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16. Abstract

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COMPARISON OF FATIGUE TEST METHODS FOR ASPHALT MATERIALS

by

Byron W. Porter
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Research Report Number 183-4

Tensile Characterization of Highway Pavement Materials

Research Project 3-9-72-183

conducted for

The Texas Highway Department

in cooperation with
U. S. Department of Transportation
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CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

April 1975

PREFACE

This is the fourth 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 which compared and evaluated fatigue results obtained by various test methods and briefly investigated the relationship between fatigue and creep.

Many people have provided help and assistance in the production of this report. Special thanks are given to Messrs. James N. Anagnos, Pat Hardeman, and Harold H. Dalrymple for their assistance in the testing program; to Messrs. Avery Smith, Gerald Peck, and James L. Brown of the Texas Highway Department, who provided technical liason for the project; and to Messrs. Calvin E. Cowher and Adedare S. Adedimila for their general assistance and consultation. Thanks are also extended to the Center for Highway Research staff who assisted in the preparation of this manuscript. The support of the Texas Highway Department and the Federal Highway Administration is greatly appreciated.

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April 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 on 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 In-Service Asphalt-Treated Materials," by Domingo Navarro and Thomas W. Kennedy, summarizes the results of a study on the fatigue response of highway pavement materials and the variation in fatigue life that might be expected in an actual roadway.

Report No. 183-3, "Cumulative Damage of Asphalt Materials Under Repeated-Load Indirect Tension," by Calvin E. Cowher and Thomas W. Kennedy, summarizes the results of a study on the applicability of a linear damage rule, Miner's Hypothesis, to fatigue data obtained utilizing the dynamic indirect tensile test.

Report No. 183-4, "Comparison of Fatigue Test Methods for Asphalt Materials," by Byron W. Porter and Thomas W. Kennedy, summarizes the results of a study comparing fatigue results of the dynamic indirect tensile test with the results from other commonly used tests and a study comparing creep and fatigue deformations.

ABSTRACT

This report describes the results of an investigation comparing various commonly used fatigue tests and evaluating the relationship between creep and fatigue. It was found that the repeated-load indirect tensile test produces results comparable with other fatigue tests if the state of stress developed in the specimen is considered. A regression analysis was conducted and an equation was developed which can be used to relate fatigue results for a variety of mixtures and test methods. A comparison of creep and fatigue results indicated that a relationship probably exists between creep and fatigue deformation and that fatigue life can possibly be estimated from creep rupture time.

KEY WORDS: dynamic indirect tensile test, fatigue, creep, dynamic test methods, asphalt materials.

SUMMARY

This report describes an investigation to compare and evaluate fatigue results obtained from commonly used test methods and a preliminary investigation into the relationship between fatigue and creep.

The fatigue tests studied in detail were the repeated-load indirect tensile test, the two-point flexure test used by Monismith et al, the rotating cantilever test used by Pell et al, and the axial load test performed by Raithby and Sterling. The large differences between test results obtained from the repeated-load indirect tensile test and from other tests were explained in terms of the biaxial state of stress developed in the indirect tensile test. By expressing stress as a stress difference, it was found that a large portion of the variations was eliminated. The remaining differences were evaluated through a regression analysis, and an equation was developed which can be used to relate fatigue results for a variety of mixtures and test methods. The equation contained asphalt content, asphalt penetration, temperature, tensile load duration, and rest periods after a tensile load. Air void content was not found to be a significant factor and the effects of aggregate type and gradation were not considered.

The investigation of fatigue and creep used the indirect tensile test and the midpoint flexure test of Majidzadeh et al. Creep and fatigue permanent deformations obtained in the indirect tensile test were found to be similar, indicating that a relationship probably exists between creep and fatigue deformations. A relationship between creep rupture time and fatigue life was established. This relationship possibly can be used to estimate fatigue life from creep rupture time.

IMPLEMENTATION STATEMENT

This study has shown that the dynamic indirect tensile test is comparable to other fatigue test methods if stress is expressed in terms of stress difference. This is significant because the dynamic indirect tensile test is easier to conduct than other commonly used fatigue test methods and uses cylindrical specimens and cores. In addition, the dynamic indirect tensile test also allows the calculation of elastic parameters, such as dynamic modulus and Poisson's ratio, if deformations are measured. Therefore, it is recommended that the Texas Highway Department begin to use both the static indirect tensile test and the dynamic indirect tensile test to obtain strength, fatigue characteristics, and elastic parameters of pavement materials.

During the study, a regression equation was developed to relate fatigue results obtained by various methods for a variety of mixtures. The equation's parameters are stress difference, testing temperature, asphalt content, asphalt penetration, tensile load duration, and length of rest after a tensile load.

Although more investigation is required, there seems to be a relationship between the creep and fatigue deformation-failure characteristics. An equation was developed by which fatigue life can be estimated from creep rupture time.

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CHAPTER 1. INTRODUCTION

Fatigue testing of pavement materials is needed to provide information related to fatigue cracking of pavements. Although a great deal of information is now available on the fatigue behavior of asphalt materials, this information was obtained using different types of fatigue tests for a variety of asphalt materials. All of this has produced apparent differences in behavioral characteristics.

In addition to the existing fatigue information, it would be desirable to utilize a test method which would be easy and economical to conduct in order to develop additional information for future design. The indirect tensile test has been used for static testing and the repeated-load indirect tensile test has been shown to be applicable to fatigue studies. The results, however, are apparently much different than the results of other commonly used tests.

