from the results of this study adequately described the fatigue lives observed in the study. However, additional information should be included in the equation to make it applicable to other types of asphalt-treated materials and to define better the effects produced by varying asphalt content.

(5) As in previous studies, fatigue life was found to correlate with stiffness, initial tensile strain, and stress-strength ratio. Fatigue life increased with

 (a) increased stiffness,

 (b) decreased initial tensile strains, and

 (c) decreased stress-strength ratios.

 Each of these correlations was associated with a large amount of scatter, as expected, since fatigue life involves a great deal of inherent variation. The stress-strength ratio provided the best correlation with fatigue life and possibly could be used to estimate fatigue life from static test results. For the variety of mixtures tested in this study, it was concluded that there was no general relationship between laboratory fatigue life and air void content, although a correlation might exist for a given mixture.

(6) The correlation between fatigue life and stress-strength ratio suggested that tensile stress should be less than 10 percent of the static indirect tensile strength, and the correlation between fatigue life and initial tensile strain indicated that the initial strain should be less than about 50 micro units, in order to obtain a satisfactory fatigue life, i.e., a relatively long fatigue life.

Cement and Lime-Treated Materials

(1) 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 long.

(2) For the lime-treated materials cured at 125° F and subjected to a tensile stress of 36 psi,

 (a) specimens compacted at a water content of 10.5 percent had a longer fatigue life than specimens compacted at a water content of 15.5 percent, and

 (b) specimens containing 62.5 percent clay had a longer fatigue life than specimens containing 37.5 percent clay.

(3) Difficulties associated with the fatigue testing of both materials make it necessary to conduct additional tests before definite conclusions can be made.

RECOMMENDATIONS

(1) Additional fatigue information is needed for all three types of stabilized materials, especially cement-treated and lime-treated materials. Special emphasis should be placed on determining whether there is a critical stress level below which the mixture can withstand many applications of tensile stress without failure.

(2) Additional research should be conducted to determine the magnitude of changes which occur in the material properties, e.g., tensile strength and modulus, under repetitive tensile stresses. This study was concerned only with fatigue life.

(3) Future research should initially investigate stabilized materials which simulate field conditions, e.g., density, moisture, and stress level, at stress levels expected to occur within the layers of pavement constructed with these mixtures.

(4) Additional research should consider the cumulative effects of repeated stresses by perhaps using compound loading programs instead of maintaining only one stress level and one frequency. Frequency of load application should be studied and random frequency of loading should also be considered.

(5) Future research should also consider controlled strain testing.

(6) Although deformation characteristics were not discussed in this study, the deformation measuring devices used for the indirect tensile test should be improved in order to measure the total and resilient deformations of stabilized materials.

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

REFERENCES

1. Ahlberg, Harold L., and William W. McVinnie, "Fatigue Behavior of Lime-Fly Ash-Aggregate Mixtures," Bulletin 335, Highway Research Board, 1962, pp 1-10.

2. Ahmed, S. B., and H. G. Larew, "A Study of the Repeated Load Strength Moduli of Soils," First International Conference on the Structural Design of Asphalt Pavement, Preprint Vol, Ann Arbor, Michigan, 1961, pp 10-97 through 10-108.

3. Anagnos, James A., Thomas W. Kennedy, and W. Ronald Hudson, "Evaluation and Prediction of Tensile Properties of Cement-Treated Materials," Research Report 98-8, Center for Highway Research, The University of Texas at Austin, December 1970.

4. Bazin, P., and J. B. Saunier, "Deformability, Fatigue and Healing Properties of Asphalt Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, 1967, pp 553-569.

5. Cochran, William G., and Gertrude M. Cox, Experimental Designs, John Wiley and Sons, New York, 1968.

6. Davies, Owen, L., Design and Analysis of Industrial Experiments, Second Edition, Hafner Publishing Company, New York, 1967.

7. Deacon, John A., "Material Characterization-Experimental Behavior," paper presented at the Workshop on Structural Design of Asphalt Concrete Pavement Systems, Austin, Texas, 1970.

8. Deacon, John A., and Carl L. Monismith, "Laboratory Flexural Fatigue Testing of Asphalt Concrete with Emphasis on Compound Loading Tests," Highway Research Record No. 158, Highway Research Board, 1967, pp 1-31.

