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16. Abstract

This report describes the results of an investigation of the fatigue life and repeated-load elastic properties of blackbase and asphalt concrete from inservice highways in Texas. Cores from seven recently constructed highway pavements were obtained and tested under repeated tensile stresses using the repeated-load indirect tensile test. Experimental estimates of fatigue life, resilient modulus of elasticity, and resilient Poisson's ratio were made. In addition, an estimate of the variation of these properties to be expected in a highway was obtained.

The relationships between the dynamic and fatigue properties and the static properties were also evaluated in an attempt to establish useful correlations.

17. Key Words
blackbase, asphalt concrete, fatigue, repeated-load, resilient properties, fatigue life, modulus of elasticity, Poisson's ratio, coefficient of variation

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FATIGUE AND REPEATED-LOAD ELASTIC CHARACTERISTICS OF INSERVICE ASPHALT-TREATED MATERIALS

by

Domingo Navarro
Thomas W. Kennedy

Research Report Number 183-2

Tensile Characterization of Highway Pavement Materials
Research Project 3-9-72-183

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

January 1975

PREFACE

This is the second in a series of reports dealing with the findings of a research project concerned with tensile and elastic characterization of highway pavement materials. This report summarizes the results of a study to determine the magnitude and variation of the fatigue life and repeated-load elastic properties, i.e., resilient modulus of elasticity and Poisson's ratio, of blackbase materials and asphalt concrete from pavements throughout the state of Texas. The primary method of test was the repeated-load indirect tensile test. In addition, possible correlations involving fatigue life, static properties, and repeated-load properties were investigated.

This report would not have been possible without the help and assistance of many people. Special appreciation is due Messrs. James N. Anagnos, Pat Hardeman, Harold H. Dalrymple, and Victor N. Toth for their assistance in the testing program, and to Messrs. Avery Smith, Gerald Peck, and James L. Brown, of the Texas Highway Department, who provided technical liaison for the project. Appreciation is extended to the district laboratory engineers who supplied the materials tested in this study. These laboratory engineers are Messrs. David Bass, Volney G. Chetty, Robert E. Long, W. L. Pumlee, and Bill Woods. Thanks are also extended to Mr. A. W. Eatman and Mr. Larry G. Walker for their cooperation in this project, and to the Center for Highway Research staff, who assisted with the manuscript. The support of the Federal Highway Administration, Department of Transportation, is gratefully acknowledged.

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January 1975

LIST OF REPORTS

Report No. 183-1, "Tensile and Elastic Characteristics of Pavement Materials," by Bryant P. Marshall and Thomas W. Kennedy, summarizes the results of a study of the magnitude of the tensile and elastic properties of highway pavement materials and the variations associated with these properties which might be expected in an actual roadway.

Report No. 183-2, "Fatigue and Repeated-Load Elastic Characteristics of Inservice Asphalt-Treated Materials," by Domingo Navarro and Thomas W. Kennedy, summarizes the results of a study to determine the magnitude and variation of the fatigue life and repeated-load elastic properties of black-base and asphalt concrete from actual highway pavements.

ABSTRACT

This report describes the results of an investigation of the fatigue life and repeated-load elastic properties of blackbase and asphalt concrete from inservice highways in Texas. Cores from seven recently constructed highway pavements were obtained and tested under repeated tensile stresses using the repeated-load indirect tensile test. Experimental estimates of fatigue life, resilient modulus of elasticity, and resilient Poisson's ratio were made. In addition, an estimate of the variation of these properties to be expected in a highway was obtained.

The relationships between the dynamic and fatigue properties and the static properties were also evaluated in an attempt to establish useful correlations.

KEY WORDS: blackbase, asphalt concrete, fatigue, repeated-load, resilient properties, fatigue life, modulus of elasticity, Poisson's ratio, coefficient of variation.

SUMMARY

This report summarizes the findings of a study to evaluate the fatigue and elastic properties of blackbase and asphalt concrete under repeated indirect tensile stresses and the variations of these properties for inservice pavements in Texas. The properties estimated were fatigue life, resilient modulus of elasticity, and resilient Poisson's ratio. In addition, density, static moduli of elasticity, and static Poisson's ratios were estimated and analyzed. The test method utilized for this study was the repeated-load, or dynamic, indirect tensile test. Blackbases and asphalt concretes from seven recently constructed pavements in five Texas Highway Department districts were studied.

The fatigue lives were found to be substantially smaller than the fatigue lives reported by other investigators using different test methods. However, when the applied stress was expressed in terms of stress difference, i.e., the maximum principal stress minus the minimum principal stress, the stress-fatigue life relationships were compatible.

The mean resilient moduli of elasticity were relatively consistent for the various projects, ranging from 221×10^3 to 615×10^3 psi. The ratio of the resilient and the static moduli ranged from 10.5 to 2.3 . Resilient Poisson's ratios ranged from 0.10 to 0.46 , with the majority in the range of 0.10 to 0.22 .

The coefficient of variation for fatigue was relatively large, ranging from 30 to 80 percent, with the magnitude being stress and project dependent. The coefficients for resilient modulus of elasticity were low, ranging from 4 to 28 percent. For the resilient Poisson's ratio the coefficients were larger, with the majority of the values in the range of 18 to 57 percent. Very little variation was detected for density.

No correlations which could be used for estimating purposes were found to exist between fatigue life and the ratio of repeated tensile stress to static tensile strength, static or resilient modulus of elasticity, or tensile strain, although the correlation with tensile strain indicated that it should be evaluated further.

IMPLEMENTATION STATEMENT

The results of this study to determine the fatigue and repeated-load elastic characteristics of blackbase and asphalt concrete from recently constructed pavements in Texas can be used immediately. Elastic layered pavement design methods currently are being developed for use by the Texas Highway Department. In addition, considerations are being given to including stochastic analyses in these design methods. The results concerning the magnitude of the fatigue life and the resilient modulus of elasticity and resilient Poisson's ratio can be utilized immediately as inputs into these elastic design methods. The information on the variation of the above properties provides an estimate of the variation which occurs in actual pavements. These variation estimates are important and needed for any stochastic design procedures. In addition to the above applications, the districts can use the information to begin to develop an understanding of the fatigue properties, elastic properties, and variations of these properties as related to pavement performance.

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CHAPTER 1. INTRODUCTION

Most current pavement design procedures are largely empirical and deterministic in nature, using single representative input values and presenting the results in terms of a single output value. At a 1970 workshop on the structural design of asphalt pavements (Ref 1), one of the most pressing areas of research need was established to be the application of probabilistic or stochastic concepts to pavement design. The workshop stated the problem as follows:

> So that designers can better evaluate the reliability of a particular design, it is necessary to develop a procedure that will predict variations in the pavement system response due to statistical variations in the input variables, such as load, environment, pavement geometry, and materials properties including the effects of construction and testing variables. As part of this research, it will be necessary to include a significance study to determine the relative effect on the system response of variations in the different input variables.

Current research at The University of Texas Center for Highway Research has developed design procedures for both rigid pavement systems (RPS) and flexible pavement systems (FPS) in which the systems approach is used to consider all phases of design, construction, and inservice performance to arrive at a series of acceptable pavement designs (Refs 2, 3, 4, 5, and 6). Trial use of these design systems by the Texas Highway Department has revealed a definite need to consider the random or stochastic nature of many of the input variables, so that design reliability can be estimated. Reliability is defined as "the probability that the pavement will have an adequate serviceability level for a specified design performance period" (Ref 7).

The FPS and RPS are currently in the empirical design stages. However, the state-of-the-art has advanced to the point that an attempt should be made to extend the application of elastic theory to consider the effects of repeated loads in design (Ref 8). A necessary step in this direction is the determination of the fatigue characteristics and the repeated-load elastic properties of pavement materials as they exist in the roadway. Furthermore, the variations in these properties from point to point in the pavement and from different geographical locations must be evaluated in order to fully implement stochastic design concepts.

The purpose of the research effort summarized in this report was to develop information concerning the fatigue and elastic characteristics of blackbase from newly constructed inservice pavements in Texas and to develop information concerning the variation of these parameters.

Comparisons were made between the elastic properties estimated using the repeated-load indirect tensile test and those determined using the indirect tensile test with a constant rate of deformation. In addition, correlations between fatigue life, repeated-load indirect tensile test results, and static indirect tensile test results were investigated in an attempt to predict fatigue life without conducting long-term tests.

Chapter 2 briefly summarizes currently available information concerning the variation of asphalt and asphalt-treated material characteristics and delineates the need for additional studies. Chapter 3 describes the approach used in this study. Chapter 4 discusses the analysis and findings of the study, and Chapter 5 summarizes the findings and conclusions.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

In order to incorporate fatigue, elastic, and reliability considerations in pavement design, it is necessary to establish estimates of these characteristics and, ideally, to develop an easy and reliable test method for obtaining this information. A review of the literature indicates a great deal of information is currently available concerning the fatigue and elastic characteristics of asphalt and asphalt-treated materials. However, most of this information relates to laboratory prepared materials, with limited information concerning the fatigue, elastic, and variational characteristics of materials from inservice pavements.

DEFINITIONS

Various terms associated with fatigue are defined in the following paragraphs.

Fatigue has been defined as "a process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations" (Ref 9).

Failure has been described in terms of fracture life and service life. Fracture life, or fatigue life, N_f is the total number of load applications necessary to completely fracture a specimen. On the other hand, service life is the total number of applications necessary for the test specimen to no longer perform as it was originally intended.

Mode of loading refers to the variation of stress and strain levels during a test. In a controlled-load, or controlled-stress, test the nominal load, or stress, is kept constant until failure occurs. If the nominal deflection, or strain, is kept constant until failure, the test is called a controlled-deflection, or controlled-strain, test. For the controlled-stress test, the strain gradually increases with an increasing number of load applications. For the controlled-strain test, the stress gradually decreases with an increasing number of load applications since the specimen is gradually damaged, requiring less load to produce the desired strain level.

Mode factor was introduced by Monismith in order to differentiate between controlled-stress and controlled-strain tests on a more quantitative basis and was defined as

$$MF = \frac{A - B}{A + B}$$

where

MF = mode factor,

A = percentage change in stress due to a stiffness decrease of C percent,

B = percentage change in strain due to a stiffness decrease of C percent, and

C = an arbitrarily fixed percent reduction in stiffness.

The mode factor equals -1 for controlled-stress loading, +1 for controlled-strain loading, and 0 in the mixed mode. Monismith and Deacon (Ref 10) have also concluded from elastic layered analyses of a series of pavement sections that the controlled-strain mode of loading is applicable to thin flexible pavements (2 inches or less) while a controlled-stress test is more applicable to thick pavements (greater than 6 inches). A mode factor between the two extreme values is applicable to pavements in the range of 2 to 6 inches in thickness.

Loading condition involves load and environmental variables during the testing period, e.g., testing temperature. A specimen is subjected to simple loading if the load pulse and environmental conditions remain constant during the testing period. If the load condition is changed during the test, the specimen is subjected to compound loading. Due to variations in both traffic and environmental conditions, actual pavements are subjected to compound loading.

TESTING TECHNIQUES

Many different test methods have been used to create tensile stresses or strains in the specimen. These tests are

(1) flexural, or bending, test,
(2) torsion test,
(3) direct tension test, and
(4) indirect tension test.

Flexural Test

Flexural tests involve subjecting beam or plate specimens to bending stresses by center-point loading, third-point loading, or cantilever loading. Pell (Ref 11) utilized a torsional bending apparatus in which cantilevered specimens with necked-down, or reduced, circular cross sections were clamped in a vertical position in the chuck of a rotating-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.

Jimenez and Galloway (Refs 12 and 13) loaded asphalt concrete diaphragms which were analyzed on circular plates fixed at the periphery with a uniform pressure acting on the bottom surface and a central load on the upper face. The test approached a controlled-stress test since the deflections of the specimen generally increased with increased load repetitions.

Monismith (Ref 14) supported beam specimens on a spring base to simulate field support conditions and subjected the beams to controlled-stress or controlled-strain loading. In the controlled-stress test, a fixed load was applied to the specimen through a pneumatic loading system while, for the controlled-strain tests, wire strain gages were bonded to the underside of the beams and the load was controlled to produce a fixed level of strain in the gages.

Equipment developed by Deacon (Ref 15) applies a constant moment through the center of the beam specimen but can be used in both controlled-stress and controlled-strain tests.

Torsion Test

Pell (Ref 11) in some of his fatigue tests performed controlled torsional strain tests by subjecting the cylindrical specimens to repeated applications of torque, or a twisting moment.

Direct Tension Test

Direct tension tests, in which a specimen is subjected to tensile stresses by pulling directly in opposite directions, have been utilized by Epps (Ref 16). Even though simple in theory, the problems of end gripping and stress concentration have restricted the use of this method.

Indirect Tension Test

Moore and Kennedy used the repeated-load, or dynamic, indirect tension test (Refs 17 and 18), in which cylindrical specimens are subjected to compressive loads distributed along two opposite radial generators, a condition which creates a relatively uniform tensile stress perpendicular to and along the diametral plane which contains the applied load.

FACTORS AFFECTING FATIGUE CHARACTERISTICS

Many factors have been found to affect the fatigue behavior of asphalt concrete mixtures. These factors and their effect have been reviewed in detail by a number of investigators (Refs 17, 19, and 20) and therefore their effects are only summarized in this report.

Deacon and Monismith (Ref 21) stated that the stiffness of a mixture is important to the fatigue characteristics of asphalt concrete materials and that any factor that affects stiffness also affects fatigue behavior. Table 1 illustrates the effect of some of these factors (Ref 20).

Epps and Monismith (Ref 22) indicated that the stiffness of a mixture alters the slopes of the relationship between the logarithm of bending stress and the logarithm of the number of applications to failure and showed that stiffer mixes had longer fatigue lives under constant stress.

The fatigue life has also been found to correlate with initial tensile strain (Refs 17, 23, and 24) and stress-strength ratio. Moore and Kennedy (Refs 17 and 18) reported that the stress-strength ratio could be used to estimate fatigue life of asphalt-treated materials for constant-stress loading. The correlation between the logarithm of the stress-strength ratio and

TABLE 1. FACTORS AFFECTING THE STIFFNESS AND FATIGUE BEHAVIOR OF ASPHALT CONCRETE MIXTURES (REF 20)

Factor	Change in Factor	Effect of Change in Factor		
		On Stiffness	On Fatigue Life in Controlled-Stress Mode of Test	On Fatigue Life in Controlled-Strain Mode of Test
Asphalt penetration	Decrease	Increase	Increase	Decrease
Asphalt content	Increase	Increase[a]	Increase[a]	Increase[b]
Aggregate type	Increase roughness and angularity	Increase	Increase	Decrease
Aggregate gradation	Open to dense gradation	Increase	Increase	Decrease[d]
Air void content	Decrease	Increase	Increase	Increase[d]
Temperature	Decrease	Increase[c]	Increase	Decrease

[a] Reaches optimum at level above that required by stability considerations.

[b] No significant amount of data; conflicting conditions of increase in stiffness and reduction of strain in asphalt make this speculative.

[c] Approaches upper limit at temperature below freezing.

[d] No significant amount of data.

the logarithm of fatigue life was reported to be linear, with a coefficient of determination of 76 percent.

VARIATIONAL CHARACTERISTICS

Although there is a great deal of information available on the fatigue characteristics of asphalt materials, information concerned with the variational characteristics is very limited, especially for inservice pavement materials. Previous findings are summarized below and supplemental data are contained in Appendix A, Tables A-1 through A-4.

Studies on Laboratory Prepared Specimens

Finn (Ref 19) reported variational characteristics of laboratory tests for stiffness modulus, fatigue life (fracture life), and initial strain in weathered and unweathered specimens of asphalt cement (Table A-1). The asphalt specimens were weathered in a rolling thin film oven developed by the California Division of Highways. The range of coefficients of variation obtained in the stiffness and initial strain determinations were generally between 7 and 22 percent, with an average value of 17.3 percent, while the coefficient of variation obtained for fatigue life was considerably higher, ranging from 53 to 73 percent and averaging 62.2.

Vallerga et al (Ref 25) made similar studies on different penetration grade asphalts, both artificially aged and unaged. Their results were comparable to those reported by Finn (Ref 19), with low to moderate variation in stiffness and initial strain and rather high variation in fatigue life.

Moore and Kennedy (Refs 17 and 18) investigated the fatigue life of asphalt-treated gravel and limestone materials under repeated indirect tensile stresses. Significant variations in fatigue life occurred, and it was found that the standard deviation tended to vary linearly with mean fatigue life, indicating a constant coefficient of variation. The coefficient of variation ranged from 30 percent for asphalt-treated limestone to more than 75 percent for asphalt-treated gravel.

Studies on Field Specimens

Finn (Ref 19) summarized work done by Monismith (Ref 26) on the laboratory-determined values of beam stiffness for surface and base course specimens of asphalt concrete obtained from the field. In these tests the average coefficient of variation was 26.2 percent and was approximately the same for both surface and base courses (Table A-2). Also shown in Table A-2, for comparison, are the results of stiffness tests on replicate laboratory compacted specimens of surface and base courses. As expected, the average coefficient of variation for the laboratory compacted specimens was lower than that for the field specimens, averaging 18.5 percent, and would have been lower if the relatively high value of 28.2 percent for the laboratory compacted specimens tested at 40°F had not been included.

In another study, Monismith et al (Ref 27) obtained field specimens of surface and base courses from an asphalt pavement in California and conducted beam tests for flexural stiffness. A total of 20 surface course specimens and 8 base course specimens were obtained from approximately the same location in the pavement (Table A-3). For a given test temperature, the coefficient of variation was essentially the same for the surface and base courses. For the test conducted at 68°F, the average coefficient of variation obtained was 27.5 percent, while, for those tests run at 40°F, the average coefficient of variation was 20.1 percent.

A great deal of information relating to the variation in material properties encountered on a construction project was gathered during the construction of the AASHO Road Test (Ref 38). It must be pointed out, however, that the AASHO Road Test was not typical of most construction projects in that extreme construction control was exercised, with upper and lower specification limits specified. Both binder courses and asphalt surface courses were tested for each of the six test loops. The results of in-place density tests (Table A-4) on the asphalt concrete pavement sections indicated that the variation was very small, averaging 1.2 percent, with a range from 0.5 to 1.8 percent. The variation in each loop was comparable to that for all loops combined.

The results of percent voids determinations (percent total volume and percent filled) for the asphalt concrete pavement are also contained in Table A-4. The average coefficient of variation for the voids (percent total volume) was 11.2 percent for the binder course and 19.3 percent for the surface course. The average coefficient of variation for the voids (percent filled) was 5.6 percent for the binder course and 7.0 percent for the surface course. The coefficients of variation for all six loops combined were not significantly different from those obtained for each of the six individual loops.

Marshall and Kennedy (Ref 28) used the static indirect tension test for investigating the tensile and elastic properties and the variation of these properties for portland cement concrete, cement-treated base, asphalt concrete, and blackbase found from inservice pavements in Texas. The average tensile strength, modulus of elasticity, and Poisson's ratio for blackbase were 105 psi, 58.2×10^3 psi, and 0.27 , respectively. The magnitude of the variations appeared to be project dependent. The coefficients of variation ranged from 14 to 27 percent for tensile strength, 24 to 59 percent for modulus, and 39 to 67 percent for Poisson's ratio.

Components of Variance

In order to arrive at a stage where application of statistical concepts is effective, estimates should be made of the components of the overall variance measured for a given material. The components of overall variance σ_T^2 can be isolated into testing variance σ_t^2 , sampling variance σ_s^2 , and inherent material variance σ_a^2 such that

$$\sigma_T^2 = \sigma_t^2 + \sigma_s^2 + \sigma_a^2$$

In order to determine inherent material variation, testing and sampling components of variation must be isolated and analyzed.