The differences between laboratory fatigue test results should be evaluated and explained in order to apply the results to design or to compare results obtained by different investigators. In addition, if the repeated-load indirect tensile test is to be used it is necessary to explain the apparent difference in results. The difficulty in comparing fatigue results from different test methods was noted by Pell and Cooper (Ref 51):

> Comparing the strain-life relationships obtained for this particular mix under conditions of rotating bending and uniaxial loading it can be seen that while similar conclusions may be made, there is a difference in quantitative results. These quantitative differences were not unexpected, and may be attributed to numerous factors, the influence of which are virtually impossible to evaluate. For example, one test is in bending, the other uniaxial stress. ... This underlines the difficulty of comparing the results of different researchers, and consequently in relating laboratory results to in situ conditions.

It has also been suggested that it may be possible to use creep tests to estimate fatigue behavior and permanent deformation characteristics due to repeated loads since the permanent deformation relationship is similar to the creep relationship. Since creep tests are more easily conducted than repeated load tests, it would also be desirable to evaluate the possibility of using creep tests to estimate repeated-load behavior.

The objectives of the study summarized in this report were

(1) to compare and evaluate fatigue results obtained using the repeated-load indirect tensile test with the results obtained from other commonly used fatigue tests, and

(2) to perform a preliminary study to evaluate the relationship between creep and fatigue.

Chapter 2 discusses the various fatigue testing methods and reviews the variables affecting fatigue behavior. The techniques used to compare fatigue tests and to evaluate creep and fatigue are described in Chapter 3. The findings of this study are presented in Chapter 4, and Chapter 5 contains a summary of the conclusions and recommendations.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

An extensive amount of work has been conducted to determine the fatigue behavior and characteristics of asphalt mixtures. The major objective of this chapter is to summarize the current status of knowledge concerning fatigue behavior and characteristics in order to establish the differences between fatigue tests and to provide information for use in evaluating testing differences. This chapter discusses fatigue behavior; methods of fatigue testing; and load, environmental, and mixture variables which affect the fatigue characteristics of asphalt mixtures.

PAVEMENT LOADING CONDITIONS

The loading of an inservice pavement includes repeated movements of vehicles over the surface of a pavement. The nature of the load and conditions surrounding its application to a pavement cause a complex loading situation. Because of the repetitive nature of the loads, the consideration of the fatigue behavior of pavement materials is important in the design and analysis of pavements.

A moving wheel load has been investigated by Pell and Brown (Ref 49), Monismith (Ref 33), and Barksdale (Ref 2). The states of stress as a wheel moves over a pavement are shown in Fig 1. The stresses change with time and are triaxial in nature. The vertical normal stresses are always compressive and the horizontal normal stresses are either tensile or compressive, depending on the depth of the element in the pavement. Since most pavement materials fail in tension, the tensile characteristics of the materials and the behavior under repeated tensile stresses or strains are critical.

TYPES OF TESTS

Since it is impractical to build full-scale test pavements and load them with moving vehicles, laboratory tests are conducted. However, because