9. Dunlap, Wayne A., "Deformation Characteristics of Granular Materials Subjected to Rapid Repetitive Loading," Research Report No. 27-4, Texas Transportation Institute, Texas A&M University, College Station, Texas, November 1967.

10. Epps, Jon A., and Carl L. Monismith, "Influence of Mixture Variables on Flexural Fatigue Properties of Asphalt Concrete," Proceedings, Association of Asphalt Paving Technologists, Vol 38, 1969, pp 423-464.

11. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Research Report 98-2, Center for Highway Research, The University of Texas at Austin, March 1969.

12. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "Correlation of Tensile Properties with Stability and Cohesiometer Values for Asphalt-Treated Materials," Research Report 98-6, Center for Highway Research, The University of Texas at Austin, June 1970.

13. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension," Research Report 98-7, Center for Highway Research, The University of Texas at Austin, July 1970.

14. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," Research Report 98-9, Center for Highway Research, The University of Texas at Austin, May 1971.

15. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," Highway Research Record No. 351, Highway Research Board, 1971, pp 35-49.

16. Hondros, G., "The Evaluation of Poisson's Ratio and the Modulus of Materials of a Low Tensile Resistance by the Brazilian (Indirect Tensile) Test with Particular Reference to Concrete," Australian Journal of Applied Science, Vol 10, No. 3.

17. Hudson, W. Ronald, and Thomas W. Kennedy, "An Indirect Tensile Test for Stabilized Materials," Research Report 98-1, Center for Highway Research, The University of Texas at Austin, January 1968.

18. Jimenez, Rudolf A., and Bob M. Gallaway, "Behavior of Asphaltic Concrete Diaphragms to Repetitive Loadings," Proceedings, International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, 1962, pp 339-344.

19. Kennedy, Thomas W., and W. Ronald Hudson, "Application of the Indirect Tensile Test to Stabilized Materials," Highway Research Record No. 235, Highway Research Board, 1969, pp 36-48.

20. Kennedy, Thomas W., and Raymond K. Moore, "Estimations of Indirect Tensile Strengths for Lime-Treated Materials," Highway Research Record No. 351, Highway Research Board, 1971, pp 66-77.

21. Kirk, J. M., "Results of Fatigue Tests on Different Types of Bituminous Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan, 1967, pp 571-575.

22. Lara-Thomas, Monrique, "Time-Dependent Deformation of Clay Soils Under Shear Stress," International Conference on the Structural Design of Asphalt Pavements, Preprint Vol, Supplement, Ann Arbor, Michigan, 1961, pp 2-11 through 2-22.

23. Larew, H. G., and G. A. Leonards, "A Strength Criterion for Repeated Loads," Proceedings, Highway Research Board, Vol 41, January 1962, pp 529-556.

24. Larsen, T. J., and P. J. Nussbaum, "Fatigue in Soil-Cement," Journal of the Portland Cement Association, Vol 9, No. 2, May 1967, pp 37-59.

25. Lee, Clyde E., "The Determination of Pavement Deflection Under Repeated Load Applications," Unpublished Dissertation, Doctor of Engineering, The University of California, Berkeley, California, 1961.

26. Lou, T. N., "Effect of Repeated Loading on the Viscosity of Paving Asphalts in Thin Films," Unpublished Thesis, Master of Science in Civil Engineering, The University of Texas, Austin, January 1964.

27. Manual of Testing Procedures, Texas Highway Department, Vol 1, September 1966.

28. Miller, S. Paul, Thomas W. Kennedy, and W. Ronald Hudson, "Evaluation of the Factors Affecting the Tensile Properties of Lime-Treated Materials," Research Report 98-4, Center for Highway Research, The University of Texas at Austin, March 1970.

29. Monismith, Carl L., "Flexibility Characteristics of Asphalt Paving Mixtures," Proceedings, Association of Asphalt Paving Technologists, Vol 27, 1958, pp 74-106.

30. Monismith, Carl L., "Asphalt Mixture Behavior in Repeated Flexure," Report No. TE-65-9, Institute of Transportation and Traffic Engineering, University of California, Berkeley, California, November 1965.

31. Monismith, Carl L., "Asphalt Mixture Behavior in Repeated Flexure," Report No. TE-66-6, Institute of Transportation and Traffic Engineering, University of California, Berkeley, California, December 1966.

32. Monismith, Carl L., "Fatigue of Asphalt Paving Mixtures," paper presented to the First Road and Streets Conference, University of Nevada, March 1969.