During the years 1966-1969, the Office of Research and Development of the Bureau of Public Roads actively promoted research programs in quality assurance. Early research revealed that little information was available for use in establishing quality levels and statistical variations in highway construction. As of 1969, 28 states had conducted research along these lines, and, according to data received, the cause of 50 percent or more of the overall variance in some studies could be assigned to sampling and testing (Ref 29). In addition, it was found that the sampling and testing components of variation generally exceeded the inherent material variation component.

Type of Distribution

In order for the coefficient of variation to be a truly meaningful test statistic, the material property being analyzed should approximate a normal distribution. Previous studies have shown that the properties of highway materials are normally distributed (Refs 8, 30, and 31).

Pell and Taylor (Ref 31) and Kasianchuk (Ref 32) have indicated that the distribution for fatigue life is logarithmic normal. Figures 1 and 2 show the results of 100 fatigue tests conducted by Pell and Taylor.

SUMMARY

Although there is a great deal of information available on the elastic and fatigue characteristics of asphalt-treated materials, there is limited information on these properties for inservice materials. In addition, there is essentially no information on the variational characteristics of the above properties from actual inservice materials. Thus, there is a definite need for information concerning the fatigue, elastic, and variational characteristics of asphalt pavement materials from inservice pavements for use in elastic and stochastic design procedures.

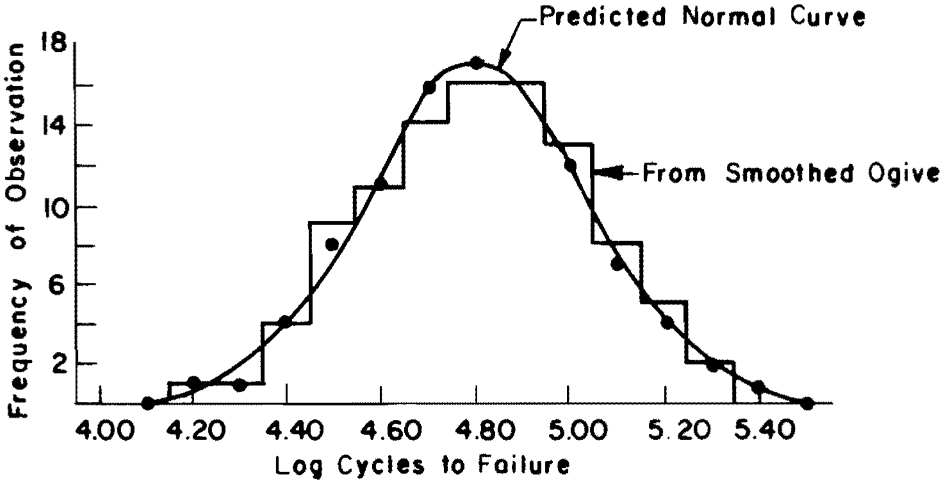


Fig 1. Histogram of 100 fatigue test results (after Pell and Taylor, Ref 31).

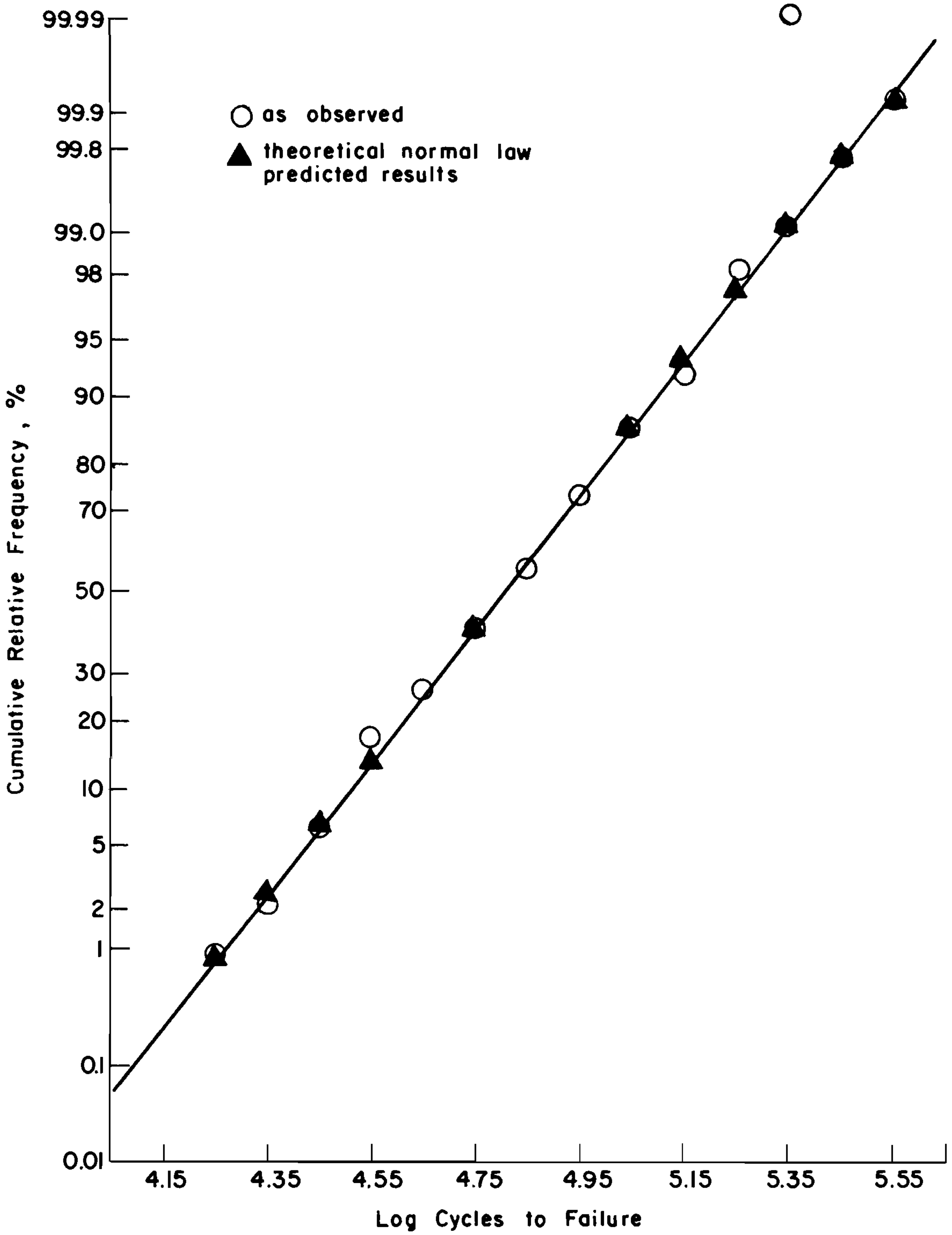


Fig 2. Normal probability plot of fatigue results (after Pell and Taylor, Ref 31).

CHAPTER 3. EXPERIMENTAL PROGRAM

The principal objectives of this investigation were (1) to characterize inservice blackbase materials in terms of fatigue life, i.e., the number of applications of a given stress required to fail the specimen; (2) to characterize inservice blackbase in terms of elastic properties, i.e., Poisson's ratio and modulus of elasticity under repeated applications of low tensile stresses; (3) to estimate the amount of variation in these properties which can be expected for an inservice pavement but not necessarily to establish the cause of the variation; and (4) to investigate possible correlations between behavior under a single static load and under repeated loading.

To accomplish these objectives, field cores of blackbase and two asphalt surfacing materials from recently constructed highway pavements in Texas were tested using both static loading and repeated loading in the indirect tensile test. The fatigue lives, elastic properties, and the variation about mean values were estimated using the repeated-loading indirect tensile test; and values of strength, modulus of elasticity, and Poisson's ratio were determined using static loading.

Pavement designers often assume that the properties of pavement material are constant along a design length of roadway, where design length is defined as a specific length along a roadway which is designed to have uniform thickness and material type. However, even under closely controlled laboratory conditions, there is some variation in properties for duplicate specimens. This variation represents inherent material variation plus testing error. In comparing the laboratory environment with a field construction site, it can be expected that more variation will result from the relatively uncontrolled construction process than from the carefully controlled laboratory conditions. Additional variation in material properties introduced along the pavement includes inherent material variation as well as variation introduced by the environment, changes in the proportions of the mix, changes in construction technique, and various other factors. This "along-the-pavement" variation can be estimated by testing cores sampled at random locations along the design length of the project.

In addition to determining the variation which occurs along the pavement, it may be of interest to determine the variation which occurs because of the effects related to depth in the pavement structure, since the lower portion of the pavement is usually subjected to the highest load-induced tensile stresses. There may be, for example, differences in the fatigue and elastic properties of different pavement layers resulting from the fact that during construction some layers receive different degrees of compaction because of the stiffness of the underlying material or the number of passes of the roller.

DESCRIPTION OF PROJECTS TESTED

Cores from seven projects in five locations in Texas were tested. Summary information relating to the projects is shown in Table 2. Figure 3 shows the geographical distribution of the Texas Highway Department Districts from which the pavement cores were obtained.

Core Sampling Plan Utilized in This Study

The Texas Highway Department normally cores blackbase pavement layers at equally spaced longitudinal intervals, except when a section of pavement is encountered in which the thickness is less than the design thickness, or when detailed information on a given section is desired. If thickness is found to be inadequate in the normal coring pattern, cores are taken at smaller regular intervals until the thickness again reaches design thickness, at which time cores are again taken at the normal intervals (Fig 4).

According to the concept of systematic random sampling, the Texas Highway Department cores can be considered to have been randomly sampled from the pavement. Thus, even though the samples were obtained in a systematic fashion, i.e., at regular intervals, they can be considered to be random since the sampling location function does not coincide with any variation distribution function that is known to exist in the pavement.

One method of estimating variation in material properties due to construction is to test cores clustered at approximately the same location in the pavement. This approach has been used for evaluating tensile and elastic

TABLE 2. DESCRIPTION OF BLACKBASE AND ASPHALT CONCRETE PROJECTS

District	County	Project	Material	Number of Specimens		Asphalt		Aggregates	Specimen Diamteter, inches Nominal
				Fatigue	Static	Type	% by wt.		
2	Tarrant-Johnson	2	Blackbase	18	5	AC-20	6.2-6.5	Limestone	6
5	Lubbock	5	Blackbase	15	5	AC-10	6.9-7.2	Limestone	6
8	Mitchell	8B	Blackbase	15	5	AC-20	4.6-5.3	Caliche Conglomerate Gravel	6
	Callahan	8C	Blackbase	11	3	AC-20	5.6-5.9	Limestone	6
17	Brazos	17B(1)	Blackbase (first lift)	15	100*	AC-10 & AC-20	4	Brazos River Gravel	4
		17B(2)	Blackbase (second lift)	15		AC-10 & AC-20	4	Brazos River Gravel	4
25	Hall	25-97(1)	Blackbase (first lift)	12	3	AC-20	6	Sandstone	4
		25-97(2)	Blackbase (second lift)	11	3	AC-20	6	Sandstone	4
		25-97(3)	Blackbase (third lift)	12	3	AC-20	3.5	Gravel	4
		25-97(S)	Asphalt concrete (surface course)	12	3	AC-20	5	Gravel	4
	Hardeman	25-100(1, 2)	Blackbase (first and second lift)	12	4	AC-20	4.5	Gravel	4
		25-100(3)	Blackbase (third lift)	10	2	AC-20	3.2	Gravel	4
		25-100(S)	Asphalt Concrete (surface course)	10	2	AC-20	4.7	Gravel	4

*From Ref 28.

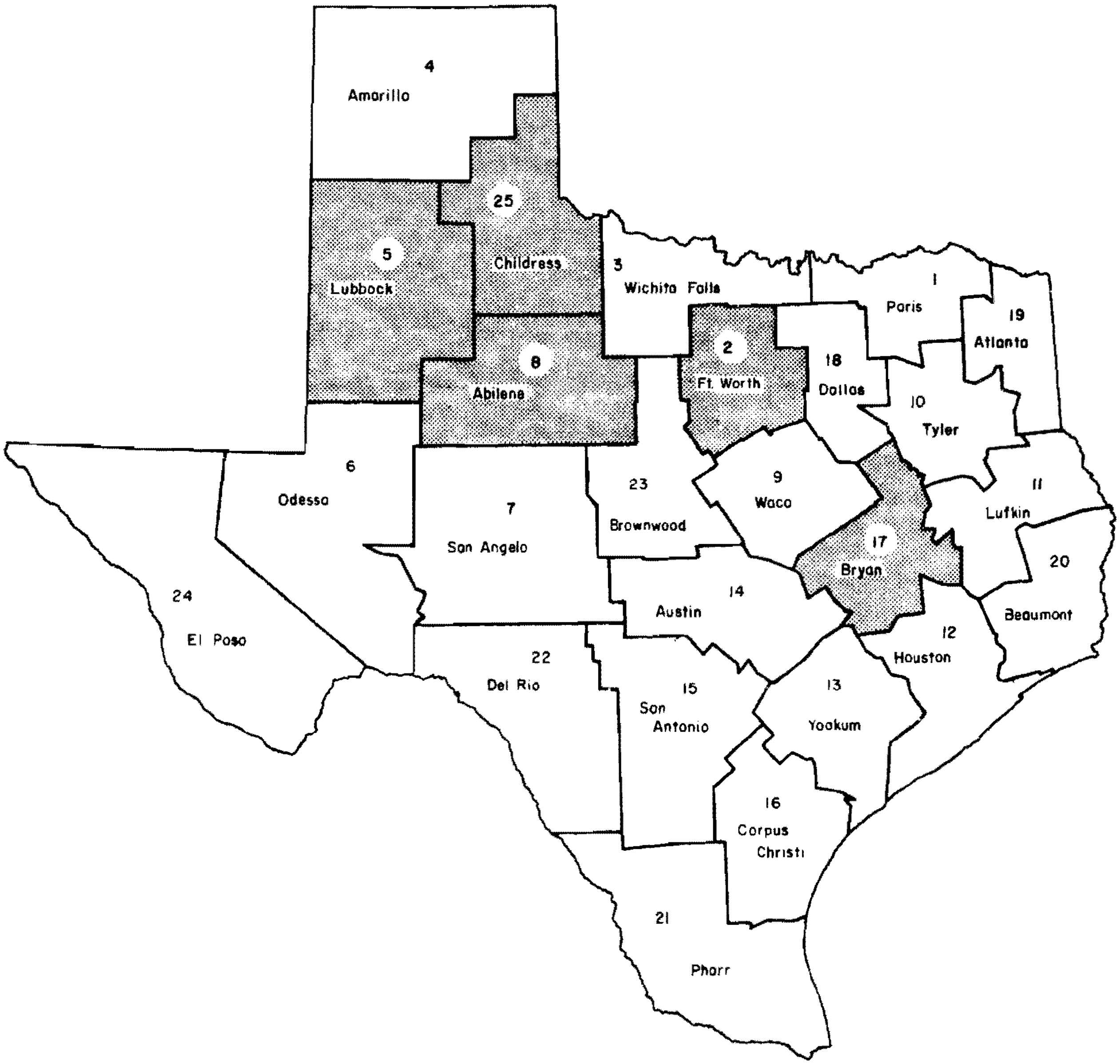


Fig 3. Texas Highway Department Districts from which cores were obtained.

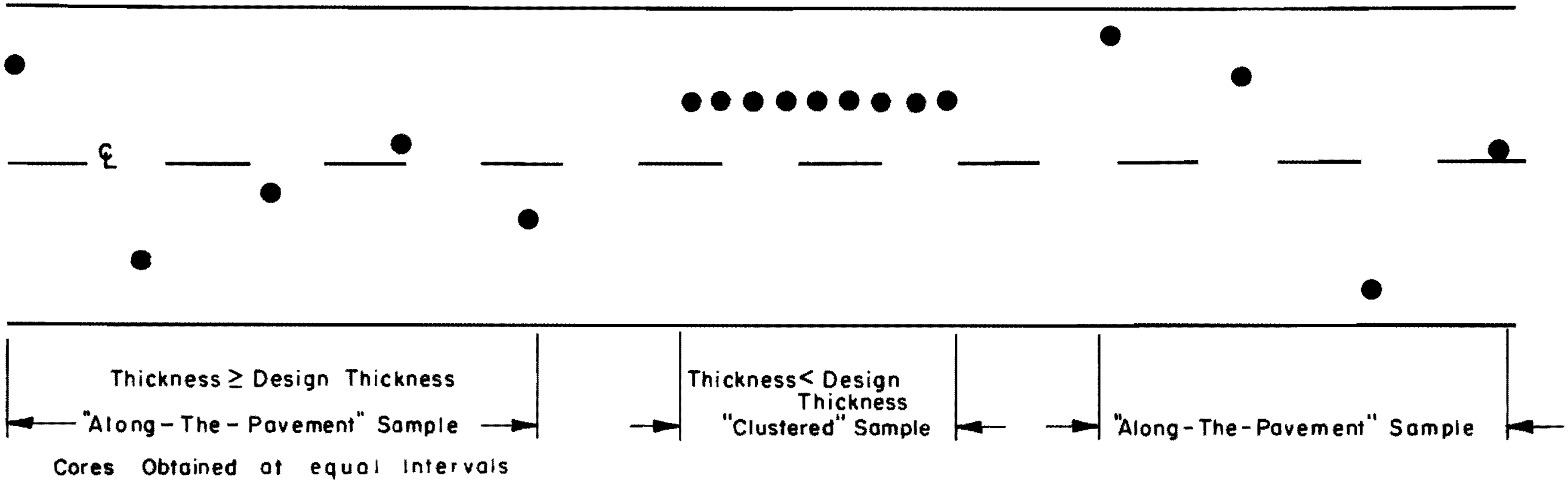


Fig 4. Typical core sampling plan used by the Texas Highway Department for blackbase and asphalt concrete.

characteristics under static loading (Refs 28 and 34); however, in this study clustered samples were not available.

The variation introduced during construction, i.e., along-the-pavement variations, as a result of changes in pit source, weather, etc., was estimated by using only the cores obtained at large longitudinal intervals.

Specimen Preparation

All blackbase and surface cores were obtained with either a 4-inch or a 6-inch inside diameter core barrel. The cores were sawed at the interface between lifts, so that each specimen represented its respective lift. A minimum of ten specimens from each project were selected by a random sampling technique from all those available and were tested using repeated loading in the indirect tensile test; three to five specimens were tested under a single slowly applied load to determine static strengths and static elastic properties of the blackbase and asphalt concrete.

The investigation of differences with respect to depth in the pavement was possible for two projects, one in District 17 and one in District 25, for which the blackbase was placed in two lifts and a large quantity of cores was available.

Before testing, the specimen dimensions were carefully measured and each specimen was weighed so that its density could be determined.

DESCRIPTION OF THE INDIRECT TENSILE TEST

The tensile, elastic, and fatigue properties of the blackbase were estimated using the indirect tensile test. Essentially the indirect tensile test involves loading a cylindrical specimen with either static or repeated compressive loads which act parallel to and along the vertical diametral plane, as shown in Fig 5. To distribute the load and maintain a constant loading area, the compressive load is applied through a half-inch-wide steel loading strip which is curved at the interface to fit the specimen. This loading configuration develops a relatively uniform tensile stress perpendicular to the plane of the applied load and along the vertical diametral plane which ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter (Fig 6).