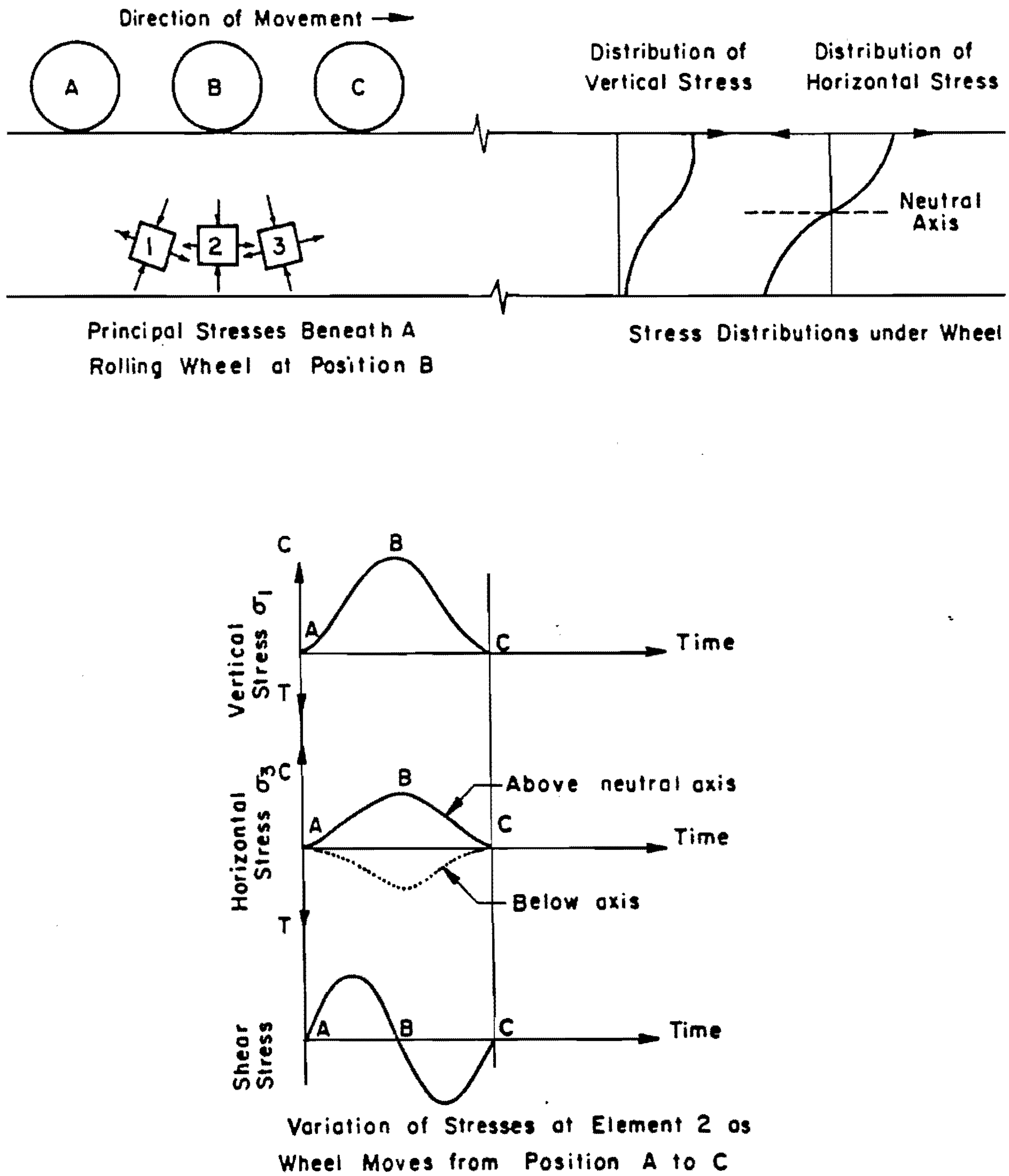


Fig 1. Stresses in a pavement caused by a moving wheel.

the field loading conditions are too complex to duplicate in the laboratory and could produce results difficult to interpret, investigators have used less complex forms of loading conditions, which are easier to analyze and produce results easier to analyze.

Various types of tests have been used to study the fatigue behavior of asphalt materials and each produces unique results. Table 1 is a summary of various types of fatigue tests, the investigators, and the related references.

Normally, in laboratory fatigue tests one of two basic types of loading is used, controlled-strain or controlled-stress. The controlled-strain test involves the application of repeated loads, which produce a constant, repeated deformation or strain throughout the test period. In the controlled-stress test a constant stress or load is repeated. These two types of loading represent the extreme conditions occurring in the field. Pavement layers that are thick and stiff are best tested using controlled-stress. Such a layer resists load and controls the magnitude of the strains that can occur. The controlled-strain mode of testing is more applicable to a thin flexible pavement layer. A thin layer adds little stiffness to the whole structure, and when a load is applied to the pavement, the layer deformation is controlled by the entire structure; thus, the resulting stress is a function of the stiffness of the entire pavement and not just the stiffness of the thin layer (Ref 33).

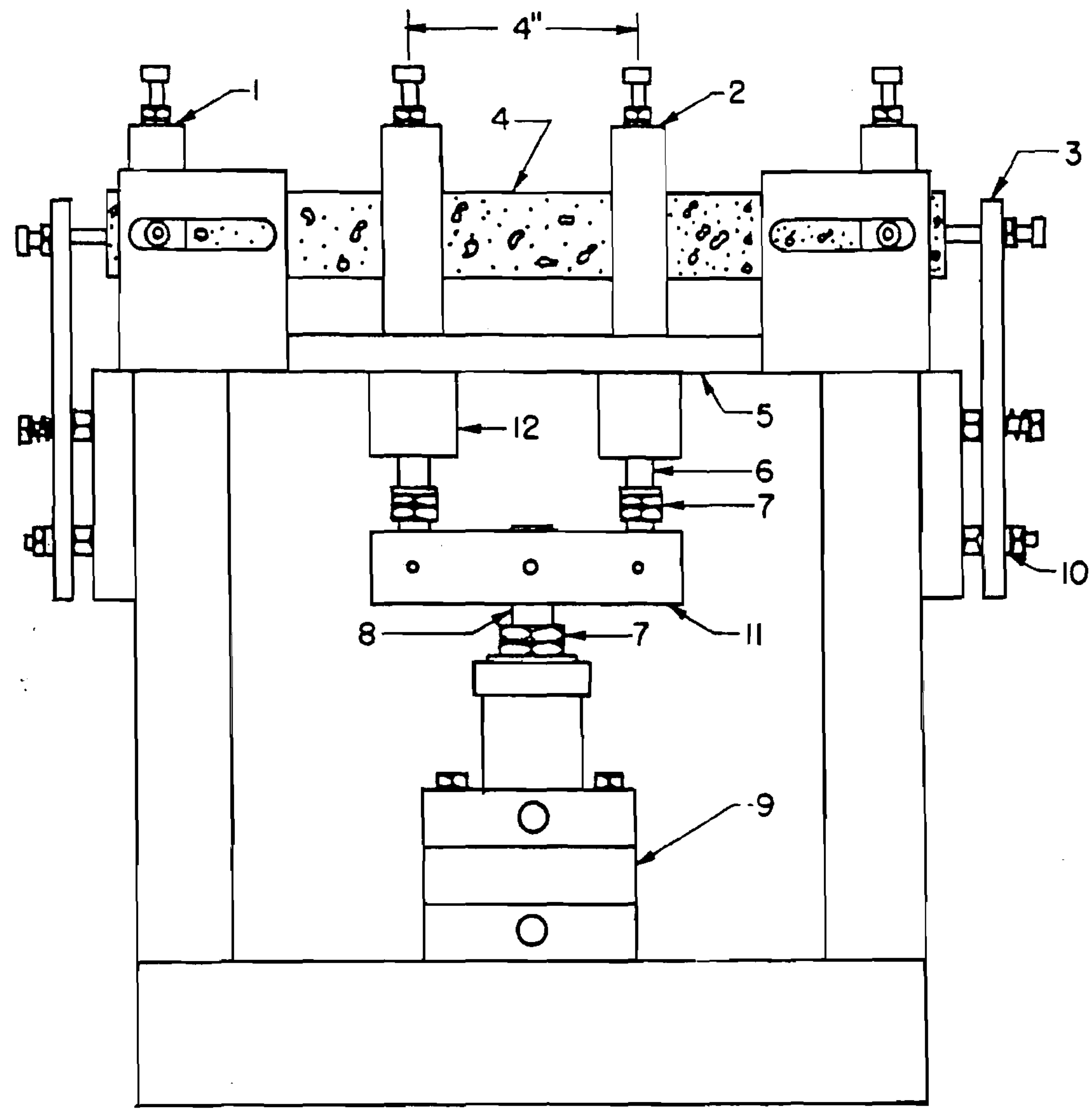
Many types of fatigue tests have been used, but only those having sufficient data for analysis and comparison are discussed here. These tests are the flexure test, rotating cantilever test, axial load test, and dynamic indirect tensile test, which is of primary importance in this study.