33. Monismith, Carl L., "Design Considerations for Asphalt Pavements," paper presented at the First Conference on Asphalt Pavements for Southern Africa, Durban, Republic of South Africa, July 1969.

34. Monismith, Carl L., and John A. Deacon, "Fatigue of Asphalt Paving Mixtures," Journal of Transportation Engineering, ASCE, Vol 95, No. TE2, May 1969, pp 317-346.

35. Monismith, Carl L., and Kenneth E. Secor, "Thixotropic Characteristics of Asphalt Paving Mixtures with Reference to Behavior in Repeated Loading," Proceedings, Association of Asphalt Paving Technologists, Vol 29, 1960, pp 114-140.

36. Monismith, Carl L., Kenneth E. Secor, and Edward W. Blackmer, "Asphalt Mixture Behavior in Repeated Flexure," Proceedings, Association of Asphalt Paving Technologists, Vol 30, 1961, pp 188-222.

37. Monismith, Carl L., H. Bolton Seed, F. G. Mitry, and C. K. Chan, "Prediction of Pavement Deflections from Laboratory Tests," Proceedings, Second International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan, 1967, pp 109-140.

38. Moore, Raymond K., James N. Anagnos, and Thomas W. Kennedy, "Estimations of Indirect Tensile Strengths for Cement-Treated Materials," Highway Research Record No. 351, Highway Research Board, 1971, pp 112-114.

39. Moore, Raymond K., Thomas W. Kennedy, and W. Ronald Hudson, "Factors Affecting the Tensile Strength of Cement-Treated Materials," Highway Research Record No. 315, Highway Research Board, 1970, pp 64-80.

40. Moore, Raymond K., Thomas W. Kennedy, and Joseph A. Kozuh, "Tensile Properties for Design of Lime-Treated Materials," Highway Research Record No. 351, Highway Research Board, 1971, pp 78-86.

41. Nguyen-van-Hue, "The Effect of Repeated Loading on the Strength and Deformation of Taylor Marl Clay Stabilized with Lime," Unpublished Thesis, Master of Science in Civil Engineering, The University of Texas at Austin, January 1966.

42. Pell, P. S., "Fatigue Characteristics of Bitumen and Bituminous Mixes," Proceedings, International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, Michigan, 1962, pp 310-323.

43. Pell, P. S., "Fatigue of Asphalt Pavement Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, 1967, pp 577-593.

44. Pell, P. S., and I. F. Taylor, "Asphaltic Road Materials in Fatigue," Proceedings, Association of Asphalt Paving Technologists, Vol 38, 1969, pp 371-422.

45. Pendola, Humberto P., Thomas W. Kennedy, and W. Ronald Hudson, "Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials," Research Report 98-3, Center for Highway Research, The University of Texas at Austin, September 1969.

46. Saal, R. N. J., and P. S. Pell, "Fatigue of Bituminous Road Mixes," Kolloid-Zeitschrift (Darmstadt), Vol 17, 1960, pp 61-71

47. Seed, H. Bolton, and C. K. Chan, "Thixotropic Characteristics of Compacted Clays," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol 83, No. SM4, paper 1427, November 1957.

48. Seed, H. Bolton, and C. K. Chan, "Effect of Stress History and Frequency of Stress Application on Deformation of Clay Subgrades Under Repetitive Loading," Proceedings, Highway Research Board, Vol 37, January 1958, pp 555-575.

49. Seed, H. Bolton, and C. K. Chan, "A Study of the Deformational Characteristics of the AASHO Road Test Subgrade Under Repeated Loading," A report to the AASHO Road Test Staff, 1960 (Unpublished).

50. Seed, H. Bolton, and C. K. Chan, "Effects of Stress Applications on the Soil Deformations Under Repeated Loading," Proceedings, Fifth International Conference on Soil Mechanics and Foundation Engineering, Vol 1, Paris, 1961, pp 341-345.

51. Seed, H. Bolton, C. K. Chan, and Clyde E. Lee, "Resilience Characteristics of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavements," International Conference on the Structural Design of Asphalt Pavements, Preprint Vol, Supplement, Ann Arbor, Michigan, 1961, pp 6-77 through 6-113.

52. Seed, H. Bolton, C. K. Chan, and Carl L. Monismith, "Effect of Repeated Loading on the Strength and Deformation of Compacted Clay," Proceedings, Highway Research Board, Vol 34, January 1955, pp 541-558.