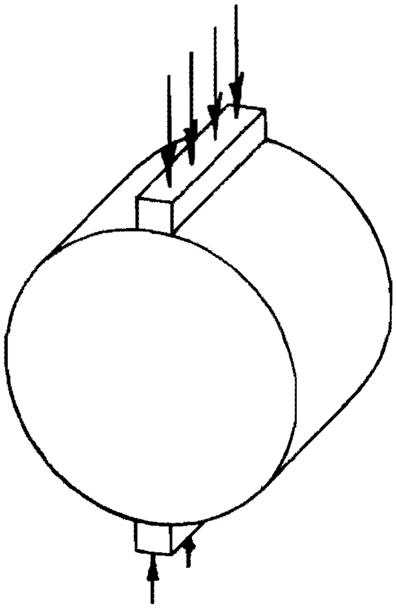


Fig 5. Cylindrical specimen with compressive load being applied.

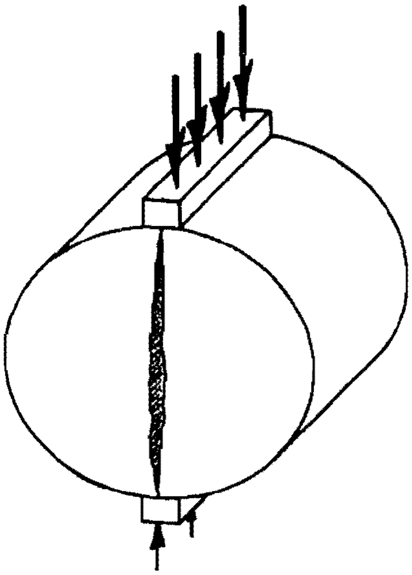


Fig 6. Specimen failing in tension under compressive load.

By continuously monitoring the applied load and the horizontal and vertical deformations of the specimen, it is possible to estimate the tensile strength, Poisson's ratio, and modulus of elasticity of the specimen.

Under repeated loads it is possible to estimate the resilient modulus of elasticity and Poisson's ratio for any given application of load, the permanent deformation accumulated for any given number of load applications, and the fatigue life by continuously or periodically monitoring load, horizontal deformation, and vertical deformation.

Indirect Tensile Test and Equipment, Static Loading

The indirect tensile test procedure for static loading was the same as previously used by Marshall and Kennedy (Ref 28). The basic testing apparatus included a loading system and a means of monitoring the applied loads, the horizontal deformation of the specimen, and the vertical deformation of the specimen.

The loading system consisted of a loading apparatus, a load aligning device, and loading strips. In this study, a closed-loop electrohydraulic system was used to apply load and to control the deformation rate. A deformation rate of 2 inches per minute was used at a testing temperature of approximately 75°F. A special loading device was used to insure that the loading platens and strips remained parallel during the test. The loading device which had proven to be satisfactory and which was used in this study is a modified, commercially available die set with upper and lower platens constrained to move parallel during the test (Fig 7). Mounted on the upper and lower platens are half-inch-wide curved steel loading strips.

The load was monitored with a load cell in order to obtain an electrical readout which could be recorded continuously. Horizontal deformation of the specimen was measured by using a device consisting of two cantilevered metal arms with strain gages attached (Fig 8). Vertical deformation was measured with a DC linear-variable differential transformer (LVDT). This displacement transducer was also used to control the vertical deformation rate during the test by providing an electrical signal relative to the movement between the upper and lower platens. The loads and deformations were monitored by two X-Y plotters, one recording load and horizontal deformation and the other recording load and vertical deformation.

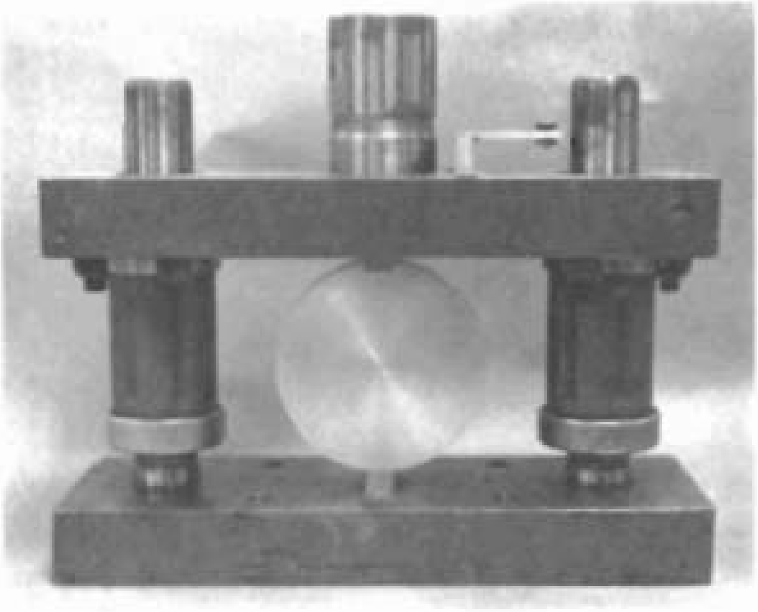


Fig 7. Loading apparatus.

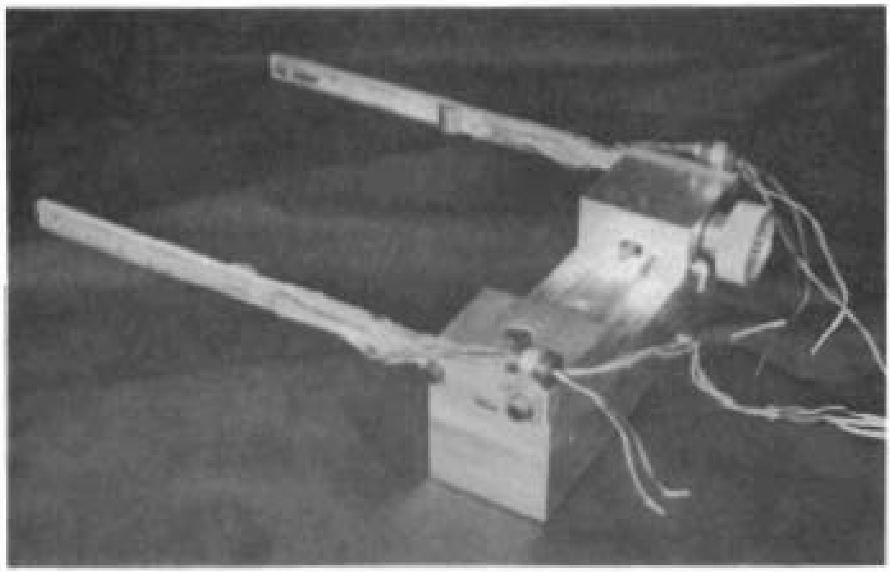


Fig 8. Total horizontal deformation measuring device.

Points picked from the X-Y plots and other weight and volume information were used as input for computer program MODLAS 9, which was developed at the Center for Highway Research at The University of Texas to calculate the tensile and elastic properties of materials tested using the indirect tensile test. Included in the printed output are estimates of Poisson's ratio, modulus of elasticity, tensile strength, and density for each specimen tested.

Indirect Tensile Test and Equipment, Repeated Loading

The basic test equipment used in the repeated-load tests was essentially the same as that used for the static loading tests, except for the use of an additional horizontal deformation transducer consisting of two LVDT's (Trans-Tek Series 350 with a working range of ± 0.050 inch and a mechanical travel of 0.14 inch) which was used to monitor the horizontal deformation of the specimen for any particular load application (Fig 9). The previously described cantilevered arm device (Fig 8) was used to monitor the accumulated permanent deformation. The basic testing equipment is shown in Fig 10.

The magnitude of the applied load was pre-programmed and was controlled with reference to a feedback signal from the load cell. Loads were applied at a frequency of one cycle per second with a 0.4-second total loading and unloading time (duration) followed by a rest period of 0.6 second. A typical load-impulse is shown in Fig 11. A minimum seating load of 20 pounds was maintained at all times in order to avoid impact loads on the specimen. All tests were conducted at 75°F.

The loads and elastic deformations due to a given load application were recorded on a 2-channel strip chart recorder. The permanent deformations were recorded on a digital data logging system. The load, elastic deformations, and permanent deformations of the specimen were measured continuously during the first 200 cycles and then were periodically monitored at increments of 100 cycles or less, depending on the expected fatigue life. Typical vertical and horizontal deformation-time relationships for a given load impulse are shown in Fig 12 and typical relationships between total and permanent deformation and the number of cycles are shown in Fig 13.

Instantaneous resilient deformations, or recoverable deformations, V_{RI} and H_{RI}, as shown in Figs 12(a) and 12(b), and the repeated-load were used as inputs for computer program MODLAS 9 to calculate the resilient

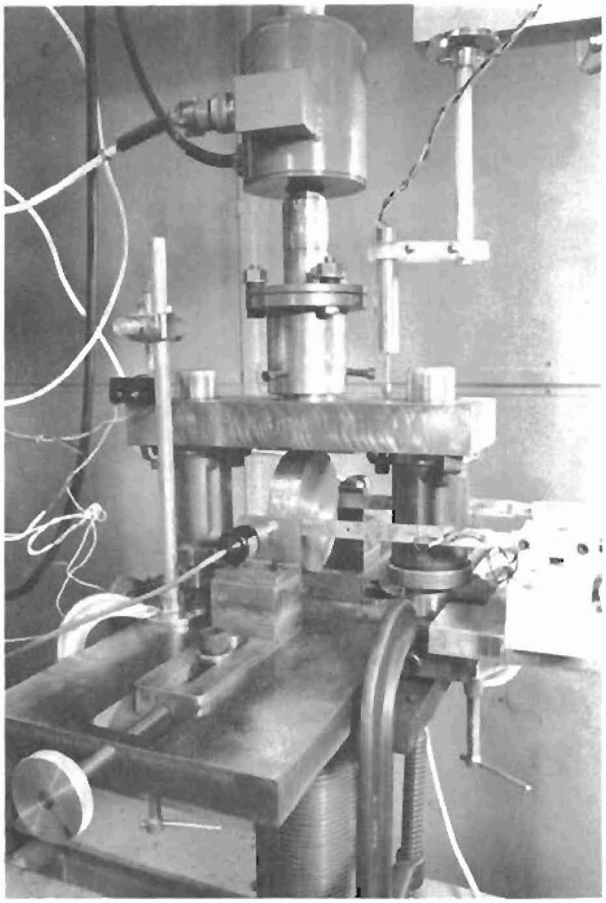


Fig 9. Linear-variable differential transformer.

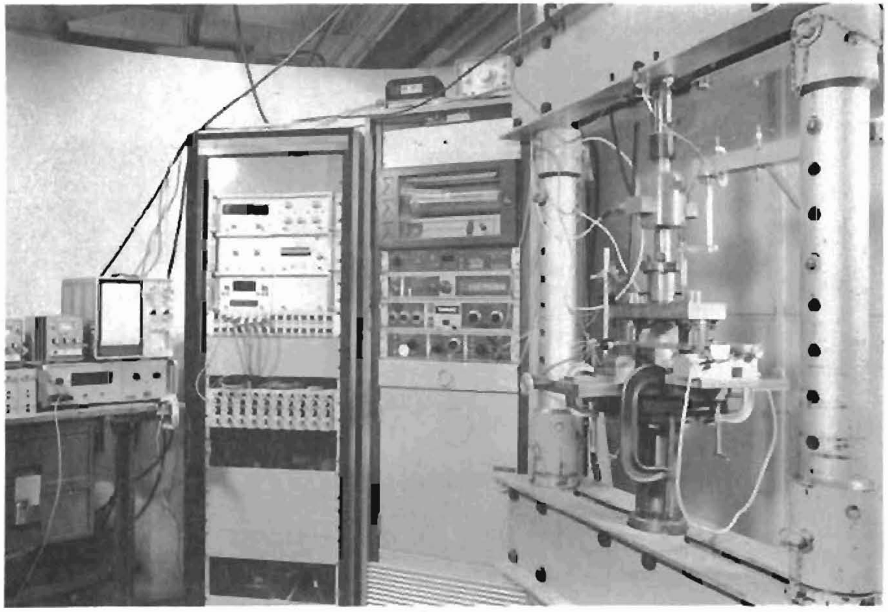


Fig 10. Basic testing equipment.

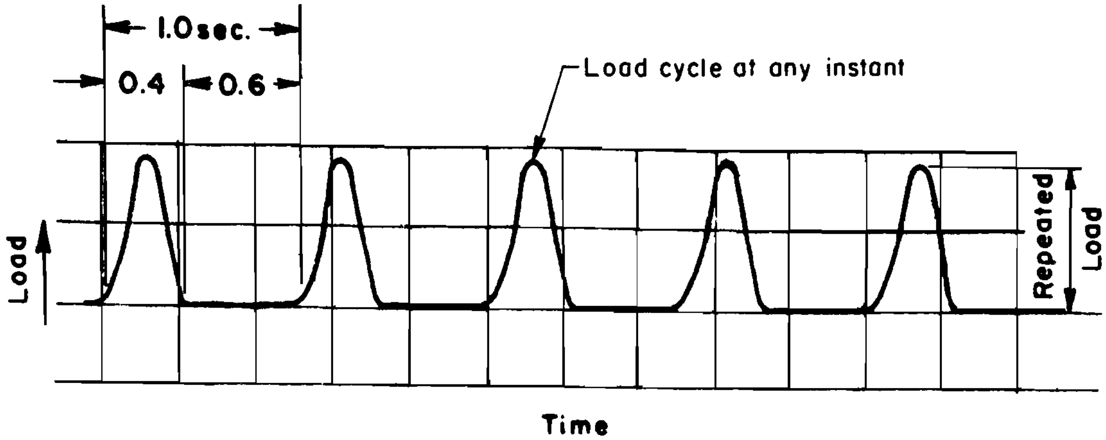
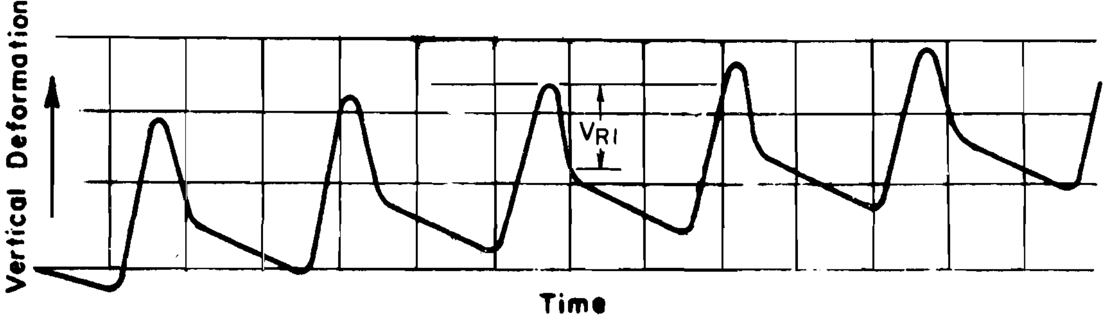
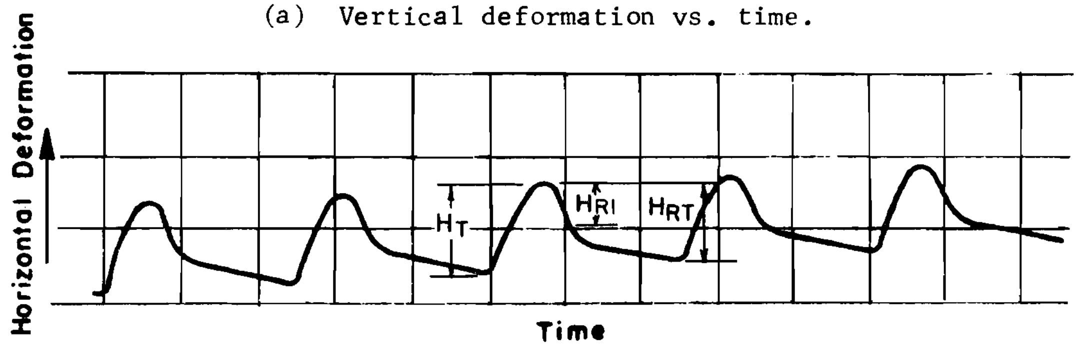


Fig 11. Load-time pulse for repeated-load indirect tensile test.



(a) Vertical deformation vs. time.



(b) Horizontal deformation vs. time.

Fig 12. Typical load and deformation vs. time relationship for repeated-load indirect tensile test.

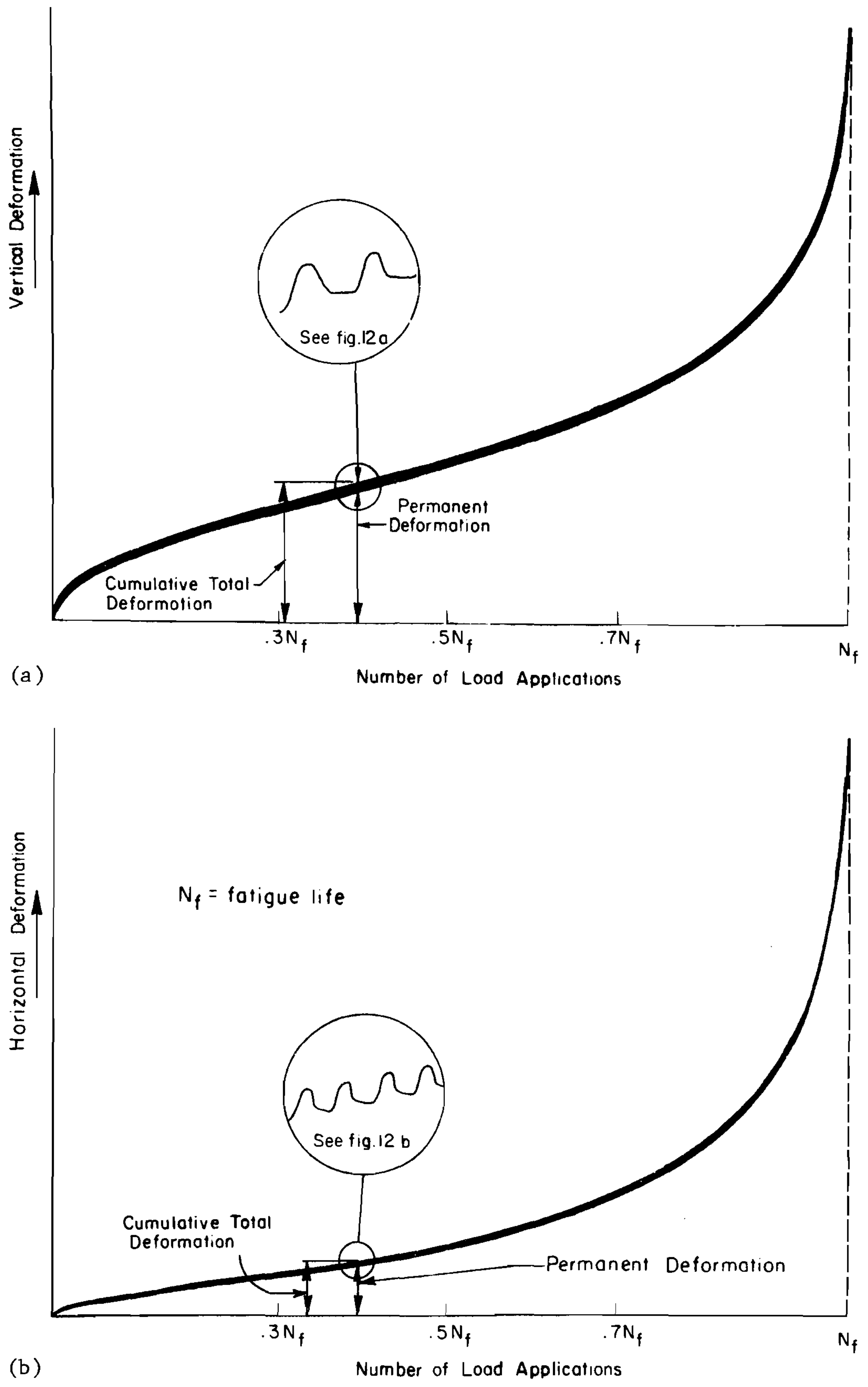


Fig 13. Typical relationship between deformation and number of load applications for the repeated-load indirect tensile test.

elastic properties under repeated loading.