Flexure Test

Deacon (Ref 6) developed a controlled-stress flexure apparatus with two-point symmetrical loading (Fig 2). This apparatus tested specimens with a cross section of 1.5 x 1.5 inches and a length of approximately 15 inches. Later the apparatus was redesigned to test specimens with cross sections up to 3 inches square (Ref 38). The connections at the end of the specimen were pinned, which allowed the specimen to rotate and translate. Using two-point loading caused a pure bending moment to be applied between the loading points. The load duration most commonly used was 0.1 second, with frequencies

TABLE 1. SUMMARY OF FATIGUE TESTS, INVESTIGATORS, AND REFERENCES

I.	FLEXURE	
	Deacon and Monismith	(Refs 6, 8)
	Epps and Monismith	(Refs 10, 11, 12)
	Kallas et al	(Refs 23, 24)
	Kirk	(Ref 25)
	Majidzadeh et al	(Ref 28)
	Monismith et al	(Refs 32, 33, 34, 36, 37, 38, 40)
	Santucci and Schmidt	(Ref 55)
II.	ROTATING CANTILEVER	
	Pell et al	(Refs 47, 48, 50)
	McElvaney	(Ref 31)
III.	UNIAXIAL	
	Kallas	(Ref 22)
	Kallas and Riley	(Ref 24)
	Howeedy and Herrin	(Ref 18)
	Raithby and Sterling	(Refs 52, 53)
IV.	REPEATED-LOAD INDIRECT TENSILE	
	Moore and Kennedy	(Refs 41, 42)
	Navarro and Kennedy	(Ref 45)
	Cowher and Kennedy	(Ref 5)
V.	CANTILEVER	
	Bazin and Saunier	(Ref 3)
	Coffman et al	(Ref 4)
	Freeme and Marais	(Ref 13)
	Van Dijk et al	(Ref 58)
VI.	TRIAXIAL	
	Barksdale and Hicks	(Ref 2)
	Haas	(Ref 15)
	Morris et al	(Refs 43, 44)
	Larew and Leonards	(Ref 27)
	Kallas and Riley	(Ref 24)
VII.	TORSIONAL	
	Pell	(Ref 48)
VIII.	DIAPHRAGM	
	Jimenez and Gallaway	(Refs 20, 21)
IX.	ROLLING WHEEL	
	Bazin and Saunier	(Ref 3)
	Van Dijk et al	(Ref 58)
	Howeedy and Herrin	(Ref 18)



Key:

1. Reaction clamp
2. Load clamp
3. Restrainer
4. Specimen
5. Base plate
6. Loading rod
7. Stop nut
8. Piston rod
9. Double-acting, Bellofram cylinder
10. Rubber washer
11. Load bar
12. Thomson ball bushing

Fig 2. Repeated flexure apparatus used by Deacon (Ref 6).

of 30 to 100 cycles per minute.

Figure 3 shows typical load and deflection versus time relationships for one loading cycle. A return load was used to force the specimen back to its original undeflected position, producing a stress reversal without strain reversal. Loads were applied by a pneumatic type loading piston and deflections were measured at the center of the specimen. Failure was defined as total fracture of the specimen. Conventional elastic theory was used in the calculations of bending stress, stiffness modulus, and bending strains (Ref 6).

Kallas and Puzinauskas (Ref 23), also, performed fatigue tests, using equipment similar to Deacon's. The major differences were in specimen size and loading system. Kallas and Puzinauskas used specimens with cross sections ranging up to 3 x 3 inches, and an MTS electrohydraulic loading system was used to apply a haversine waveform with a 0.1-second load duration and a 0.4-second rest period. A load of about 10 percent of the applied load which returned the specimen to its original position was used to prevent creep.