53. Seed, H. Bolton, and Robert L. McNeill, "Soil Deformations in Normal Compression and Repeated Loading Tests," Bulletin 141, Highway Research Board, 1956, pp 44-56.

54. Seed, H. Bolton, and Robert L. McNeill, "Soil Deformations Under Repeated Stress Applications," American Society for Testing and Materials, STP No. 232, 1957, pp 177-197.

55. Seed, H. Bolton, Robert L. McNeill, and J. deGuenin, "Increased Resistance to the Deformation of Clay Caused by Repeated Loadings," Journal of Soil Mechanics and Foundations Division, ASCE, Vol 84, No. SM2, paper 1645, May 1958.

56. Shen, Chih-Kang, and James K. Mitchell, "Behavior of Soil Cement in Repeated Compression and Flexure," Highway Research Record No. 128, Highway Research Board, 1966, pp 68-100.

57. Snedecor, George W., and William G. Cochran, Statistical Methods, Iowa State University Press, Ames, Iowa, 1968.

58. Swanson, T. E., and Marshall R. Thompson, "Flexural Fatigue Strength of Lime-Soil Mixtures," Highway Research Record No. 198, Highway Research Board, 1967, pp 9-19.

59. Texas Highway Department, Construction Division, "Design of Laboratory Mixes, Selection of Optimum Asphalt Content," Bulletin C-14, September 1964, pp 10-12.

60. Tulloch, Walter S., III, W. Ronald Hudson, and Thomas W. Kennedy, "Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials," Research Report 98-5, Center for Highway Research, The University of Texas at Austin, June 1970.

61. Whittle, J. P., and H. G. Larew, "Effects of Repeated Loads on Elastic Micaceous Soils Stabilized with Portland Cement," Highway Research Record No. 86, Highway Research Board, 1965, pp 28-38.

62. Wood, L. E., and W. H. Goetz, "Strength of Bituminous Mixtures and Their Behavior Under Repeated Loads," Proceedings, Highway Research Board, Vol 35, 1956, pp 405-417.

63. Wood, L. E., and W. H. Goetz, "Strength of Bituminous Mixtures and Their Behavior Under Repeated Loads, Part II," Proceedings, Highway Research Board, Vol 36, 1957, pp 318-333.

APPENDIX 1

BATCHING AND MIXING PROCEDURES

APPENDIX 1. BATCHING AND MIXING PROCEDURES

ASPHALT-TREATED MATERIALS

(1) Batch material by dry weight in storage containers, mixing fines and coarse fractions.

(2) Heat aggregate and asphalt to the appropriate mixing temperature (either 250° F or 350° F $\pm$ 5° F).

(3) Mix aggregate and asphalt at the specified temperature (either 250° F or 350° F $\pm$ 5° F) for 3 minutes in an automatic mixer.

CEMENT-TREATED MATERIALS

(1) Select the cement content and moisture content from the mix designs in experimental treatment combinations. Batch the material by dry weight as follows:

  (a) Weigh and store that portion of aggregate retained on the No. 10 sieve.

  (b) Weigh and store in a separate container that portion of material passing the No. 10 sieve.

(2) Add the appropriate quantity of water to the portion of material retained on the No. 10 sieve and stir the mixture thoroughly.

(3) Add the appropriate quantity of cement to the portion of material passing the No. 10 sieve and mix by hand.

(4) Add the cement and fines to the wet coarse aggregate (plus No. 10).

(5) Machine mix for one minute, remove the fines adhering to the bottom of the mixing bowl, and continue to mix for an additional minute.

LIME-TREATED MATERIALS

(1) Select the clay content to be used. Batch the material by weight in the following way:

  (a) Weigh the portion of aggregate retained on No. 10 sieve and store in a container.

  (b) Weigh the appropriate portion of clay and the portion of aggregate passing No. 10 sieve and store in a different container.

(2) Add the appropriate amount of lime to the portion of aggregate passing No. 10 sieve.

(3) Mix the fine aggregate and clay with the lime by hand.

(4) Add half of the appropriate mixing water to the coarse portion of the aggregate and hand mix until the surfaces of all the coarse aggregate are wet.

(5) Add the fines and lime to the wet coarse aggregate and spread the fines over the coarser aggregate; then, add the remaining water.