The permanent and total horizontal and vertical deformation values can be used to characterize the relationships between total deformation and fatigue life and to study the permanent deformation characteristics.

METHOD OF ANALYSIS

The primary objectives of this study were

(1) to determine the fatigue life of blackbase materials from inservice pavements and establish stress-fatigue life relationships,

(2) to determine the instantaneous resilient modulus of elasticity and instantaneous resilient Poisson's ratio, for blackbase materials from inservice pavements,

(3) to estimate the variation of the above fatigue life and elastic properties, and

(4) to investigate possible correlations between properties under a single static load and under repeated loads.

Because of limitations of time and, in some cases, the small number of specimens available, only a limited number of fatigue tests could be conducted. Specimens from a given project were randomly selected and placed in a minimum of three groups, at a chosen tensile stress. In some cases it was necessary to change the stress level in order to complete the testing program in a reasonable period of time. The number of stress levels was limited to three because of the limitation on the number of tests which could be conducted; however, it was felt that three levels were adequate to establish the tensile stress versus fatigue life relationships and permit a determination of whether these relationships were essentially linear as shown by previous work. In order to shorten the test program, relatively high stress levels were used; this resulted in very low fatigue lives.

Fatigue Failure

Failure was considered to occur when the specimen fractured completely, or, in terms of permanent horizontal (tensile) deformation, when deformation increased without additional load applications (Fig 13). Fatigue life N_f, therefore, is the number of cycles corresponding to this large increase in deformation.

Elastic Characteristics under Repeated Loading

Since the deformational characteristics of the material are continuously changing with increasing load applications, it was necessary to define the instantaneous resilient modulus of elasticity and Poisson's ratio in a manner which would be meaningful to designers. As shown in Fig 13, permanent and total deformations increase substantially during the first few cycles of load and then the rate of change becomes essentially constant until failure. Based on an analysis of a large number of permanent deformation relationships it was concluded that the essentially linear portion of the curve occurred between about 15 and 85 percent of fatigue life. Since this range represents a significant portion of the design life of the materials, estimates of instantaneous resilient modulus and Poisson's ratios were calculated at 30, 50, and 70 percent of the fatigue life. These values were then averaged to obtain a representative value for each specimen.

Variation

One of the objectives of this study was to obtain an estimate of the variation in the fatigue life and in the elastic properties of blackbase materials from inservice pavement. For this purpose, the coefficient of variation, which is the sample standard deviation divided by the sample mean, was used since it relates variation to the mean value.

As discussed in Chapter 2, previous studies have shown that many of the properties of highway materials approximate a normal distribution, and other work on this project has shown that the static indirect tensile properties of pavement materials tend to be normally distributed.

Correlations

In order to develop techniques for estimating the fatigue life and elastic properties under repeated loads without conducting costly and time-consuming repeated-load tests, possible correlations between the repeated-load properties and the static or mixture properties were investigated.

CHAPTER 4. ANALYSIS AND EVALUATION OF TEST RESULTS

The primary objective of this study was to synthesize information on the fatigue and elastic properties of inservice blackbase and asphalt concrete and the variation of these properties for use in the design of pavements.

The properties estimated using the indirect tensile test were fatigue life, instantaneous resilient and static modulus of elasticity, and instantaneous resilient and static Poisson's ratio. Density was estimated by measuring the dimensions and weight of the specimens.

Cores were obtained from a total of seven projects from five Texas Highway Department Districts. In addition, Projects 17B and 25-97 involved two lifts of blackbase, for which there were an adequate number of specimens for the evaluation of lift differences of variation occurring vertically between the upper and lower portion of the pavement. Since these lifts were placed at different times, these specimens can be considered to be somewhat independent of each other. Samples were obtained from each lift by sawing the core at the interface.

The fatigue life, elastic properties under repeated loads, and static indirect tensile properties for each project are shown in Tables 3, 4, 5, and 6. Values for the individual specimens are shown in Appendix B.

FATIGUE LIFE

The blackbase specimens from each project were subjected to a minimum of three different stress levels in order to define the stress versus fatigue life relationship and to measure the inherent variation of fatigue life which can be expected.

Fatigue Life-Stress Relationships

The mean fatigue life and coefficient of variation obtained for the specimens from each project are given in Table 3. The relationships between the logarithm of tensile stress and the logarithm of fatigue life were

TABLE 3. SUMMARY OF FATIGUE RESULTS FOR INSERVICE BLACKBASE AND ASPHALT CONCRETE

Project	Tensile Stress σ_T, psi	Number of Specimens	Fatigue Life N_f		$N_f = K_2 (\frac{1}{\sigma_T})^{n_2}$		
			Mean, cycles	CV, %	K_2	n_2	R^2*
2	16	3	16984	—	3.24×10^9	4.48	85%
	24	5	1842	29			
	32	5	869	52			
	40	5	252	78			
5	16	5	3179	30	4.72×10^6	2.66	73%
	24	5	1063	49			
	32	5	567	52			
8B	24	5	5277	60	9.20×10^6	2.32	42%
	32	4	4281	40			
	40	5	2586	84			
8C	40	4	7124	38	8.38×10^{10}	4.44	84%
	48	2	3513	—			
	56	4	1678	65			
17B(2) Second lift	16	5	3253	49	1.28×10^6	2.18	53%
	24	5	1593	45			
	32	5	748	52			
17B(1) First lift	16	5	3582	26	2.79×10^6	1.58	50%
	24	5	1985	40			
	32	5	1374	56			

* R^2 for regression equation expressed in the form $\log N_f = \log K_2 - n_2 \log \sigma_T$.

(Continued)

TABLE 3. (Continued)

Project	Tensile Stress σ_T, psi	Number of Specimens	Fatigue Life N_f		$N_f = K_2 (\frac{1}{\sigma_T})^{n_2}$		
			Mean, cycles	CV, %	K_2	n_2	R^2*
25-97(1) First lift (asphalt stab. base)	32	5	1393	80	5.53×10^7	3.18	39%
	40	2	382	—			
	48	5	313	61			
25-97(2) Second lift (asphalt stab. base)	32	1	27795	—	5.22×10^{10}	4.61	45%
	40	5	1582	75			
	48	2	924	—			
	56	3	1081	—			
25-97(3) Third lift (type A spec.)	40	5	1015	69	2.32×10^8	3.39	56%
	48	2	450	—			
	56	5	309	50			
25-97(S) Surface course (type D spec.)	40	5	1271	41	7.13×10^{12}	5.08	49%
	48	2	460	—			
	56	5	297	74			
25-100(1, 2) First two lifts (asphalt stab. base)	16	4	12223	66	1.22×10^9	4.21	89%
	24	2	2346	—			
	32	4	655	59			
	48	2	108	—			
25-100(3) Third lift (type A spec.)	40	4	799	49	2.07×10^{10}	4.68	50%
	48	2	296	—			
	56	4	180	64			
25-100(S) Surface course (type D spec.)	16	1	38157	—	3.14×10^9	4.14	89%
	40	3	644	—			
	48	2	512	—			
	56	4	195	38			

* R^2 for regression equation expressed in the form $\log N_f = \log K_2 - n_2 \log \sigma_T$.

TABLE 4. SUMMARY OF RELATIONSHIPS BETWEEN FATIGUE LIFE AND STRESS DIFFERENCE FOR INSERVICE BLACKBASE AND ASPHALT CONCRETE

Project	$N_f = K_2' (\frac{1}{\Delta\sigma})^{n_2}$		
	K_2'	n_2	R^2*
2	1.60×10^{12}	4.48	85
5	1.88×10^{8}	2.66	73
8B	2.29×10^{8}	2.32	42
8C	3.93×10^{13}	4.44	84
17B(1)	2.49×10^{6}	1.58	53
17B(2)	2.63×10^{7}	2.18	50
25-97(1)	4.52×10^{9}	3.18	39
25-97(2)	3.10×10^{13}	4.61	45
25-97(3)	2.55×10^{10}	3.39	56
25-97(S)	8.18×10^{15}	5.08	49
25-100(1, 2)	4.20×10^{11}	4.21	89
25-100(3)	1.36×10^{13}	4.68	50
25-100(S)	9.80×10^{11}	4.14	89

* R^2 for regression equation expressed in the form

$$\log N_f = \log K_2' - n_2 \log \Delta\sigma$$

where $\Delta\sigma = 4\sigma_T$

TABLE 5. SUMMARY OF ELASTIC PROPERTIES FOR REPEATED LOAD INDIRECT TENSILE TESTING

Project	Tensile Stress, psi	Number of Specimens*	Instantaneous Resilient Modulus of Elasticity		Instantaneous Resilient Poisson's Ratio	
			Mean, 10^3 psi	CV, %	Mean	CV, %
2	16	3	285	—	0.31	—
	24	5	266	7	0.27	31
	32	5	278	9	0.44	46
	40	5	299	4	0.58	12
5	16	5	225	8	0.11	47
	24	5	230	4	0.13	39
	32	5	257	9	0.18	28
8B	24	5	384	14	0.12	53
	32	4	408	12	0.06	10
	40	5	479	28	0.18	54
8C	40	4	513	12	0.11	23
	48	2	528	—	0.13	—
	56	4 (3)	456	9	0.16	—
17B(2) Top lift	16	5	439	25	0.09	49
	24	4	545	5	0.13	37
	32	5 (4)	450	22	0.22	76
17B(1) Bottom lift	16	5	516	17	0.11	18
	24	4	615	14	0.13	50
	32	5	485	17	0.11	18

*Numbers in parentheses are the number of specimens analyzed to determine the instantaneous resilient Poisson's ratio.

(Continued)

TABLE 5. (Continued)

Project	Tensile Stress, psi	Number of Specimens*	Instantaneous Resilient Modulus of Elasticity		Instantaneous Resilient Poisson's Ratio	
			Mean, 10^3 psi	CV, %	Mean	CV, %
25-97(1)	32	5	251	17	0.32	33
First lift	40	2	269	—	0.46	—
(asph. stab. base)	48	5	250	4	0.39	38
25-97(2)	40	5	289	21	0.28	37
Second lift	48	2	353	—	0.31	—
(asph. stab. base)	56	3	306	10	0.31	27
25-97(3)	40	5 (2)	385	9	0.16	—
Third lift	48	2	498	—	0.22	—
(type A spec.)	56	5	405	9	0.23	33
25-97(S)	40	5	403	8	0.18	44
Surface course	48	2	387	—	0.33	—
(type D spec.)	56	4 (3)	434	16	0.41	57
25-100(1, 2)	16	3	221	—	—	—
First two lifts	24	2	259	—	0.24	—
(asphalt	32	2	302	—	—	—
stab. base)	48	1	310	—	—	—
25-100(3)	40	3	344	—	0.13	—
Third lift	48	2	358	—	0.15	—
(type A spec.)	56	3 (2)	344	—	0.14	—
25-100(S)	40	3	308	—	0.16	—
Surface course	48	2	344	—	0.15	—
(type D spec.)	56	3	329	—	0.29	—

*Number in parentheses are the number of specimens analyzed to determine the instantaneous resilient Poisson's ratio.

TABLE 6. SUMMARY OF STATIC INDIRECT TENSILE STRENGTHS AND ELASTIC PROPERTIES

Project	Number of Specimens	Indirect Tensile Strength		Modulus of Elasticity		Poisson's Ratio	
		Mean, psi	CV, %	Mean, 10^3 psi	CV, %	Mean	CV
2	5	61	24	70	27	0.21	34
5	5	71	23	94	21	0.32	25
8B	5	106	26	110	14	0.10	57
8C	3	159	—	169	—	0.22	—
17B*	100	104	27	55	44	0.24	41
25-97(1)	3	101	—	62	—	0.21	—
25-97(2)	3	132	—	46	—	0.20	—
25-97(3)	3	139	—	73	—	0.27	—
25-97(S)	3	132	—	94	—	0.27	—
25-100(1, 2)	4	90	16	61	15	0.03	—
25-100(3)	2	122	—	75	—	0.35	—
25-100(S)	2	87	—	60	—	0.12	—

*Values from Project 17B are those reported previously by Marshall and Kennedy (Ref 28).

essentially linear, but the slopes varied, indicating that the relationships were material, or project, dependent. The linear relationships as determined by the method of least squares are graphically illustrated in Fig 14 and can be expressed in the form

$$N_f = K_2 \left(\frac{1}{\sigma_T}\right)^{n_2}$$

where

N_f = fatigue life, cycles to failure,
σ_T = repeated tensile stress, psi,
K_2 = a material constant,
n_2 = a material constant, the absolute value of the slope.

As can be seen in Fig 14, and by the values of n_2 in Table 3, the slopes were fairly consistent except for four projects - 5, 8B, 17B(1), and 17B(2). Values ranged from 1.58 to 5.08, with most of the slopes ranging from 3.18 to 5.08. Values for projects 5, 8B, 17B(1), and 17B(2) were smaller, varying from 1.58 to 2.66. Monismith et al (Ref 27) reported smaller values of K_2 and n_2 from previous work on field cores. Their values of n_2 ranged from 1.85 to 6.06 and, thus, the values obtained in this study were in the range previously reported. In addition, it was suggested that n_2 was a function of stiffness of the mixture. A review of Table 2 shows that three of the four projects with the smaller values of n_2 involved mixtures containing AC-10 rather than AC-20 which may relate to the lower values of n_2. In addition, project 8B mixtures, which contained an AC-20, involved a different basic aggregate type.

Previously reported values of K_2 were 8.00×10^7 and 4.10×10^{18} (Ref 20). Values in this study were smaller, ranging from 2.79×10^5 to 7.13×10^{12}. Thus, the fatigue lives for the materials tested are generally smaller than values previously reported.

Porter and Kennedy (Ref 33) compared the fatigue relationships obtained by various investigators using different test methods. This comparison indicated that the fatigue life obtained using the repeated loading indirect tensile testing was significantly less than the fatigue life obtained by

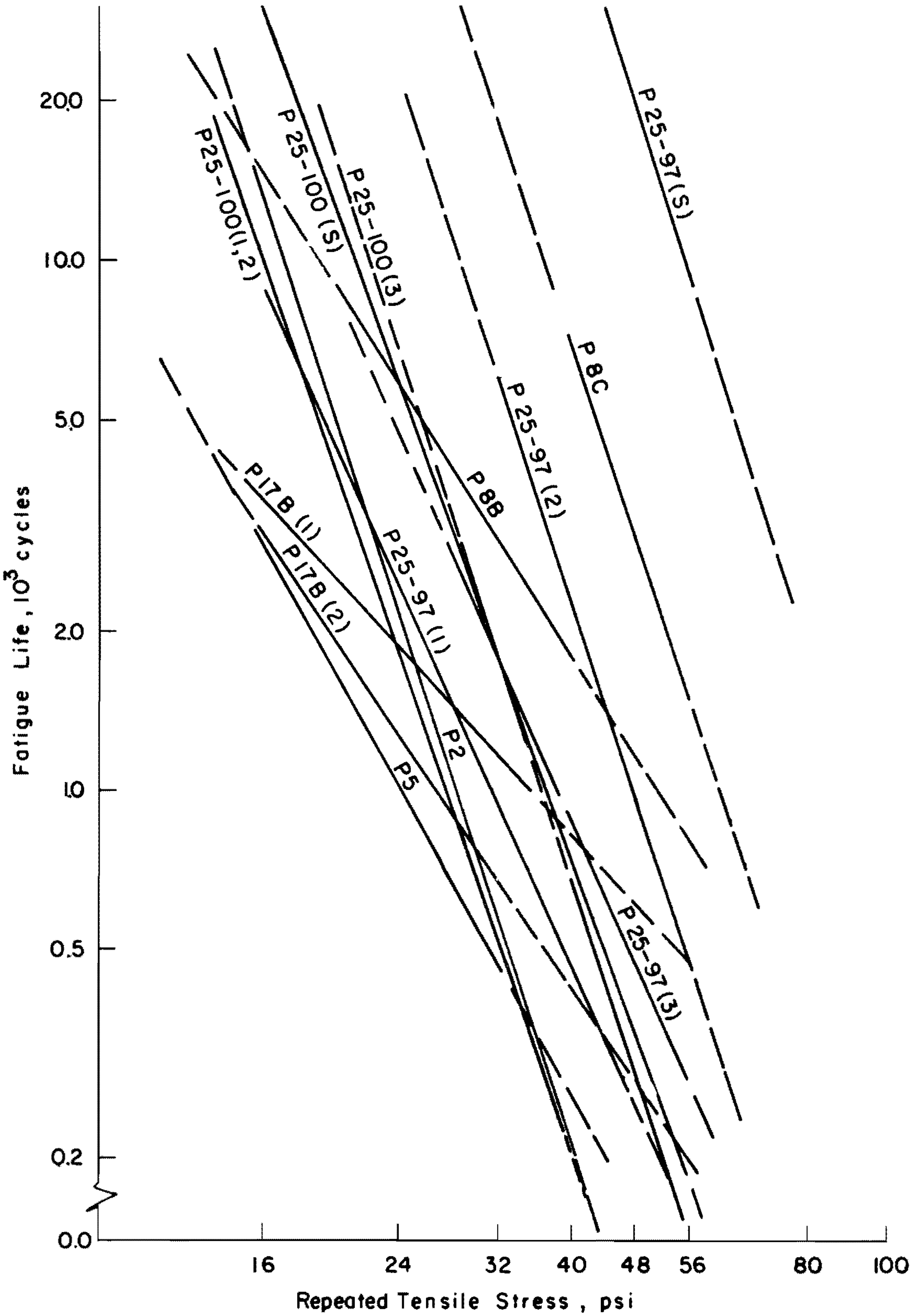


Fig 14. Relationships between the logarithms of tensile stress and fatigue life.

other investigators using other test methods, but that the slopes of the log fatigue life versus log stress relationships were essentially equal. While a number of contributing factors were identified, a large portion of the difference was attributed to the fact that the indirect tensile test involves a biaxial state of stress while most of the other test methods involve a uniaxial state of stress. The result of the investigation suggested that stress could be expressed in terms of a stress difference, i.e., the maximum principal stress minus the minimum principal stress.

The relationships between the logarithm of fatigue life and the logarithm of stress difference are shown in Fig 15. According to theory, the stress difference is approximately $4\sigma_T$ in the zone of failure. Values of n_2 did not change since the lines were merely shifted along the X axis. Values of the K coefficient, designated K_2' , however, were significantly larger than K_2 , ranging from 2.49×10^6 to 8.18×10^{15}, with the majority of the values in the range of 10^{10} to 10^{13} (Table 4). These values are consistent with the previously reported values of K_2 .

Variations of Fatigue Life

The coefficients of determination R^2 for the various relationships shown in Figs 14 and 15 are summarized in Tables 3 and 4. These values indicate that a great deal of the variation in data could not be explained by the linear relationships. In addition, as shown in Table 3, the coefficients of variation were not constant but, rather, were stress and project dependent. Coefficients ranged from 26 to 84 percent; however, a portion of this variation can be accounted for by stress since the coefficients increased with increasing stress or decreasing fatigue life (Figs 16 and 17).

A portion of the within-project variation for Projects 8B and 8C possibly can be attributed to large aggregates in the mixtures. A visual inspection of specimens after failure revealed larger aggregates for these two projects than for the other projects. In addition, the cores from Project 25-100(1, 2) were very rough, which would contribute to the total variation by increasing the testing error.