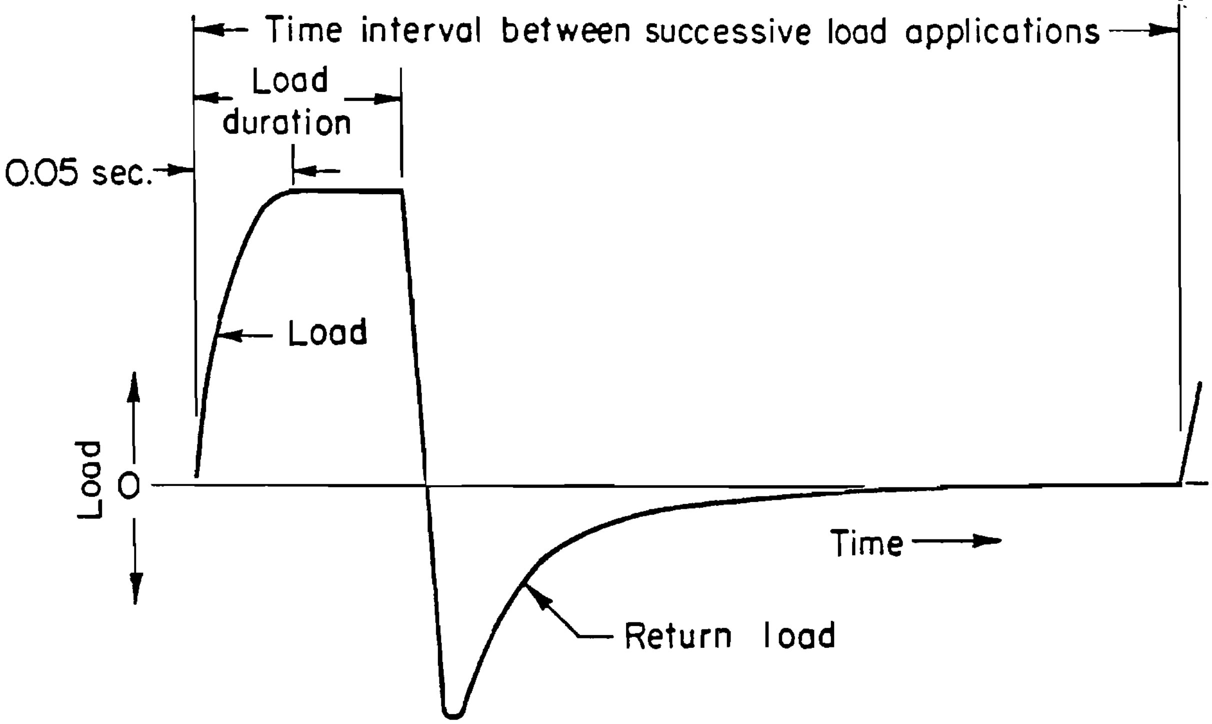
A controlled-strain test was performed by Santucci and Schmidt (Ref 55) with equipment similar to Deacon's. Load was applied for 0.05 second which was followed by a 0.55-second rest period, at temperatures of 77°F and 39°F. At the higher temperature, a load reversal was used to eliminate creep. Failure service life was arbitrarily defined as the number of loading cycles required to reduce the initial stiffness to 60 percent.

Rotating Cantilever Test

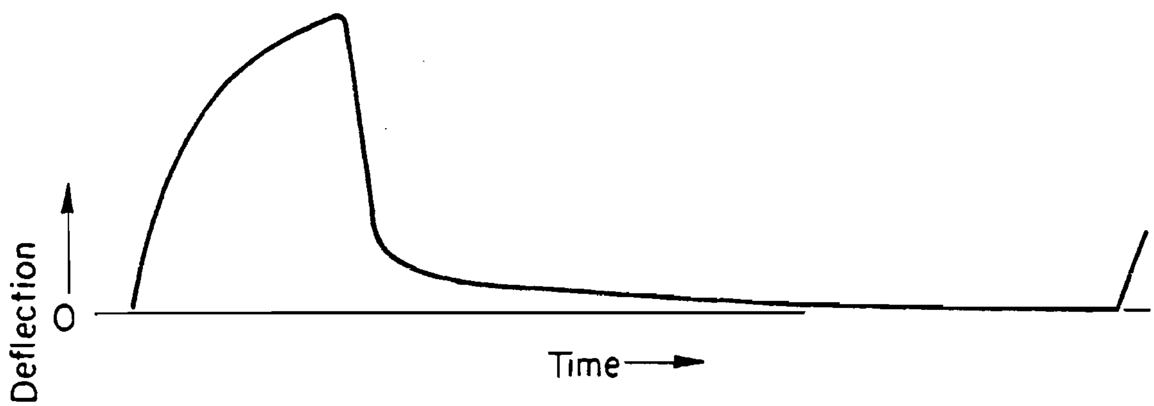
Pell (Ref 48) and McElvaney (Ref 31) used the rotating cantilever type testing apparatus illustrated in Fig 4. The necked cylindrical specimen was subjected to a controlled-stress load by a wire connected to the specimen's head. The specimen was rotated and the constant load in the wire produced a sinusoidal tension and compression stress on the outside fiber. A system of pulleys was used so that weights hung on the wire produced the desired stress in the specimen. Testing frequency ranged from 80 to 3000 cycles per minute, the most common value being 1000 cycles per minute. The maximum stress, calculated by elastic theory, occurred at the neck-down section of the specimen, and complete rupture was defined as failure.

Axial Load Test

Raithby and Sterling (Refs 52 and 53) used a direct tension and compression



(a) Idealized load-time curve.



(b) Idealized deflection-time curve.