(6) Machine mix in a bowl for one minute; remove the fines stuck to the bottom and mix an additional minute.

APPENDIX 2

COMPACTION PROCEDURES

APPENDIX 2. COMPACTION PROCEDURES

ASPHALT-TREATED MATERIALS

(1) The mixes are placed in preheated ovens and brought to the required compaction temperature (either 200° F or 300° F ± 5° F).

(2) The mixes are then compacted at the specified temperature by the Texas gyratory-shear compactor as specified in test method TEX-206-F (Ref 27).

(3) Extrude the specimen, weigh, and measure the height and diameter of the specimen.

CEMENT-TREATED MATERIALS

(1) Coat the mold and base plate with a thin layer of kerosene, and place a circular-shaped piece of filter paper at the bottom of the mold.

(2) Transfer the laboratory mixes into the mold in approximately three equal layers. Rod each layer and use a small spatula to remove the larger particles away from the mold wall. Place a circular-shaped piece of filter paper on top of the mixture.

(3) Slide mold onto the platen and center it in molding position beneath the ram.

(4) Apply pressure to the specimen until 30 psi is reached on the low pressure gage. Gyrate the specimen three times and stop. Repeat the three gyrations until the desired compactive effort (85, 110, or 135) is registered on the low-pressure gage.

(5) At approximately one stroke per second, increase the pressure to 1,000 psi, as measured on the high-pressure gage. Then release the pressure and pump the ram up and out of the mold.

(6) Extract the 2-inch-high by 4-inch-diameter specimen from the mold.

(7) Weigh and measure the height and diameter of the specimen.

LIME-TREATED MATERIALS

(1) Coat the mold and base plate with a thin layer of kerosene, and place a circular piece of filter paper at the bottom of the mold.

(2) With a bent spoon, transfer the laboratory mixture into the mold, in three approximately equal layers. Press each layer down lightly with the spoon and move the larger particles away from the mold wall with a small spatula. Place a circular piece of paper on top of the mixture.

(3) Place a small amount of oil in the center of the motorized press platen, on the surface of the lower bearing, and around the periphery of the mold on the top surface of the hardened steel ring.

(4) Slide the mold onto the platen and center it in molding position beneath the ram of the press.

(5) Pump the ram into the center of the mold until the low pressure gage registers 40 psi.

(6) Pull the handle on the cam lever down to the horizontal position, cocking the mold to the proper angle for gyration.

(7) Push the reset button and then the start button.

(8) As soon as the last gyration is completed, raise the cam lever handle into a vertical position, leveling the mold.

(9) Repeat steps 5 through 8 until one smooth full stroke of the pump handle will cause the low pressure gage to indicate the desired full stroke pressure for that specimen. During molding, when one stroke of the pump handle causes the gage to come to rest between 40 psi and the desired full stroke pressure, drop the pressure below 40 psi and then pump the pressure back up to 40 psi.

(10) When the desired full stroke pressure is reached, at approximately one stroke per second, pump the pressure up to 200 psi, as measured on the high pressure gage.

(11) Release the pressure and pump the ram up and out of the mold.

(12) Slide the mold out of the press.

(13) Extrude the specimen. Weigh and measure the height and diameter of the specimen.

APPENDIX 3

CURING PROCEDURES

APPENDIX 3. CURING PROCEDURES

APHALT-TREATED MATERIALS

Cure the specimens for 2 days at room temperature, 75° F ± 2° F.

CEMENT-TREATED MATERIALS

(1) Immediately after compaction and weighing and measuring the height and diameter, wrap each specimen with one layer of PVC film and secure the film with rubber bands.

(2) Place each specimen in the appropriate temperature environment as required in the experiment (75° F, 100° F, or 125° F) for seven days.

(3) At the end of seven days take each specimen from its environmental chamber, remove the PVC film; weigh and measure the height and diameter of specimen.

LIME-TREATED MATERIALS

(1) Wrap each specimen with one layer of PVC film and secure the film with rubber bands.

(2) Place each specimen in the appropriate temperature environment, i.e., oven or air-conditioned laboratory.

(3) Allow each specimen to cure for three weeks.

THE AUTHORS

Raymond K. Moore is a Research Engineer Assistant with the Center for Highway Research at The University of Texas at Austin. He is the author of several technical papers and is currently involved in research concerned with the behavior of stabilized materials.

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