Since there were significant differences in the coefficients of variation for the various projects and stress levels, no definite recommendation can be made concerning an exact value for the expected coefficient of variation, but it is possible to establish a range of values to be expected.

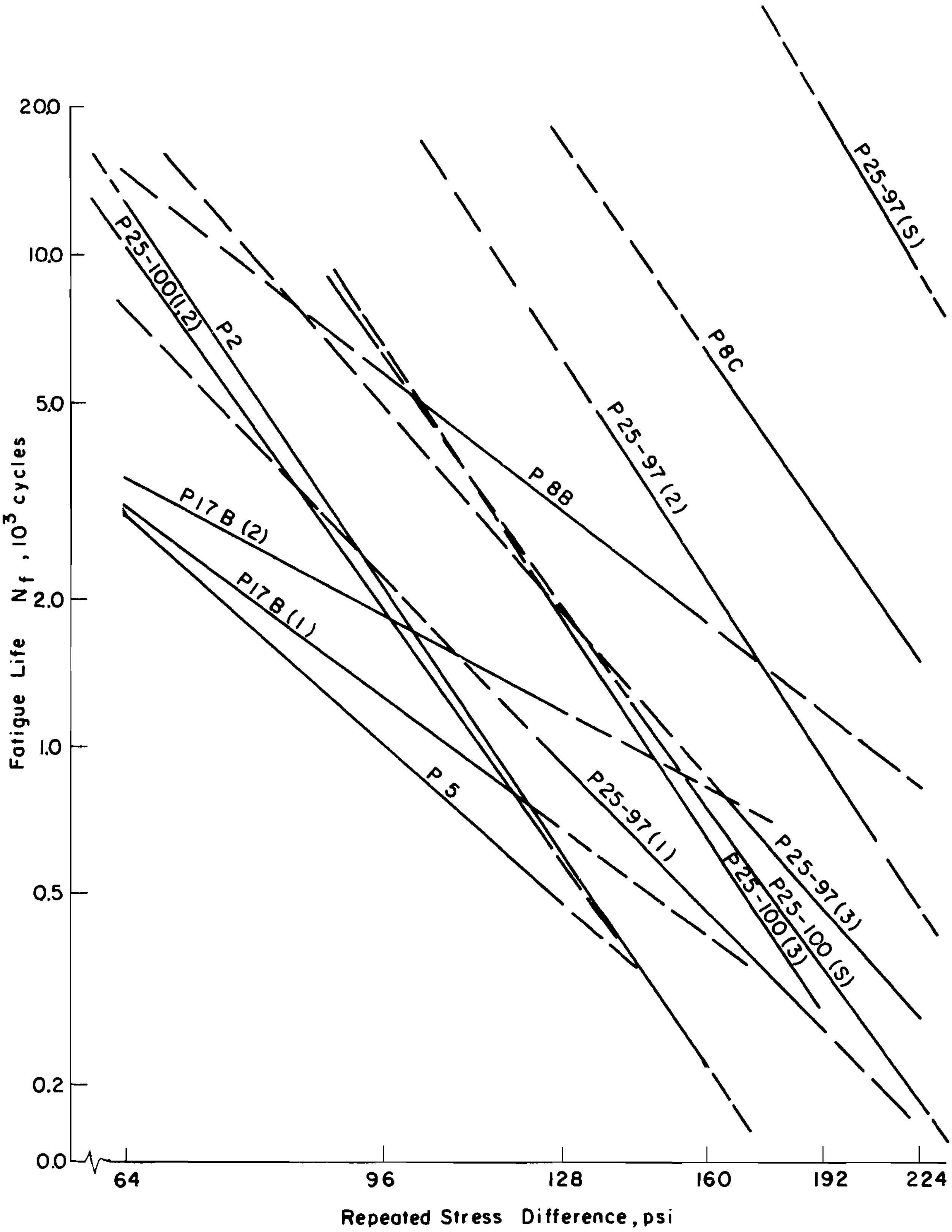


Fig 15. Relationships between the logarithms of stress difference and fatigue life.

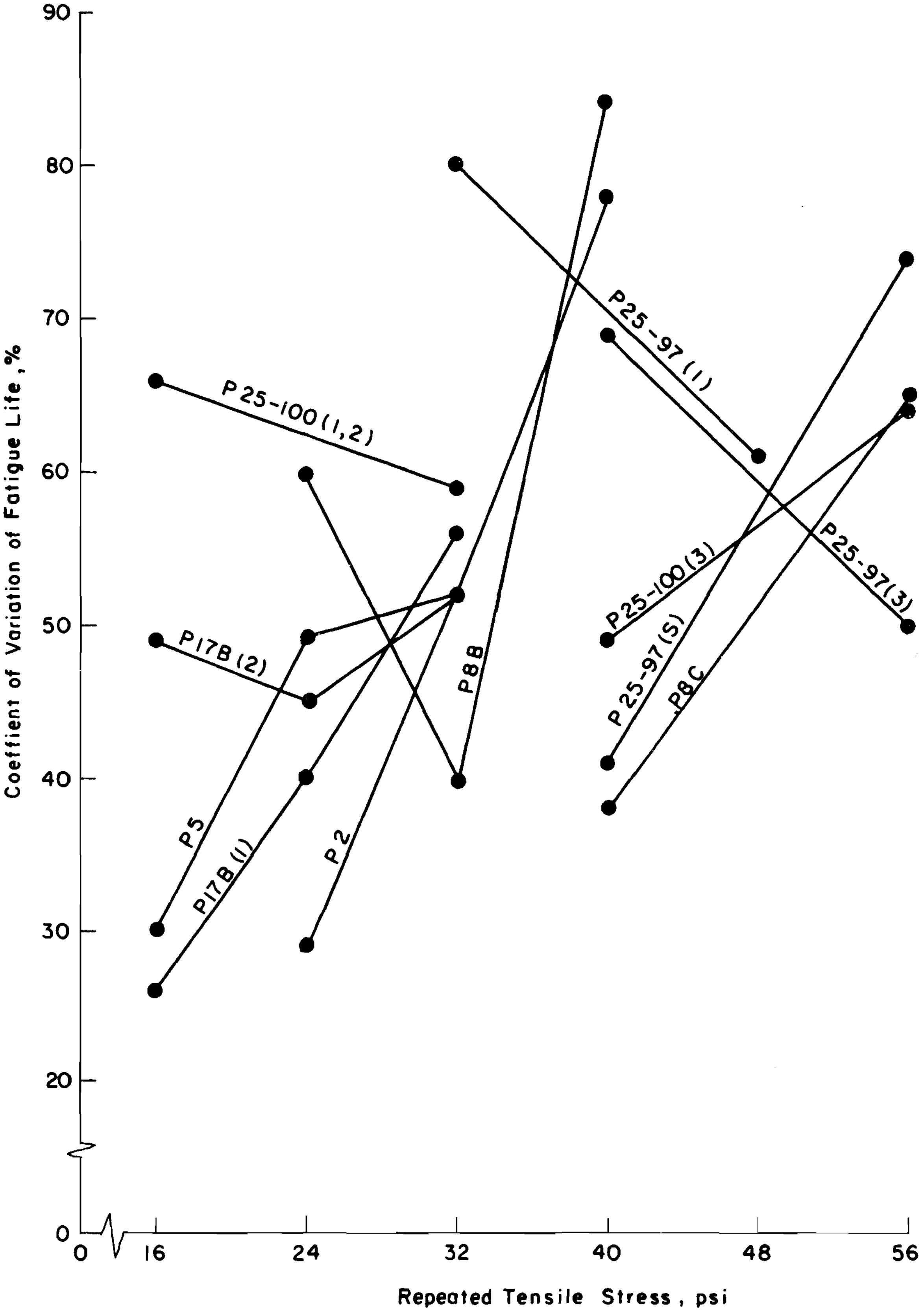


Fig 16. Relationship between dynamic tensile stress and coefficient of variation for fatigue life.

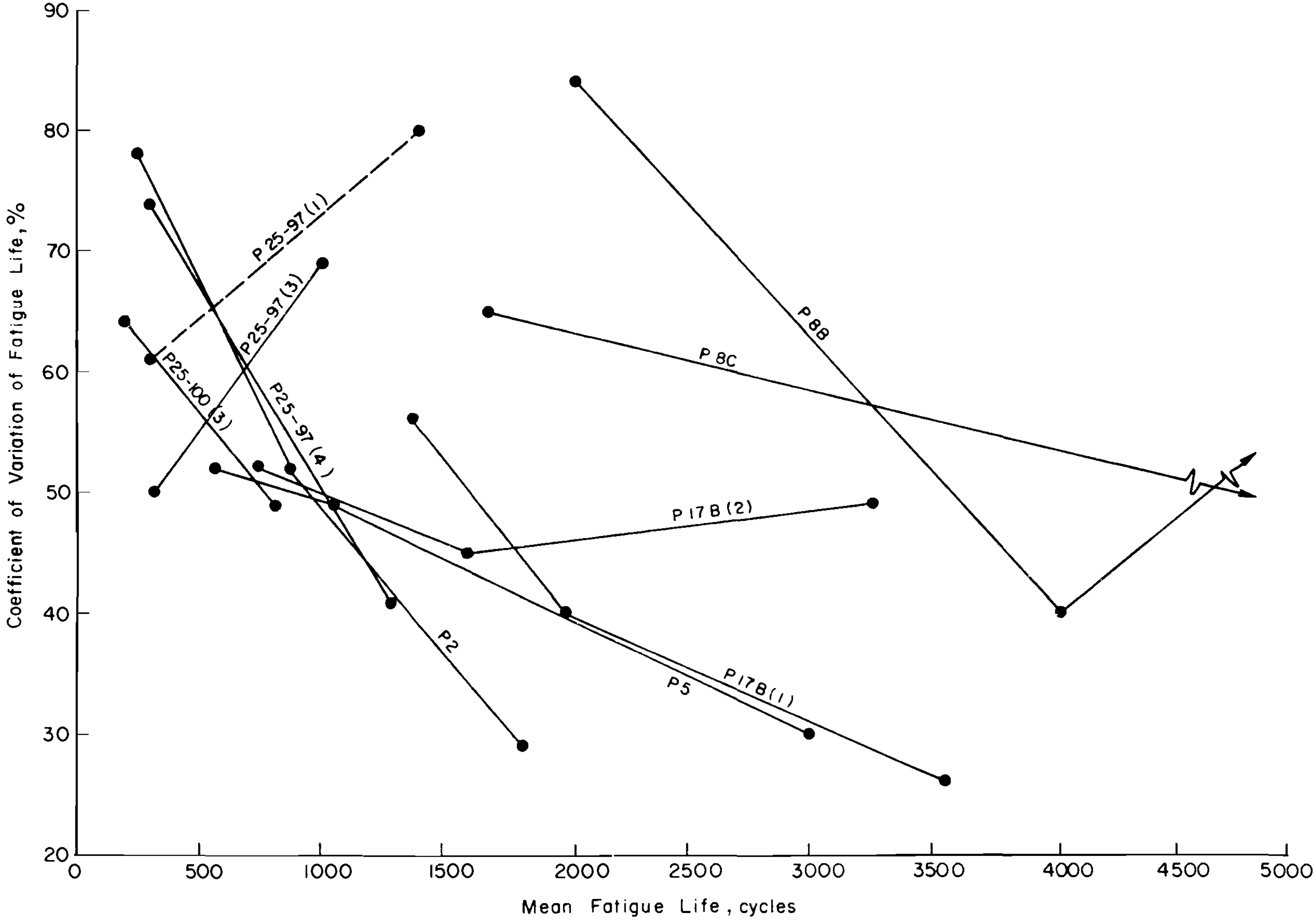


Fig 17. Relationship between mean fatigue life and the coefficient of variation.

Based on this study it appears that the coefficients of variation would range from about 30 to 80 percent.

Comparison Between Layers

Comparing the top and bottom layers for Projects 17B and 25-97, the two projects which had an adequate number of specimens for comparison, indicates that the top layers, designated by (2), generally had longer fatigue lives than the lower layers, designated by (1). In Figs 14 and 15, it can be seen that the stress-fatigue life relationship for Project 25-97(2) is above that for Project 25-97(1) but that for Projects 17B(2) and 17B(1) the reverse is true. However, if the K coefficients for the two projects are compared, the upper lifts exhibit larger values, indicating that at lower stress values the fatigue lives would be larger for both projects. However, the slope value n_2 is larger for the upper lifts, indicating that fatigue life decreased more rapidly with increased stress.

ELASTIC CHARACTERISTICS

The instantaneous resilient modulus of elasticity and Poisson's ratio for each specimen were estimated by averaging the values calculated from the instantaneous resilient vertical and horizontal deformation occurring under repeated loading at approximately 30, 50, and 70 percent of the fatigue life. Moduli of elasticity, Poisson's ratio, and densities for each specimen are shown in Appendix B. Means and coefficients of variation for each project and stress level are summarized in Table 5. Table 5 also summarizes the static values of tensile strength, modulus of elasticity, and Poisson's ratio obtained for the same projects.

Instantaneous Resilient Modulus of Elasticity

As shown in Table 5, the mean instantaneous resilient moduli were consistent for the various projects, ranging from 221×10^3 to 615×10^3 psi. More important, however, is the consistency within a given project and the fact that the modulus value was not overly sensitive to the magnitude of the applied stress for the range of stresses used in testing. As a result of this consistency, it can be seen that the coefficients of variation for any given project and stress level were low, ranging from 4 to 28 percent.

In contrast, mean static moduli (Table 6) for similar materials tested using the static indirect tensile test (Refs 28 and 34) were much lower (38.6×10^3 to 91.5×10^3 psi) and the coefficients of variation were much higher (24 percent to 59 percent). Mean values ranged from 55.2×10^3 to 169×10^3 psi, which is consistent with the previously reported values, and the coefficient of variation ranged from 14 to 27 percent, which is smaller than previously reported static coefficients but somewhat larger than the coefficients of variation for the moduli resulting from repeated loads. Although not completely substantiated by these results, it is felt that a large portion of the variation associated with static testing can probably be attributed to testing errors due to surface irregularities which would not have a large effect on repeated-load tests.

A comparison of the mean static moduli and the mean resilient moduli is shown in Fig 18. From this figure it is evident that the dynamic moduli were significantly larger than the static moduli. The ratio of the resilient and static moduli ranged from 10.5 to 2.3, with the higher values associated with the materials with low static moduli (Fig 19).

Instantaneous Resilient Poisson's Ratio

Mean resilient Poisson's ratios are shown in Table 5. Except for Projects 2 and 25-97, values were fairly consistent, ranging from 0.06 to 0.29 with the majority of the values in the range from about 0.10 to 0.22. Values for Projects 2 and 25-97 were much higher, ranging from 0.16 to an indicated value of 0.58, with the majority in the range of 0.22 to 0.46.

These values tend to be lower than those for similar materials which were previously tested using the static indirect tensile test, which ranged from 0.16 to 0.34 (Refs 28 and 34). A comparison of the static Poisson's ratio (Table 6) and resilient Poisson's ratios obtained from this study indicates that the resilient and static Poisson's ratios were essentially of the same magnitude (Fig 20). In most projects the mean values tended to increase with increasing stress (Fig 21).

Coefficients of variation for Poisson's ratio were much higher than those for resilient modulus of elasticity, ranging from 10 to 76 percent, with the majority of the values in the range between 18 and 57 percent. Nevertheless, these coefficients are lower than the static Poisson's ratios

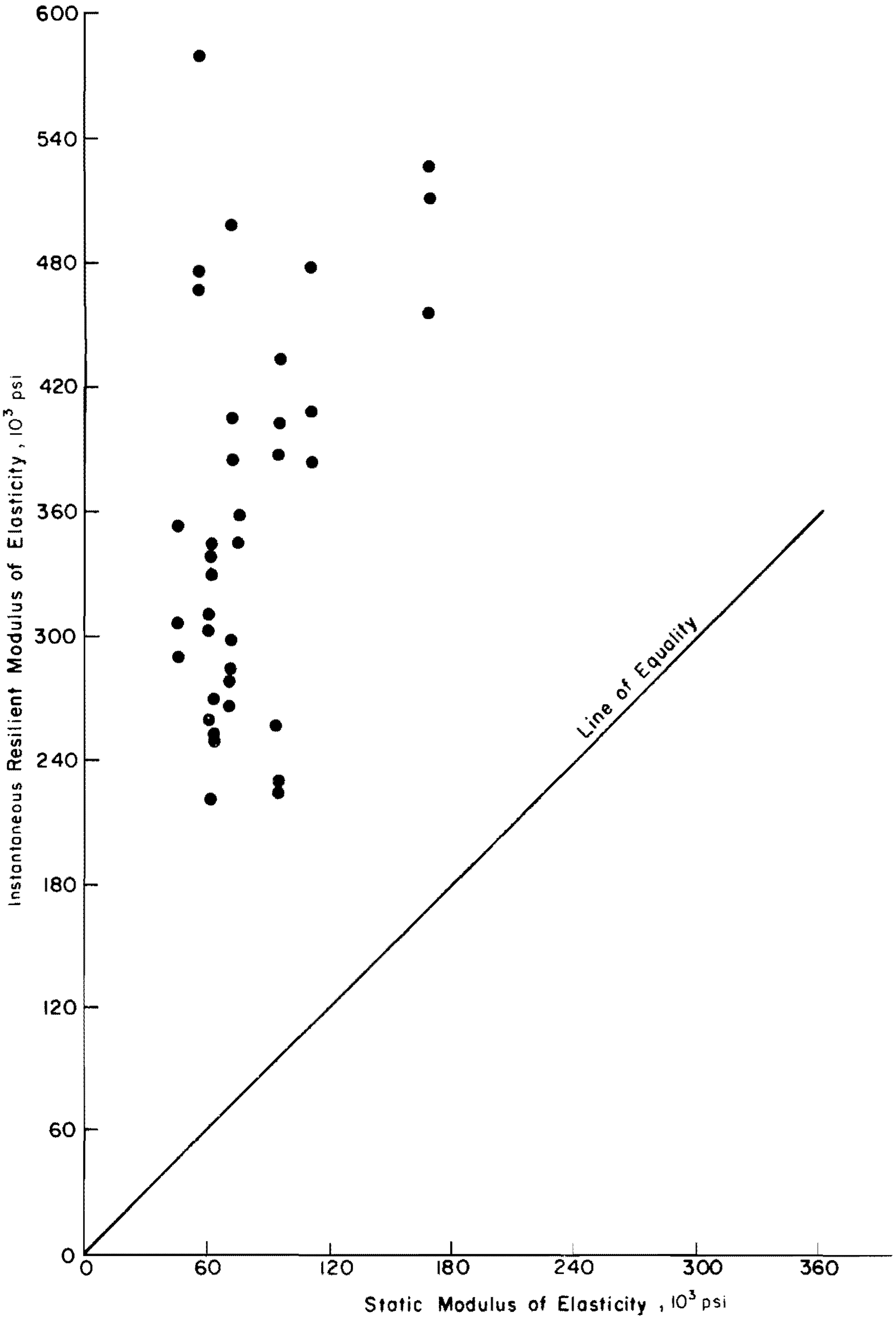


Fig 18. Relationship between static and instantaneous resilient moduli of elasticity.