Fig 3. Load vs time and deflection vs time relationships for constant-stress flexure apparatus used by Deacon (Ref 6)

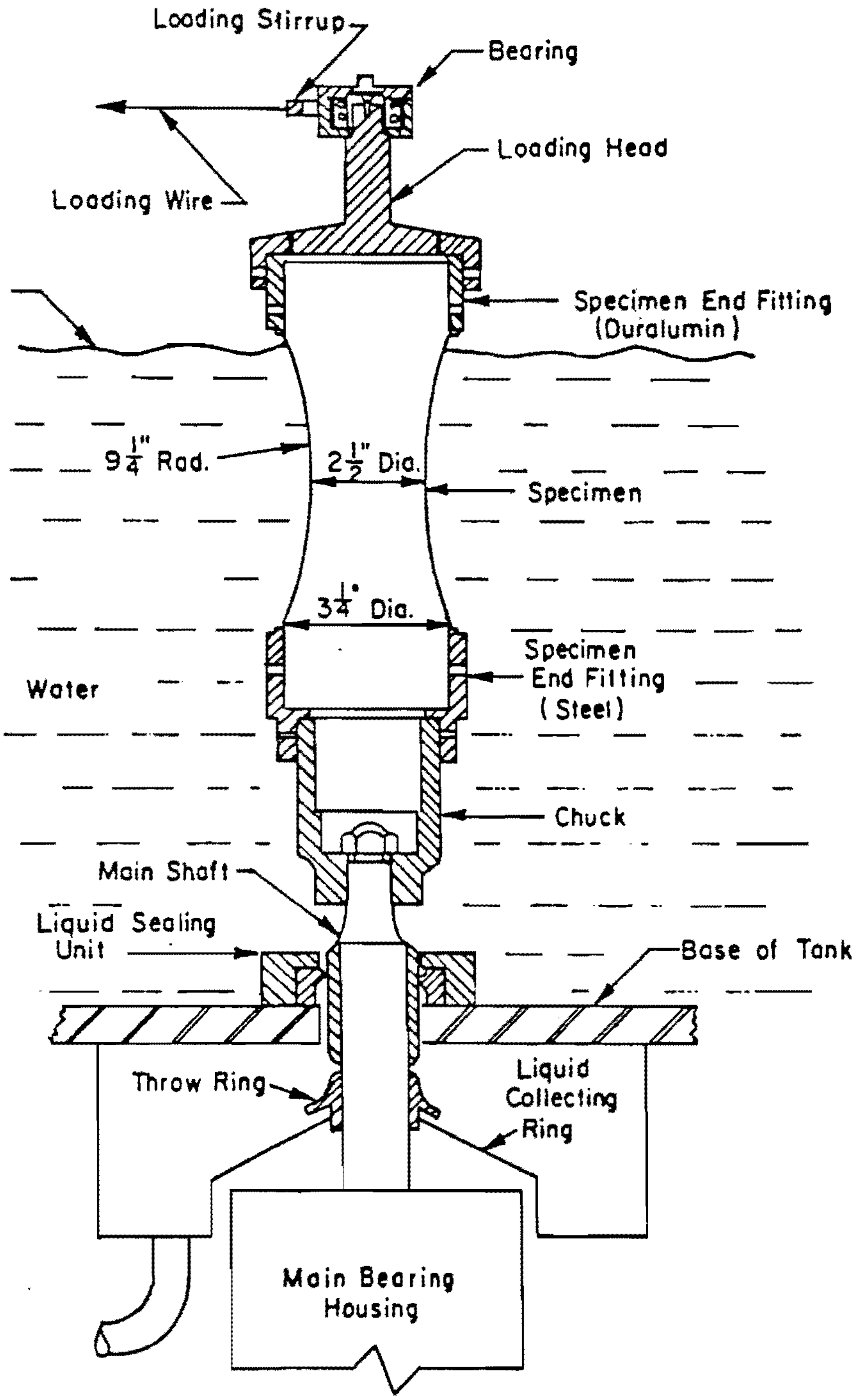


Fig 4. Rotating cantilever loading system (Refs 31 and 48).

axial load fatigue test on specimens 75 mm square and 225 mm long. A variety of tensile and compressive wave patterns (Tables 2 and 3) were applied hydraulically to specimens through loading caps epoxied to the ends of the specimens. Loading durations ranged from 0.04 to 0.4 second and rest periods ranged from none up to 1.0 second, causing frequencies of 0.833 to 25.0 cycles per second. Axial deformations were measured using LVDT's, and elastic theory was used to calculate stiffness, stress, and strain. Fracture of the specimen was considered failure.

Kallas (Ref 22) used axial loading in tension, compression, and a combination of both to determine dynamic moduli. Several loading frequencies were used, but loading was not continued to failure.

Repeated-Load Indirect Tensile Test

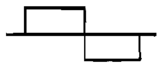
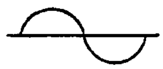
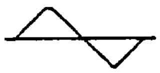
Most of the use of the repeated-load indirect tensile test has been at the Center for Highway Research at The University of Texas at Austin (Refs 5, 41, 42, and 45). Moore and Kennedy (Refs 41 and 42) conducted a preliminary evaluation of the use of the repeated-load indirect tensile test for fatigue studies; Navarro and Kennedy (Ref 45) investigated the fatigue and dynamic characteristics of inservice asphalt materials; and Cowher and Kennedy (Ref 5) studied cumulative damage. Schmidt (Ref 56) has used a type of repeated-load indirect tensile test to determine elastic modulus, but he has not performed fatigue tests.

The repeated-load indirect tensile test used by Kennedy et al applies repeated loads to the sides of a right circular cylinder through 0.5-inch loading strips. Hondros (Ref 17) analyzed this loading condition and presented equations for the resulting state of stress. Figure 5 schematically illustrates the geometry of the specimen and loading conditions used in the stress calculation for the loading apparatus shown in Fig 6. The center of the specimen is in a biaxial state of stress, as shown in Fig 7, and the resulting stresses are calculated as follows:

$$\sigma_T = \frac{2P}{\pi a h} \left(\sin 2\alpha - \frac{a}{2R}\right) \tag{2.1}$$

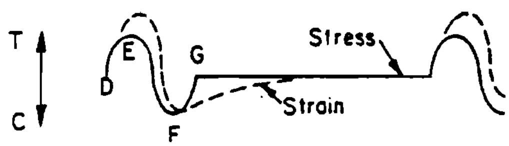
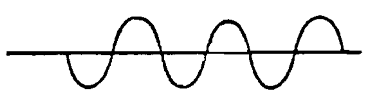
$$\sigma_C = -\frac{6P}{\pi a h} \left(\sin 2\alpha - \frac{a}{2R}\right) \tag{2.2}$$

TABLE 2. EFFECT OF SHAPE OF WAVEFORM ON FATIGUE LIFE (REF 53)

Waveform	Temp., °C	Stress Amp., MN/m	Initial Strain Amp.*	Geometric Mean Fatigue Life, Cycles	Relative Lives
	25	±0.33 (48 psi)	1.7×10^{-4}	24,690	0.42
	25		1.2×10^{-4}	58,950	1.0
	25		0.67×10^{-4}	85,570	1.45

*These represent values after approximately 200 cycles.

TABLE 3. VARIOUS UNIAXIAL LOADING WAVEFORM SHAPES USED BY RAITHBY AND STERLING (REF 53)

Waveform	Geometric Mean Fatigue Life, Cycles*
1) 	11,190
2) 	6,649
3) 	8,748
4) 	196,200
5) 	4,690

*Peak stress = 110 psi; temperature = 25°C.

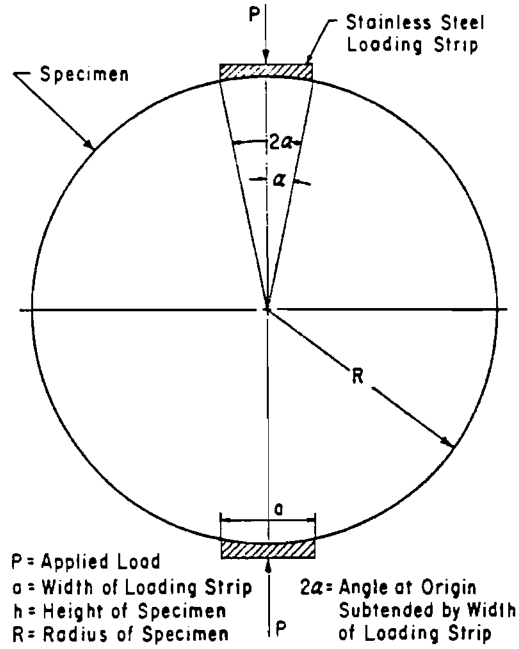


Fig 5. Indirect tensile test.