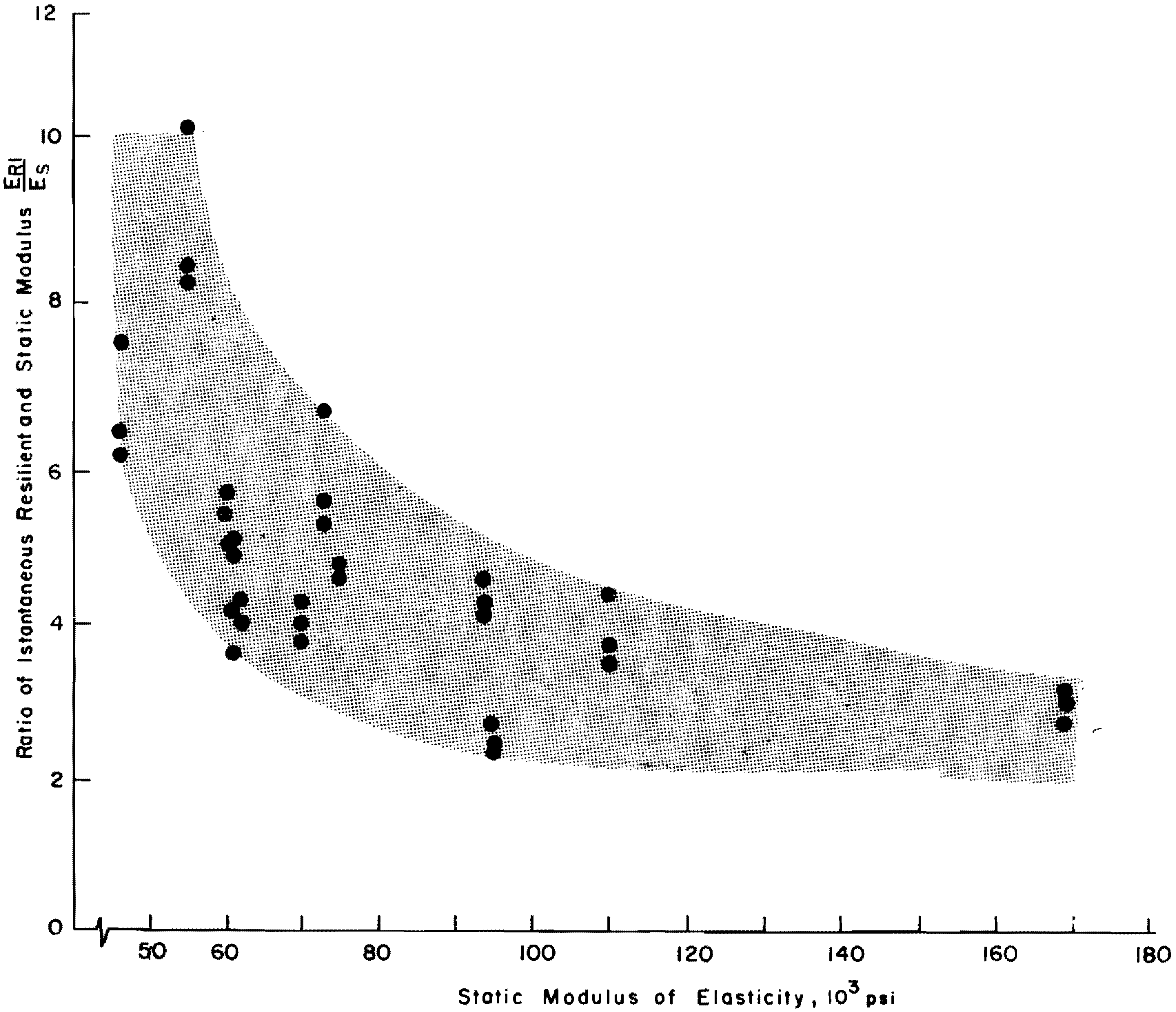


Fig 19. Relationship between static modulus and the ratio of static and instantaneous resilient moduli.

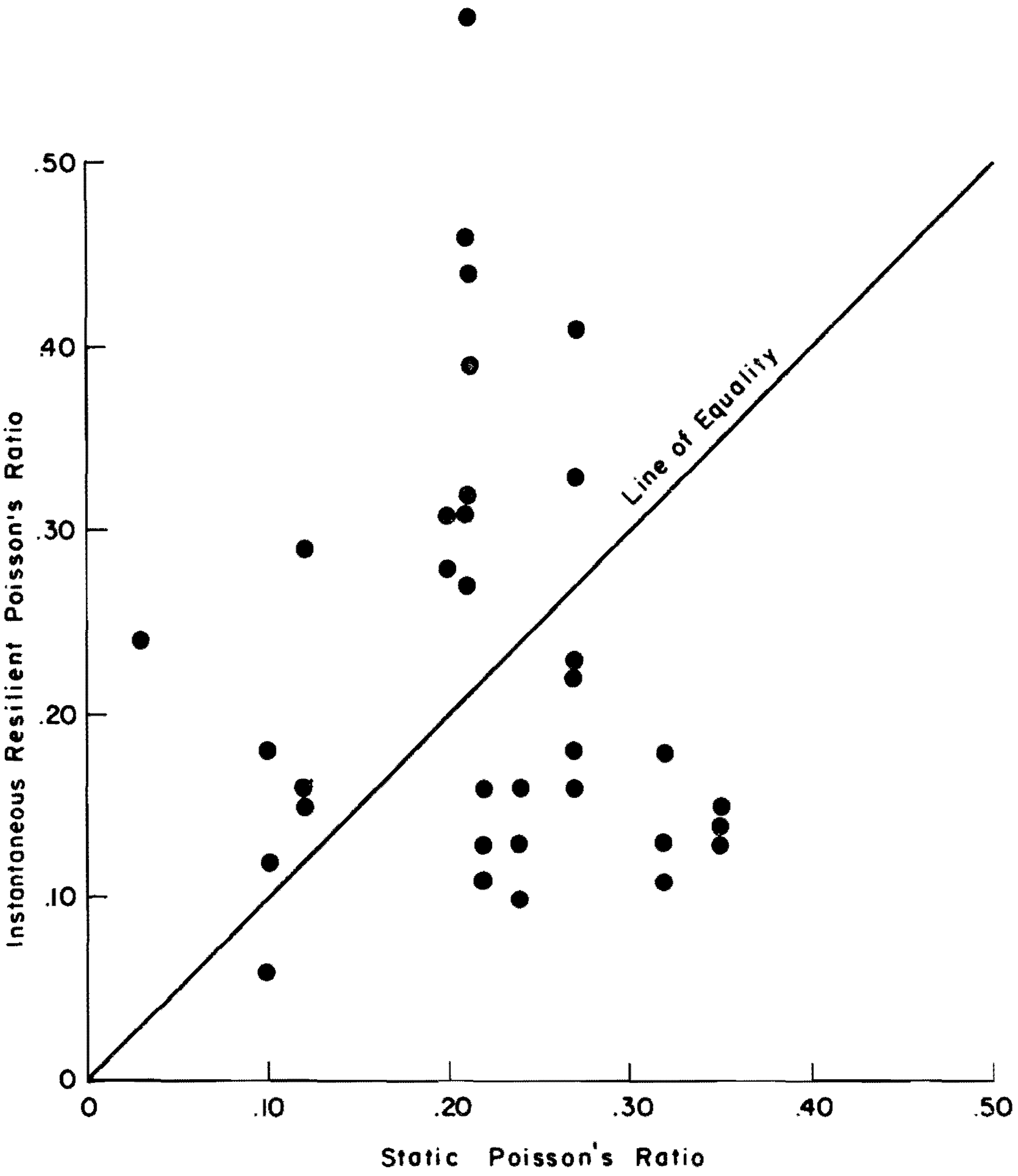


Fig 20. Relationship between static and instantaneous resilient Poisson's ratio values.

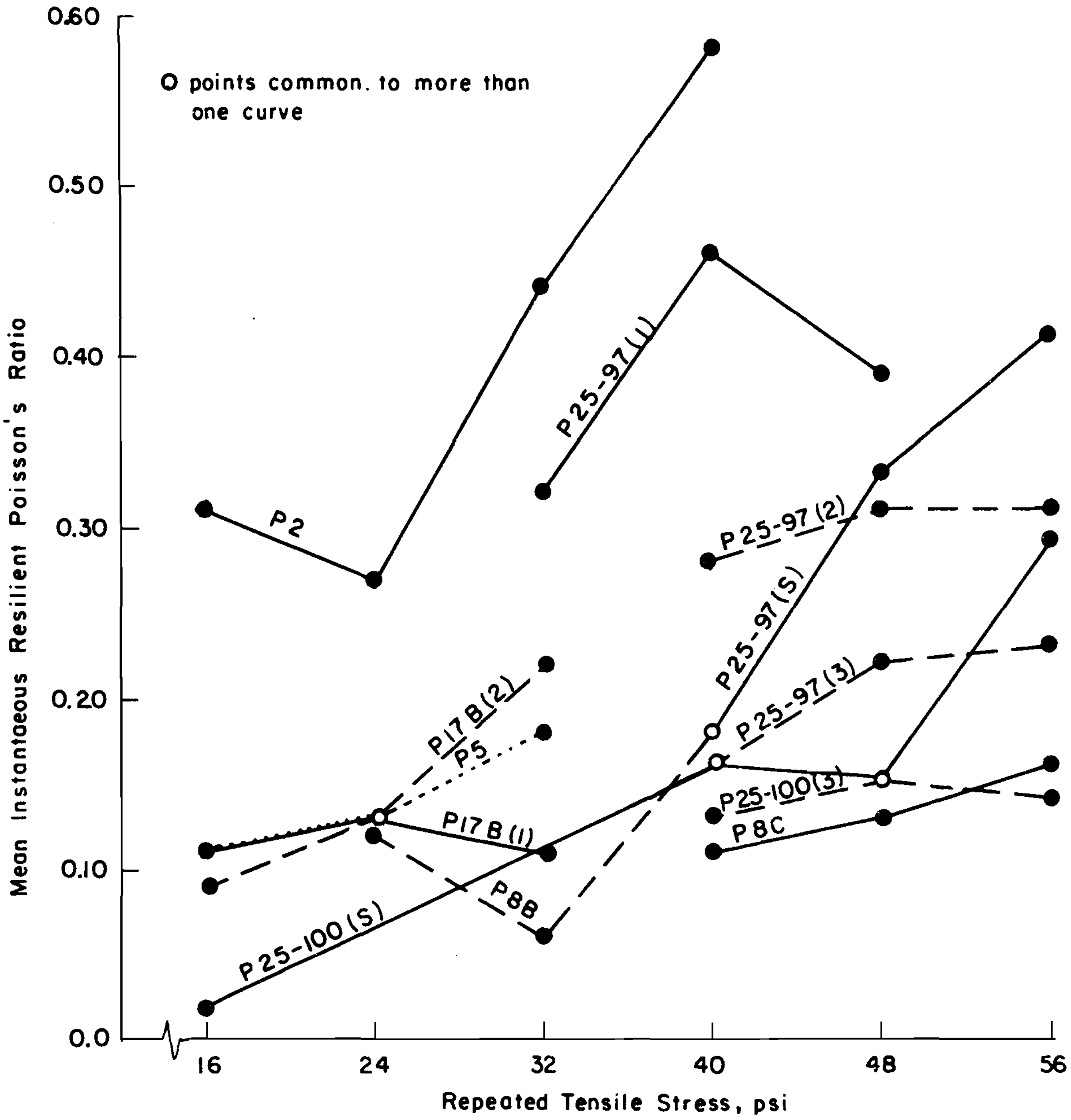


Fig 21. Relationship between repeated tensile stress and resilient Poisson's ratio.

for similar materials, for which coefficients ranged from 39 to 67 percent (Refs 28 and 34). Coefficients of variation for the static Poisson's ratios from this study ranged from 25 to 41 percent.

Densities

As previously reported (Ref 28) densities exhibit very small coefficients of variation, with values ranging from 1.4 to 4.6 percent (Table 7).

CORRELATIONS WITH FATIGUE LIFE

It is desirable to evaluate possible correlations between fatigue life and static properties and between fatigue life and repeated-load properties since repeated-load tests are time-consuming and costly to conduct. If correlations exist, it would be possible to estimate fatigue properties using the much simpler static test or a short-term repeated-load test. Such correlations also could lead to a better understanding of the fatigue behavior of pavement materials.

Mean tensile strengths (Table 6) ranged from 61 to 159 psi; however, with the exception of Project 8C, the range was 61 psi to 139 psi. The high strength, 159 psi, for Project 8C can probably be attributed to the larger aggregates used in the mixture. Mean modulus values varied from 46×10^3 to 169×10^3 psi. Poisson's ratios generally varied from 0.10 to 0.35.

The coefficients of variation for tensile strength, modulus of elasticity, and Poisson's ratio were low to moderate, ranging from 16 to 27 percent for strength, 14 to 44 percent for modulus, and 25 to 57 percent for Poisson's ratio.

Stress-Strength Ratio

Previous work reported by Moore and Kennedy (Refs 17 and 18) found a relatively good linear correlation between the logarithm of the ratio of applied tensile stress to static tensile strength and the logarithm of fatigue life. Such a relationship allows fatigue life to be estimated from static test results.

The stress-strength ratio, defined as the ratio of the repeated tensile stress to the mean static tensile strengths, are reported in Table 6 for this study. The relationship between the logarithm of the estimated stress-

TABLE 7. SUMMARY OF MEAN DENSITIES AND COEFFICIENTS OF VARIATION

Project Identification	Number of Specimens	Mean Density, pcf	Coefficient of Variation, %
2	23	129.1	1.6
5	20	126.2	1.8
8B	20	135.7	2.4
8C	14	137.6	3.0
17B(1)	15	137.4	1.7
17B(2)	15	136.5	1.7
25-97(1)	15	130.4	1.4
25-97(2)	15	135.5	1.6
25-97(3)	15	150.2	1.4
25-97(S)	15	141.7	3.3
25-100(1, 2)	16	133.8	2.0
25-100(3)	12	149.9	1.9
25-100(S)	12	133.8	4.6

strength ratio and the logarithm of fatigue life is shown in Fig 22. A linear line of best fit was developed for the data by the method of least squares. In addition, the relationship previously developed by Moore and Kennedy (Refs 17 and 18) is shown for comparison. A cursory evaluation of the relationship and the coefficient of determination R^2 of 51 percent indicates that while a correlation exists, the reliability of a predicted fatigue life would be questionable and large errors would be expected.

Stiffness

Previous work has indicated that stiffness is an important characteristic related to fatigue life.

Deacon and Monismith (Ref 21) stated that any factor that affects stiffness also affects fatigue behavior. Deacon (Ref 35) reported that the effect of stiffness is a function of the mode of loading. Under controlled-stress loading, a material with a high stiffness will perform well as long as the mixture is not brittle and is well proportioned, but the reverse is true under controlled-strain loading. Epps and Monismith (Ref 22) presented data which indicated that stiffness alters the slope of the logarithmic relationships between fatigue life and bending stress and showed that a stiff mixture had a longer fatigue life. There was an indication that this was true in this study.

Moore and Kennedy (Refs 17 and 18) found relatively poor relationships between the logarithm of fatigue life and estimated modulus of elasticity, which was estimated with previously developed regression equations obtained from testing similar material (Ref 36 and 37).

Since previous work has indicated that stiffness can be used to estimate fatigue behavior, an attempt was made to establish a correlation between modulus of elasticity and fatigue life. Figure 23 illustrates the relationship between the mean static modulus of elasticity and the mean fatigue life for each project. Since fatigue life is dependent on stress, the points pertaining to a given stress level are connected.

For the limited number of projects and conditions involved, there was no definite correlation, although materials with higher static moduli of elasticity tended to have longer fatigue lives.

Figure 24 illustrates the relationship between fatigue life and the mean resilient modulus of elasticity, which to a certain extent considers stress.

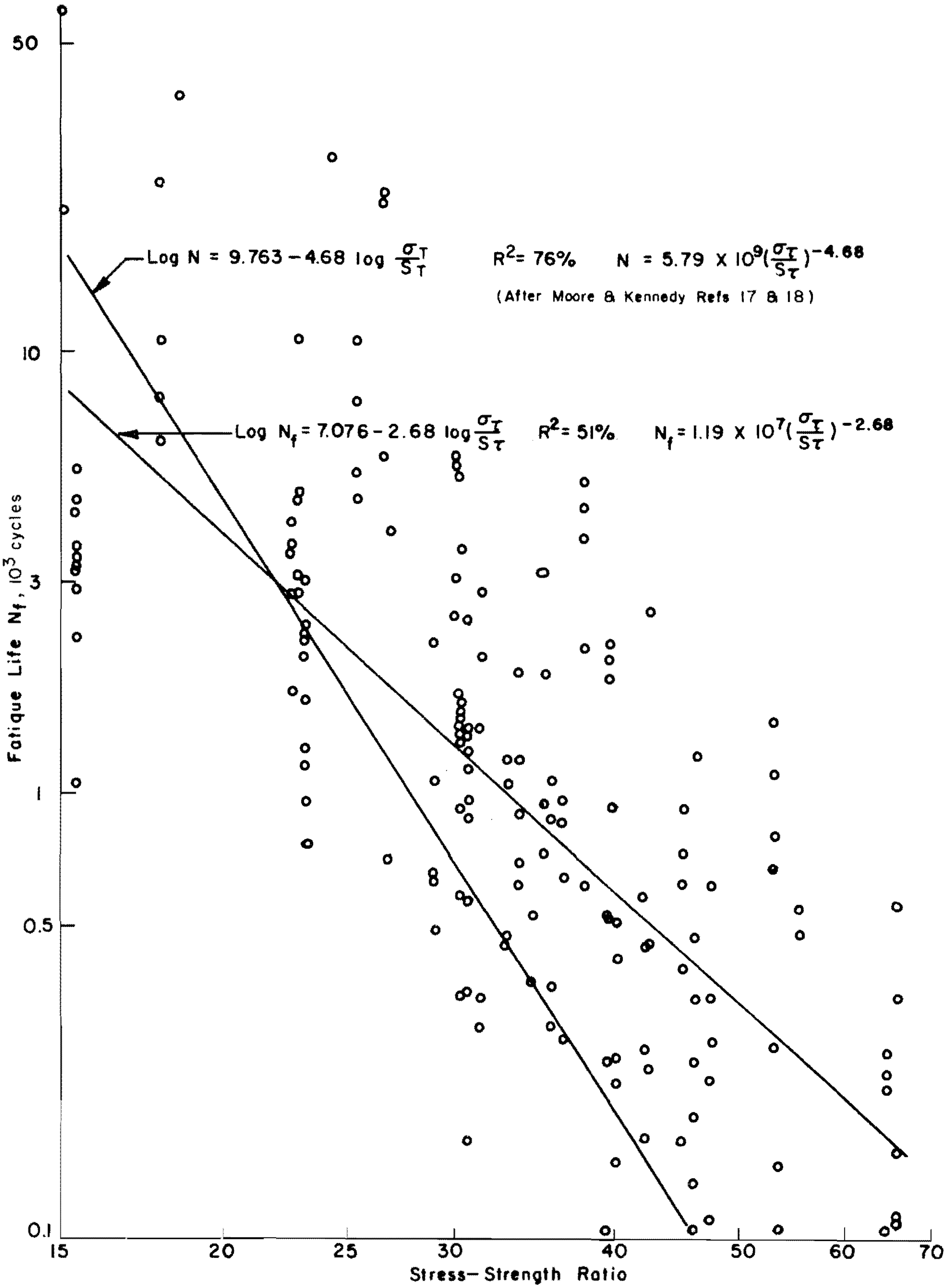


Fig 22. Logarithmic relationship between stress-strength ratio and fatigue life.

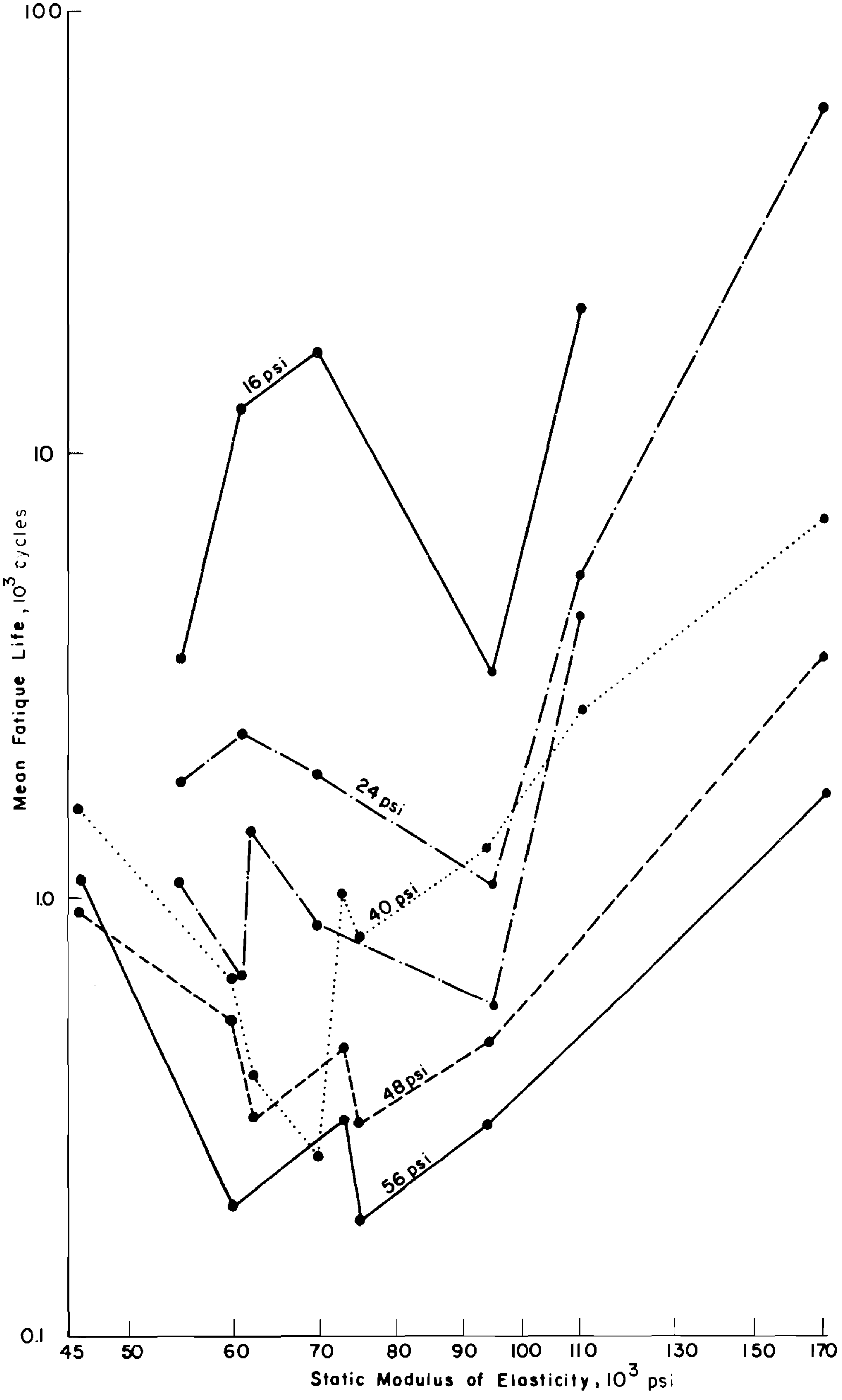


Fig 23. Logarithmic relationship between mean static modulus of elasticity and mean fatigue life.

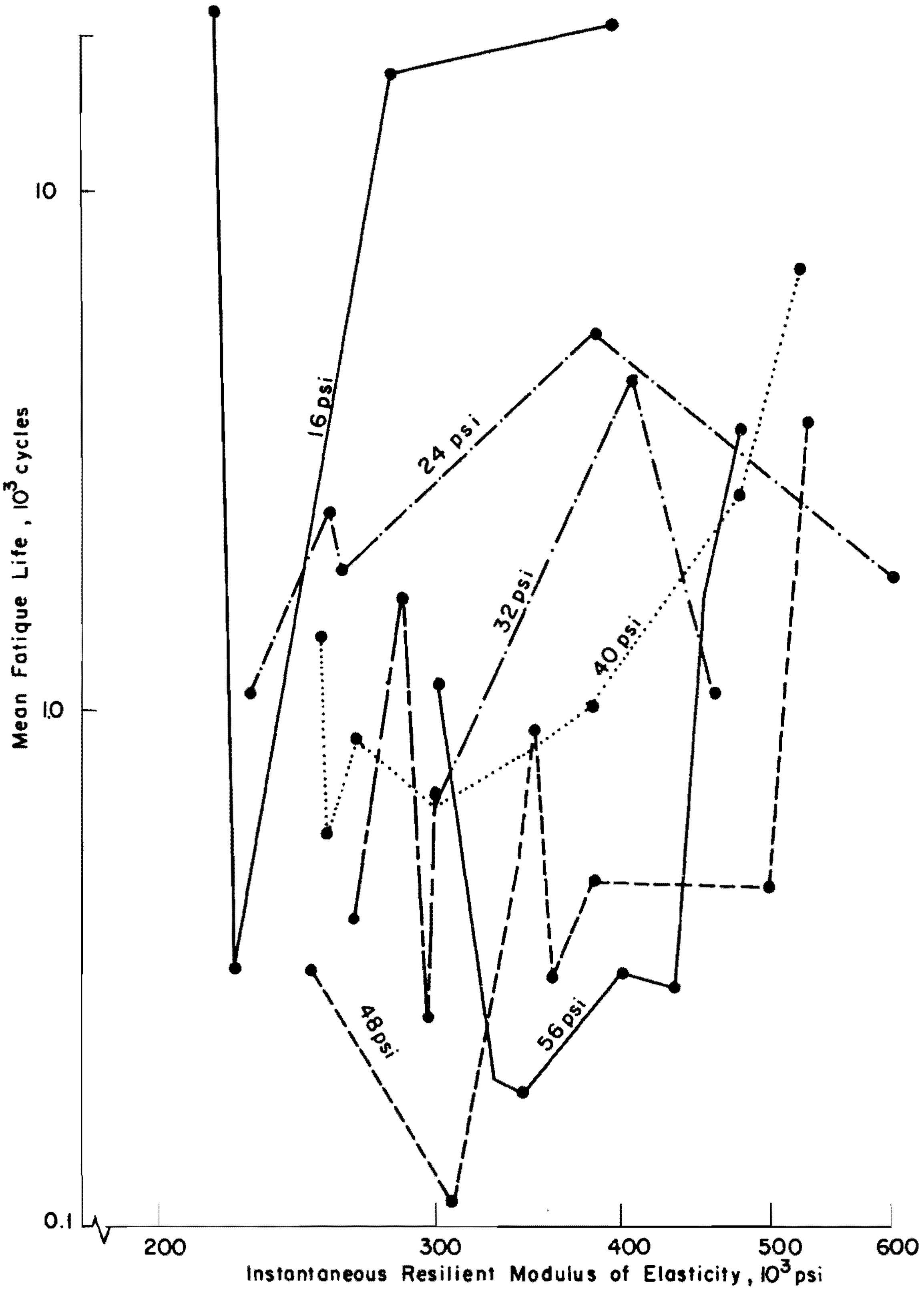


Fig 24. Mean instantaneous resilient modulus of elasticity and mean fatigue life.

As with the static modulus there was no correlation. A comparison of the fatigue life and instantaneous resilient modulus of elasticity for each specimen showed absolutely no correlation.

Tensile Strain

Previous investigators have shown that fatigue life is related to strain (Ref 17). Saal and Pell (Ref 23) found the relationship between the logarithm of strain and the logarithm of the number of cycles to failure was linear for constant stress loading. Pell (Ref 24) stated that the relationship between the logarithm of strain and the logarithm of fatigue life was essentially independent of temperature and speed of loading, and it was concluded that the fatigue life of a sandsheet mixture within the ranges studied was controlled primarily by the magnitude of the applied strain and not by stress. Moore and Kennedy (Refs 17 and 18) evaluated the relationship between fatigue life and initial strains, which were estimated using regression equations from previous work on the same material (Refs 36 and 37). A definite relationship was established; however, it was not recommended that the relationship be used for estimating fatigue life.

Figure 25 illustrates the relationship between fatigue life and tensile strain. Tensile strains were estimated by dividing the tensile stress σ_T by the resilient modulus of elasticity E_{RI} . Included for comparison is the relationship previously established by Moore and Kennedy (Refs 17 and 18).

As shown, there was a definite trend when the data for Project 17B were excluded. The relationship for all of the other projects exhibited a coefficient of determination R^2 of 67 percent, indicating that a great deal of variation would be accounted for by the relationship but that substantial estimation errors could be expected if the relationship were used to predict fatigue life. The relationship, excluding Project 17B, was essentially parallel to that previously established by Moore and Kennedy (Refs 17 and 18) but the fatigue lives for a given strain were less. A portion of this difference is possibly due to the fact that this investigation was of field cores while the previous study involved laboratory specimens.

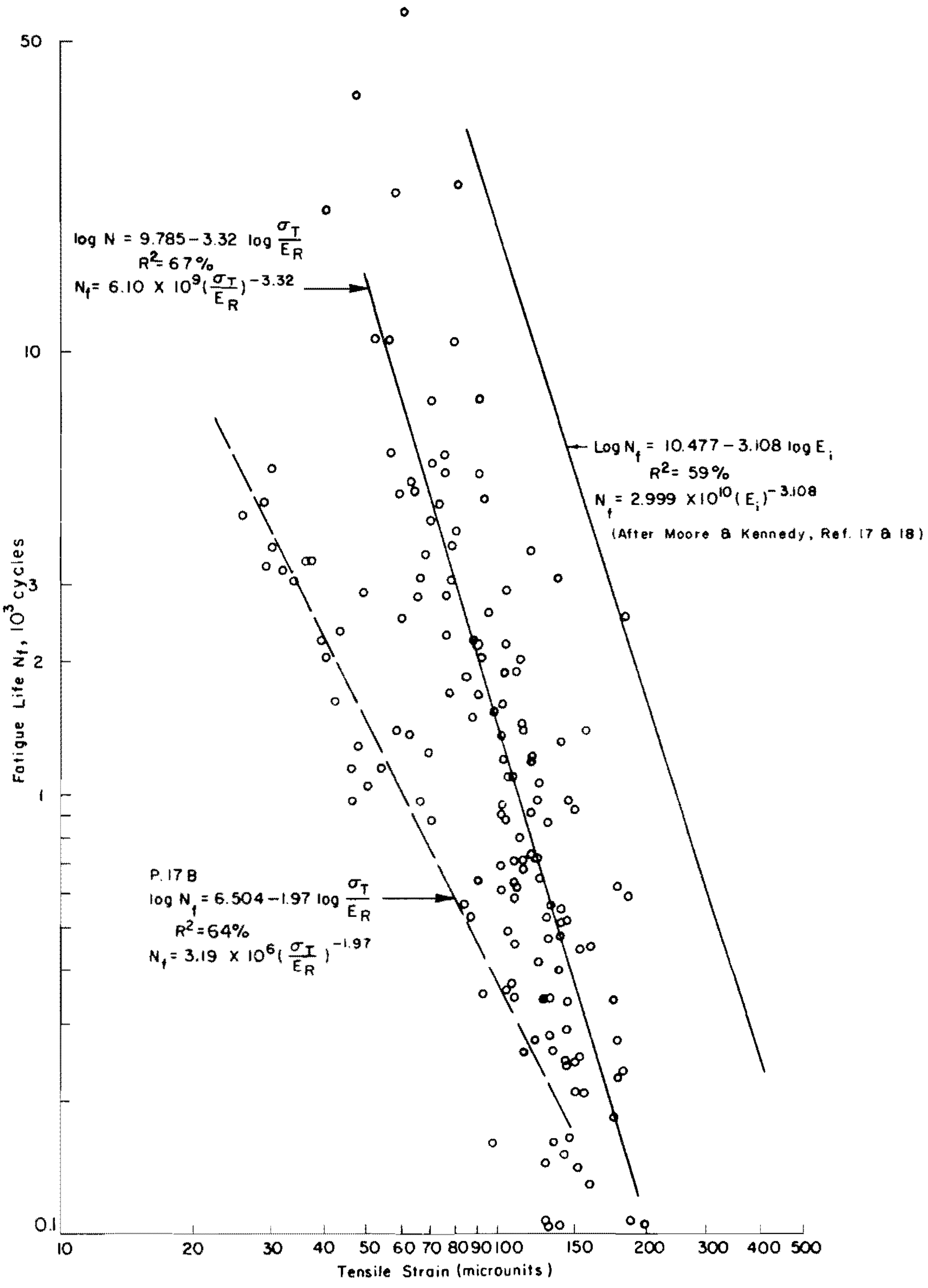


Fig 25. Relationship between the logarithms of fatigue life and tensile strain.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the findings of a study to determine (1) the fatigue characteristics and elastic properties of asphalt-treated materials, blackbase and asphalt concrete, from inservice highways and (2) the variations associated with these properties for use in pavement design procedures incorporating stochastic and reliability concepts. Cores from seven newly constructed pavements were obtained and subjected to repeated tensile stresses using the indirect tensile test. Estimates of fatigue life, resilient modulus of elasticity, resilient Poisson's ratio, and the variations in these parameters were made for these inservice pavements. In addition, three to five specimens from each project were tested at a constant rate of deformation, using the static indirect tensile test, from which the static tensile strength, modulus of elasticity, and Poisson's ratio were determined.

In order to estimate fatigue life without conducting long-term fatigue or load tests, possible correlations involving fatigue life, repeated-load properties, and static properties were evaluated. The conclusions and recommendations based on the findings of this study are stated below.

CONCLUSIONS

Fatigue Life

(1) Fatigue failures occurred at indirect tensile stresses ranging from 16 to 56 psi, which was 15 to 65 percent of the indirect tensile strength.

(2) The relationships between the logarithm of stress and the logarithm of fatigue life were essentially linear and could be expressed in the form

$$N_f = K_2 \left(\frac{1}{\sigma_T}\right)^{n_2}$$

where

N_f = fatigue life, cycles to failure,

σ_T = repeated tensile strength, psi,
n_2 = absolute value of the slope,
K_2 = a material constant related to the intercept of the logarithmic relationship.

(3) Values of n_2 ranged from 1.58 to 5.08, which are approximately equal to those previously reported. In addition, it appeared that n_2 was related to the viscosity of the asphalt with mixtures containing stiffer asphalts exhibiting lower values of n_2 .

(4) Values of K_2 ranged from 2.79×10^5 to 7.13×10^{12}, which are significantly smaller than previously reported values, indicating lower fatigue lives.

(5) Relating the logarithm of fatigue life to the logarithm of stress difference, i.e., the maximum principal stress minus the minimum principal stress, did not change the values of n_2 but the K coefficients, designated K_2' , were increased, ranging from 2.49×10^6 to 8.18×10^{15}, with the majority of the values in the range of 10^{10} to 10^{13}. These values are consistent with previously reported values.

(6) The coefficient of variation generally ranged from 30 to 80 percent, with the magnitude being stress and project dependent. Variation tended to increase with increasing stress or decreasing fatigue.

(7) There was an indication that the upper layers had longer fatigue lives than the lower layers. However, additional study is required since only two projects could be evaluated.

Elastic Properties under Repeated Loads

(8) The mean resilient moduli of elasticity were fairly consistent for the various projects, ranging from 221×10^3 to 615×10^3 psi.

(9) The resilient moduli of elasticity were significantly larger than the static moduli of elasticity. The ratio of the resilient and the static moduli ranged from 10.5 to 2.3, with the higher values associated with the materials with low static moduli.

(10) The coefficients of variation for the resilient moduli of elasticity were low, ranging from 4 to 28 percent.

(11) The majority of the mean resilient Poisson's ratios ranged from 0.10 to 0.22; however, for two projects the values were much higher, ranging from 0.22 to 0.46. Generally Poisson's ratios tended to increase with increased stress.

(12) Coefficients of variation for resilient Poisson's ratio were higher than for resilient modulus of elasticity, with the majority of the values in the range between 18 and 57 percent.

Density

(13) The coefficients of variation for density were very small, ranging from 1.4 to 4.6 percent.

Correlations with Fatigue Life

(14) A correlation between fatigue life and the ratio of the repeated tensile stress to the static tensile strength was found to exist; however, large errors would be expected if it were used to predict fatigue life.

(15) No correlations were found between fatigue life and static modulus of elasticity nor between fatigue life and resilient modulus of elasticity, except that higher moduli tended to have longer fatigue lives.

(16) A correlation between the logarithm of fatigue life and the logarithm of tensile strain, which is repeated tensile stress divided by the resilient modulus of elasticity, was found to exist, which was essentially parallel to a similar relationship previously reported. This relationship, however, should not be used to predict fatigue life because of relatively large errors which could be expected.

RECOMMENDATIONS

(1) The information obtained from this study on the fatigue and repeated-load characteristics of asphalt-treated materials should be used in the development and application of stochastic pavement design procedures based on elastic theory.

(2) Additional research should be conducted to investigate the effect of repeated applications of load on the tensile and elastic properties of asphalt-treated materials. An example would be the determination of the nature of the change in resilient modulus of elasticity produced by repeated tensile stresses.

(3) A large number of additional field cores should be tested to determine the type of distribution for fatigue life.

(4) Permanent deformation data from the repeated loading indirect tensile test should be analyzed to determine whether the test can be used to predict rutting or fatigue failure.

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APPENDIX A

SUPPLEMENTAL DATA - CURRENT STATUS OF KNOWLEDGE

TABLE A-1. VARIATION IN FATIGUE LIFE, INITIAL STRAIN, AND FLEXURAL STIFFNESS OF WEATHERED AND UNWEATHERED ASPHALT CEMENT AT 68°F (Ref 19)

			Fatigue Life			Initial Strain, microunits			Stiffness		
Specimen Description	Stress (psi)	No. of Spec.	Mean, cycles	Std. Dev., cycles	Coeff. of Var., %	Mean	Std. Dev.	Coeff. of Var., %	Mean, psi	Std. Dev., psi	Coeff. of Var., %
Unweathered asphalt	200	4	6,474	4,909	75.8	972	200	20.6	213,000	44,600	20.9
	150	4	17,997	11,438	63.6	717	88	12.3	200,000	42,800	21.4
	90	4	363,025	194,385	53.5	431	77	17.8	211,000	39,400	18.6
Weathered asphalt	375	4	1,665	1,108	66.5	662	109	16.4	582,000	112,000	19.2
	280	4	16,172	9,238	57.1	464	106	22.8	624,000	131,000	20.9
	120	3[1]	252,926	142,348	56.3	253	24	9.5	476,000	34,000	7.2

[1] Test of fourth specimen discontinued after approximately 70,000 cycles of loading.

TABLE A-2. FLEXURAL STIFFNESS MEASUREMENTS ON FIELD SAMPLES OF ASPHALTIC CONCRETE USING PULSE LOADING METHOD (Ref 19)

		Measured Stiffness (10^5 psi)					
		68° F			40° F		
Sample Group	No. of Specimens	Mean	Std. Dev.	CV (%)	Mean	Std. Dev.	CV (%)
Specimens From Surface Course							
1	19	1.79	0.42	23.5	6.80	1.53	22.5
2	20	1.65	0.39	23.6	7.03	1.91	27.2
3	20	1.52	0.41	26.9	7.12	1.41	19.8
4	19	1.34	0.37	27.6	5.90	1.11	18.8
Lab compacted	26	1.29	0.22	17.0	5.76	0.74	12.8
Specimens From Base Course							
1	12	1.57	0.42	26.6	5.95	1.54	25.9
2	12	1.39	0.26	18.7	5.66	3.14	55.5
3	8	1.47	0.41	27.9	4.40	0.90	20.4
4	10	1.42	0.42	29.6	4.96	1.22	24.6
Lab compacted	29	1.19	0.19	16.0	5.31	1.50	28.2

TABLE A-3. FLEXURAL STIFFNESS MEASUREMENTS ON PAVEMENT SAMPLES FROM STA 308 + 10 (Ref 27)

		Measured Stiffness (psi x 10^5)					
		68° F			40° F		
Location	No. of Specimens	Mean	Standard Deviation	CV (%)	Mean	Standard Deviation	CV (%)
Surface course	20	1.52	0.41	27.0	7.12	1.41	19.8
Base course	8	1.47	0.41	27.9	4.40	0.90	20.4

TABLE A-4. ASPHALTIC CONCRETE COMPACTION DATA FROM AASHO ROAD TEST (Ref 38)

Lab. Data	Field Data									
		Density (pcf)			Voids (% tot. vol.)			Voids (% filled)		
Loop	No. Tests	Mean	Std. Dev.	CV (%)	Mean	Std. Dev.	CV (%)	Mean	Std. Dev.	CV (%)
Binder Course										
1	64	148.7	1.45	1.0	7.84	0.87	11.1	55.8	3.16	5.7
2	12	148.6	0.67	0.5	7.92	0.42	5.3	55.3	1.43	2.6
3	86	148.5	1.52	1.0	7.90	0.94	11.9	55.6	3.48	6.3
4	128	149.5	1.49	1.0	7.31	0.87	11.9	58.0	3.35	5.8
5	128	148.5	1.38	0.9	8.02	0.88	11.0	54.9	3.24	5.9
6	192	149.3	1.77	1.2	7.46	1.09	14.6	57.2	3.84	6.7
All	609	149.0	1.60	1.1	7.66	0.99	12.9	56.5	3.49	6.2
Surface Course										
1	64	144.4	2.52	1.8	8.00	1.61	20.1	60.4	4.89	8.1
2	44	145.3	2.41	1.7	7.58	1.52	20.1	61.2	4.88	8.0
3	84	147.4	2.33	1.6	6.32	1.43	22.6	66.1	5.36	8.1
4	84	147.8	1.70	1.2	5.68	1.05	18.5	69.0	4.15	6.0
5	84	146.7	1.92	1.3	6.60	1.09	16.5	64.9	3.87	6.0
6	84	148.2	1.31	0.9	5.76	0.82	14.2	67.7	3.18	4.7
All	443	146.8	2.40	1.6	6.51	1.49	22.9	65.4	5.29	8.1

APPENDIX B

ELASTIC PROPERTIES UNDER REPEATED LOAD FOR EACH SPECIMEN

TABLE B-1. ELASTIC PROPERTIES UNDER REPEATED LOAD FOR EACH SPECIMEN

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
2	16	5933	279.2	292.2	278.4	283.2	0.28	0.44	0.56	0.43	130.9
		21973	278.7	—	—	278.7	0.21	—	—	0.21	130.5
		23046	291.4	300.1	291.4	294.3	0.31	0.29	0.31	0.30	130.3
	24	2181	263.4	279.3	271.1	271.3	0.25	0.28	0.27	0.27	127.3
		1830	287.9	287.7	287.4	287.7	0.24	0.30	0.39	0.31	127.6
		2032	270.8	255.6	255.3	260.6	0.15	0.21	0.29	0.22	123.6
		2231	271.2	279.4	271.1	273.9	0.15	0.16	0.21	0.17	129.0
		937	242.8	235.3	230.3	236.1	0.32	0.35	0.49	0.39	129.8
	32	684	279.3	278.9	279.1	279.1	0.28	0.42	0.37	0.36	130.9
		812	278.4	291.4	291.0	286.9	0.24	0.33	0.45	0.34	130.6
		1112	307.6	292.6	307.1	302.4	0.29	0.41	0.44	0.38	126.6
		1472	292.2	279.0	278.4	283.2	0.26	0.24	0.42	0.31	131.1
		263	244.4	243.7	225.0	237.7	0.54	0.78	1.07	0.80	128.2
	40	344	319.0	294.4	293.7	302.4	0.49	0.51	0.74	0.58	130.0
		102	295.2	294.7	318.2	302.7	0.43	0.59	0.91	0.64	128.6
		107	293.3	317.2	316.9	309.1	0.51	0.66	0.74	0.64	128.2
		558	308.1	296.1	295.6	299.9	0.38	0.43	0.59	0.47	132.2
		151	273.8	294.3	272.3	280.1	0.35	0.55	0.88	0.59	129.7
	Static										129.2
											130.3
											129.4
											127.9
											125.7

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
5	16	2831	255.1	254.9	235.4	248.5	0.15	0.24	0.20	0.20	127.1
		2504	235.9	235.8	235.5	235.7	0.04	0.06	0.18	0.09	126.0
		1701	211.2	211.1	204.1	208.8	0.07	0.09	0.11	0.09	122.4
		4171	235.7	227.0	218.6	227.1	0.06	0.05	0.20	0.10	128.2
		3686	204.3	204.2	204.1	204.2	—	—	0.07	0.07	123.9
	24	696	230.6	242.7	230.5	234.6	0.08	0.10	0.14	0.11	124.3
		904	236.3	242.2	229.7	236.1	0.04	0.18	0.32	0.18	126.4
		1200	236.0	230.0	229.7	231.9	0.12	0.16	0.26	0.18	127.3
		1894	236.7	230.6	230.5	232.6	—	0.03	0.08	0.06	127.3
		620	219.7	219.6	209.4	216.2	0.07	0.12	0.19	0.13	124.6
	32	400	236.7	219.7	236.4	230.9	0.12	0.13	0.24	0.16	125.0
		925	279.1	279.1	255.6	271.3	0.10	0.10	0.17	0.12	129.9
		719	267.5	256.3	256.1	260.0	0.13	0.15	0.24	0.17	130.2
		160	245.7	236.1	226.6	236.1	0.22	0.28	—	0.25	126.5
		633	292.8	292.5	279.2	288.2	0.14	0.24	0.24	0.21	127.1
	Static										129.3
											124.5
											123.2
											129.1
											123.2

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
8B	16	20897	411.0	410.9	385.1	402.3	—	—	—	—	138.9
	24	4877	384.0	383.3	353.7	373.7	—	0.15	0.17	0.16	128.7
		4787	404.0	418.3	399.8	406.2	0.10	0.17	0.24	0.17	136.9
		3127	383.4	353.6	353.4	363.5	0.10	0.17	0.23	0.17	134.9
		2857	328.8	306.8	306.4	314.0	—	0.01	0.15	0.08	130.8
		10736	484.5	460.4	438.3	461.1	0.03	0.01	0.04	0.03	137.7
	32	5587	473.0	455.4	438.9	455.8	—	—	—	—	139.3
		3100	410.1	409.8	409.6	409.8	—	0.03	0.08	0.06	135.3
		5885	424.1	438.9	423.8	428.9	—	0.05	0.05	0.05	139.4
		2552	341.7	332.4	341.3	338.5	0.02	0.03	0.12	0.06	138.6
	40	613	403.5	383.3	382.6	389.8	0.08	0.08	0.26	0.14	134.2
		2532	547.6	547.5	547.8	547.6	0.11	0.12	0.08	0.10	133.4
		2291	528.8	547.4	503.9	526.7	0.12	0.16	0.23	0.17	141.1
		381	306.5	290.0	305.4	300.6	0.26	0.34	0.36	0.35	132.0
		5111	638.9	666.5	589.5	631.6	0.14	0.15	0.17	0.15	139.2
	Static										134.0
											132.9
											134.3
											136.6
											136.4

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
8C	24	59585	397.1	393.7	—	395.4	0.03	0.02	—	0.03	131.7
	40	4719	423.7	423.4	447.9	431.7	0.07	0.12	0.21	0.13	134.0
		5360	564.4	543.8	507.6	538.6	0.06	0.13	0.13	0.11	136.8
		10612	525.8	508.4	491.6	508.6	—	—	0.07	0.07	136.4
		7806	586.7	586.2	544.3	572.4	0.06	0.13	0.13	0.11	144.6
	48	5348	508.5	538.1	537.6	528.1	0.08	0.15	0.24	0.16	135.3
		1677	538.5	538.3	508.2	528.3	0.06	0.09	0.12	0.09	144.1
	56	975	464.6	445.1	444.7	451.5	0.04	0.07	0.15	0.09	141.8
		1874	508.7	508.4	494.6	503.9	0.07	0.12	0.06	0.08	133.9
		735	484.6	463.2	442.9	463.6	0.19	0.26	0.49	0.31	133.1
		3127	411.7	411.7	396.5	406.6	—	—	—	—	137.5
	Static										136.1
											141.7
											139.2

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
17B(1)	16	3412	478.1	433.5	422.8	444.8	—	—	0.11	0.11	139.4
		4625	582.4	620.2	515.8	572.8	—	—	0.08	0.08	136.4
		3309	617.4	515.8	485.8	539.0	0.01	0.09	0.20	0.10	137.2
		2246	400.0	417.1	415.7	410.9	—	0.02	0.21	0.12	134.3
		4318	622.5	622.0	589.8	611.6	—	—	0.14	0.14	141.5
	24	2050	597.7	597.4	595.5	596.8	—	0.01	0.17	0.09	138.0
		3041	850.8	679.3	600.5	710.2	—	0.05	0.36	0.21	138.5
		2396	763.4	667.6	512.5	647.8	—	—	0.07	0.07	140.9
		1277	548.9	547.0	420.5	505.5	0.02	0.21	0.25	0.16	137.6
		1163	—	—	—	—	—	—	—	—	135.8
	32	1247	476.0	509.3	409.2	464.8	—	0.06	0.14	0.10	136.7
		1401	628.2	559.5	465.6	551.1	0.01	0.11	0.19	0.10	136.8
		351	386.7	347.8	315.7	350.1	0.05	0.09	0.18	0.11	132.2
		1372	595.7	510.6	457.1	521.2	—	—	0.10	0.10	138.5
		2498	574.4	574.2	459.8	536.1	0.16	0.18	0.12	0.15	137.7

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
17B(2)	16	3232	536.2	481.1	468.6	495.3	0.04	0.05	0.11	0.06	134.7
		5470	608.3	538.3	470.5	539.0	—	0.02	0.08	0.05	136.5
		3632	520.6	506.2	534.2	520.3	—	0.02	0.12	0.07	137.3
		1050	299.4	331.1	318.5	316.3	0.05	0.11	0.31	0.16	133.7
		2880	334.0	333.9	310.9	326.3	—	—	0.09	0.09	140.3
	24	970	546.2	546.1	469.5	520.6	0.12	0.14	0.28	0.18	133.8
		1635	591.2	522.3	465.7	526.4	0.01	—	0.14	0.08	137.9
		2355	613.3	625.3	475.1	571.2	—	0.14	0.06	0.10	139.3
		2235	603.1	542.7	540.5	562.1	—	—	0.16	0.16	139.2
		771	—	—	—	—	—	—	—	—	134.1
	32	880	493.1	459.9	405.5	472.8	0.11	0.16	0.22	0.16	137.7
		973	518.0	509.7	438.9	488.9	0.03	0.12	0.21	0.12	134.1
		160	360.1	342.6	286.5	329.7	0.35	0.41	0.65	0.47	135.0
		1155	704.7	568.3	502.3	591.7	—	—	—	—	138.8
		570	400.5	400.2	359.9	386.9	0.09	0.13	0.18	0.13	135.1

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-97(1)	32	343	242.1	241.5	257.4	247.0	0.18	0.32	0.62	0.37	129.1
		2028	279.7	290.6	278.5	282.9	0.17	0.23	0.41	0.27	132.8
		2902	303.3	302.8	302.0	302.7	0.03	0.15	0.29	0.17	133.1
		1401	201.8	201.5	200.8	201.4	0.25	0.32	0.52	0.36	127.5
		291	226.3	225.8	212.1	221.4	0.31	0.45	0.56	0.44	127.4
	40	246	283.1	265.6	236.0	261.6	0.29	0.46	0.84	0.53	128.2
		518	283.6	282.8	265.2	277.2	0.20	0.37	0.56	0.38	131.1
	48	223	271.5	257.6	234.4	254.5	0.40	0.62	0.81	0.61	130.7
		272	259.2	258.8	235.7	251.2	0.24	0.32	0.46	0.34	132.2
		344	258.9	258.3	257.2	258.1	0.28	0.41	0.66	0.45	131.9
		107	237.0	236.4	225.8	233.1	0.20	0.35	0.54	0.36	130.7
		620	248.0	259.1	247.1	251.4	0.10	0.24	0.30	0.21	130.3
	Static										131.9
											128.9
											130.5

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-97(2)	32	27795	—	—	—	—	—	—	—	—	138.5
	40	932	283.7	252.2	265.7	267.2	0.18	0.18	0.46	0.27	133.4
		589	207.1	206.8	189.1	201.0	0.04	0.12	0.25	0.14	132.4
		3626	350.1	349.1	323.5	340.9	0.12	0.28	0.40	0.27	137.0
		1321	302.5	282.9	281.8	289.1	0.27	0.40	0.62	0.43	133.1
		1444	349.8	349.5	346.5	348.6	0.09	0.14	0.62	0.28	138.0
	48	976	340.1	339.1	318.5	332.6	0.23	0.40	0.51	0.38	135.2
		871	341.4	389.0	388.1	372.8	0.07	0.24	0.37	0.23	136.3
	56	452	352.3	333.4	332.8	339.5	0.32	0.39	0.48	0.40	135.7
		233	289.1	288.4	287.0	288.2	0.14	0.26	0.54	0.31	135.1
		2559	276.9	302.3	288.4	289.2	0.10	0.28	0.32	0.23	138.4
	Static										135.4
											136.5
											131.4

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-97(3)	40	1088	379.5	378.7	335.6	364.6	0.03	0.14	0.32	0.16	145.2
		490	380.8	380.5	364.9	375.4	—	—	—	—	151.6
		638	478.7	432.4	412.3	441.1	0.03	0.16	0.22	0.15	151.4
		2204	380.4	414.6	380.2	391.7	—	—	—	—	151.4
		657	350.9	350.7	350.2	350.6	—	—	0.01	—	152.3
	48	529	568.4	544.2	542.9	551.8	0.15	0.31	0.44	0.30	150.8
		370	455.5	455.0	418.7	443.1	0.03	0.10	0.28	0.14	146.4
	56	214	353.8	397.1	317.0	356.0	0.10	0.23	0.35	0.23	148.8
		249	398.6	397.6	373.0	389.7	—	0.12	0.31	0.22	151.1
		421	490.0	454.7	397.0	447.2	0.07	0.11	0.23	0.14	150.2
		143	454.1	452.9	372.3	426.4	0.21	0.37	0.46	0.35	150.7
		516	424.8	397.8	396.7	406.4	0.09	0.15	0.40	0.21	148.5
	Static										149.8
											152.8
											151.7

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-97(S)	40	1626	413.2	378.8	378.5	390.2	0.14	0.14	0.18	0.15	137.7
		1363	414.1	379.6	378.8	390.8	0.10	0.10	0.21	0.14	136.2
		1487	454.0	454.0	453.2	453.7	0.16	0.16	0.27	0.20	143.3
		1538	433.7	414.0	380.0	409.2	0.10	0.10	0.07	0.09	143.0
		345	412.7	478.1	323.1	371.3	0.22	0.25	0.43	0.30	145.2
	48	646	389.6	389.2	363.3	380.7	0.18	0.24	0.24	0.22	134.0
		274	452.6	387.7	337.7	392.7	0.32	0.37	0.62	0.44	147.8
	56	449	399.9	355.4	336.8	364.0	—	—	—	—	136.8
		583	530.5	588.8	588.2	502.5	0.10	0.21	0.28	0.20	143.4
		163	397.1	395.9	351.1	381.4	0.23	0.40	0.52	0.38	146.4
		31	—	—	—	—	—	—	—	—	145.5
		258	525.8	485.3	449.7	486.9	0.62	0.62	0.74	0.66	144.8
	Static										138.8
											135.6
											146.8

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-100(1, 2)	16	6278	—	—	—	—	—	—	—	—	130.9
		7909	173.4	173.5	181.9	176.3	—	—	—	—	133.2
		10591	279.4	302.3	279.0	286.9	—	0.01	0.03	—	132.6
		24114	192.0	202.6	202.5	199.0	—	—	—	—	133.5
	24	715	227.8	217.9	217.2	221.0	—	0.07	0.27	0.17	135.9
		3976	302.4	302.2	285.7	296.8	0.25	0.28	0.40	0.31	138.2
	32	363	304.2	304.0	291.7	300.0	—	—	—	—	135.5
		297	—	—	—	—	—	—	—	—	130.1
		1079	—	—	—	—	—	—	—	—	137.0
		880	304.0	303.9	303.7	303.9	—	—	—	—	134.7
	48	139	304.2	321.4	303.3	309.6	—	—	0.03	—	130.1
		76	—	—	—	—	—	—	—	—	131.9
	Static										130.7
											132.9
											137.6
											136.3

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, pcf
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-100(3)	40	472	—	—	—	—	—	—	—	—	153.1
		457	350.2	378.8	378.7	369.2	0.01	0.09	0.10	0.07	147.4
		1197	360.8	315.1	337.1	337.7	0.01	0.12	0.37	0.17	148.3
		1068	325.0	324.2	323.9	324.4	—	0.11	0.18	0.15	149.2
	48	60	377.6	302.1	—	339.9	0.17	0.18	—	0.18	152.8
		531	395.0	373.0	357.5	375.2	0.03	0.09	0.21	0.11	147.0
	56	69	—	—	—	—	—	—	—	—	152.3
		182	288.8	302.3	316.2	302.4	0.10	0.13	0.35	0.19	145.4
		128	328.4	342.2	349.0	339.9	—	0.02	0.13	0.08	151.0
		339	398.6	388.3	381.9	389.6	—	—	0.26	—	152.8
	Static										146.9
											152.3

(Continued)

TABLE B-1. (Continued)

Project	Tensile Stress, psi	Fatigue Life, Cycles	Instantaneous Resilient Modulus of Elasticity, 10^3 psi				Instantaneous Resilient Poisson's Ratio				Density, psi
			$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	$0.3N_f$	$0.5N_f$	$0.7N_f$	Mean	
25-100(S)	16	38157	363.3	330.4	324.4	339.4	0.02	—	0.02	0.02	134.0
	40	244	291.0	283.3	259.9	278.1	0.13	0.22	0.34	0.23	127.4
		474	315.6	315.1	283.0	304.6	0.09	0.16	0.30	0.18	131.8
		1215	372.8	349.7	302.9	341.8	0.05	0.08	0.11	0.08	137.2
	48	545	340.2	348.6	330.8	339.9	0.12	0.18	0.31	0.20	139.5
		479	354.0	348.9	339.8	347.6	0.02	0.11	0.18	0.10	137.9
	56	87	245.8	243.0	276.3	255.0	0.27	0.48	0.65	0.47	124.7
		211	365.5	382.5	356.2	368.1	0.13	0.22	0.30	0.22	137.2
		255	373.3	373.2	344.5	363.7	0.15	0.16	0.21	0.17	139.7
		227	—	—	—	—	—	—	—	—	142.5
	Static										125.5
											128.5