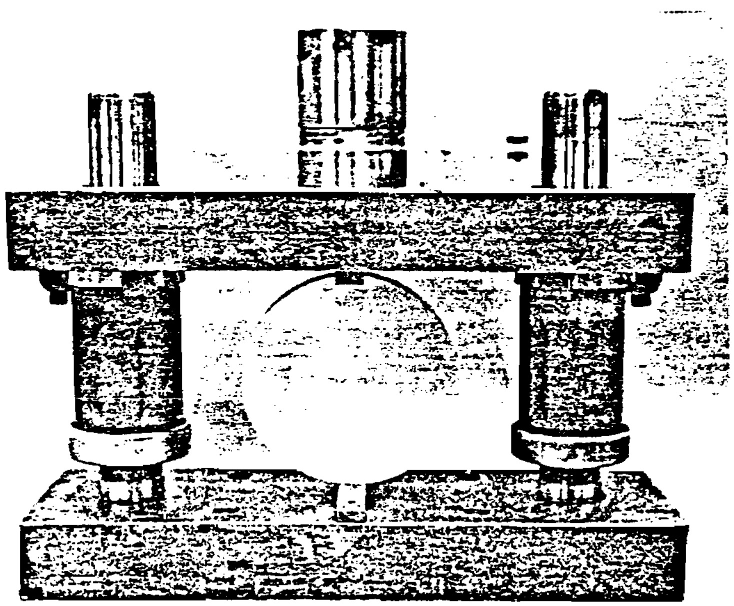
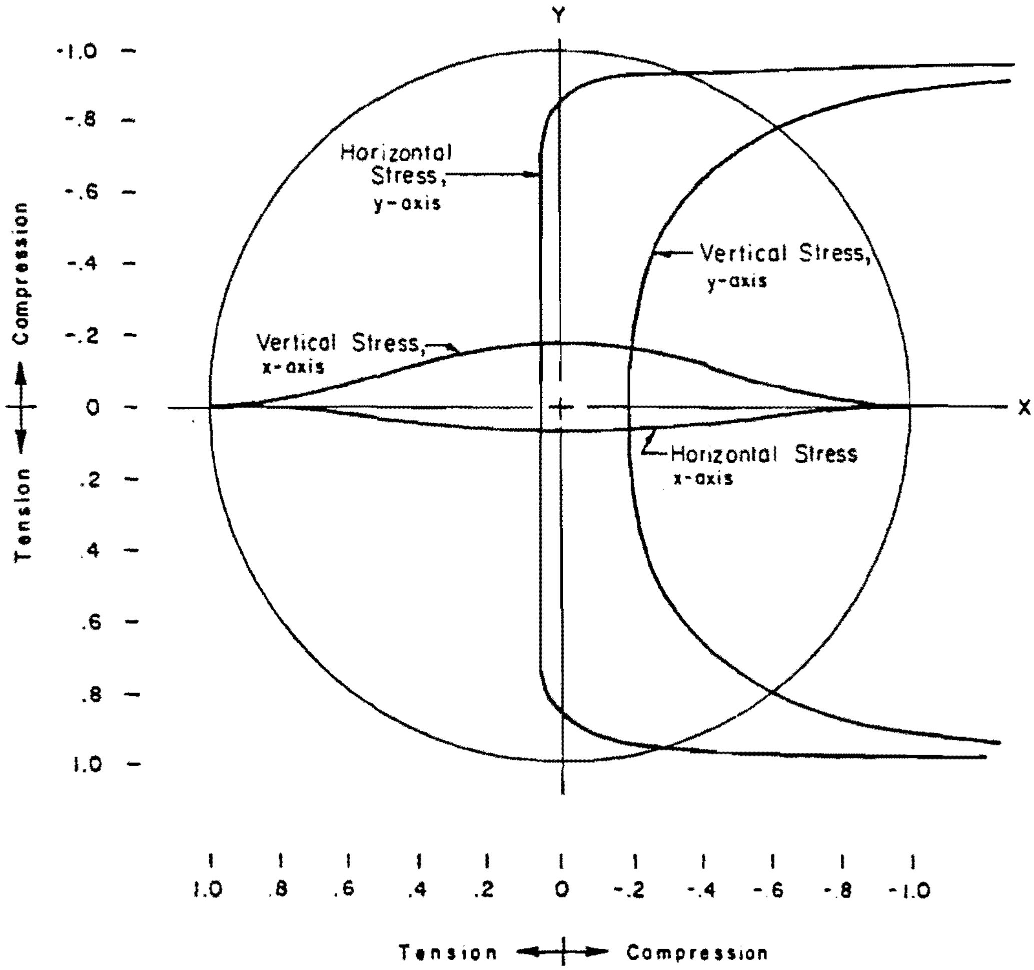


Fig 6. Indirect tensile loading device.



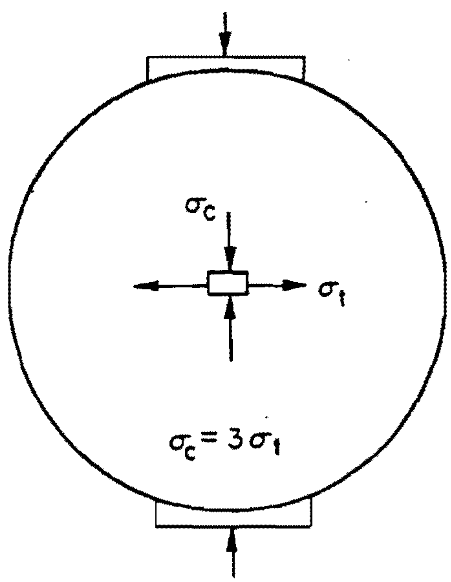


Fig 7. Relative stress distributions and element showing biaxial state of stress for the indirect tensile test.

where

σ_T = indirect tensile stress, in psi;

σ_C = indirect compressive stress, in psi;

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

a = width of loading strip, in inches;

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

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

R = radius of specimen, in inches.

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

The testing apparatus includes a loading device, shown in Fig 6, to hold the specimen. Load is applied using a closed loop electrohydraulic testing apparatus. A haversine load pulse with and without a rest period has been used at a frequency of one cycle per second. When the rest period was used, the haversine load was applied for 0.4 second with a 0.6-second rest period. Typical load and deformation curves are shown in Figs 8 and 9. A constant preload of 20 pounds, which produces a tensile stress of 1.6 psi for a typical specimen 2 inches thick and 4 inches in diameter, was used to prevent the loading head from leaving the specimen and causing impact loading. Permanent and creep deformations were allowed to occur, as shown in Fig 9. Failure of the specimen was assumed to have occurred when the specimen could no longer carry the applied load.

<u>Other Types of Fatigue Tests</u>

Many other types of fatigue tests have been used, but a meaningful evaluation of these tests is difficult because of limited test results. These tests include cantilever, torsional, diaphragm, rolling wheel, triaxial, and flexure on a simulated subgrade.

The cantilever tests performed by the various investigators used a truncated pyramid-shaped specimen, which caused a constant stress along the outside fiber of the specimen (Refs 3, 4, 13, and 58). Pell (Ref 48) performed torsional tests on solid specimens, applying a constant strain amplitude. A pure-shear biaxial state of stress was achieved using torsion. The diaphragm tests of Jimenez and Gallaway (Refs 20 and 21) made use of a device called a deflectometer. The diaphragm-shaped specimen was clamped on top of a membrane covered reservoir which was used to simulate a subgrade. Repeated loads were

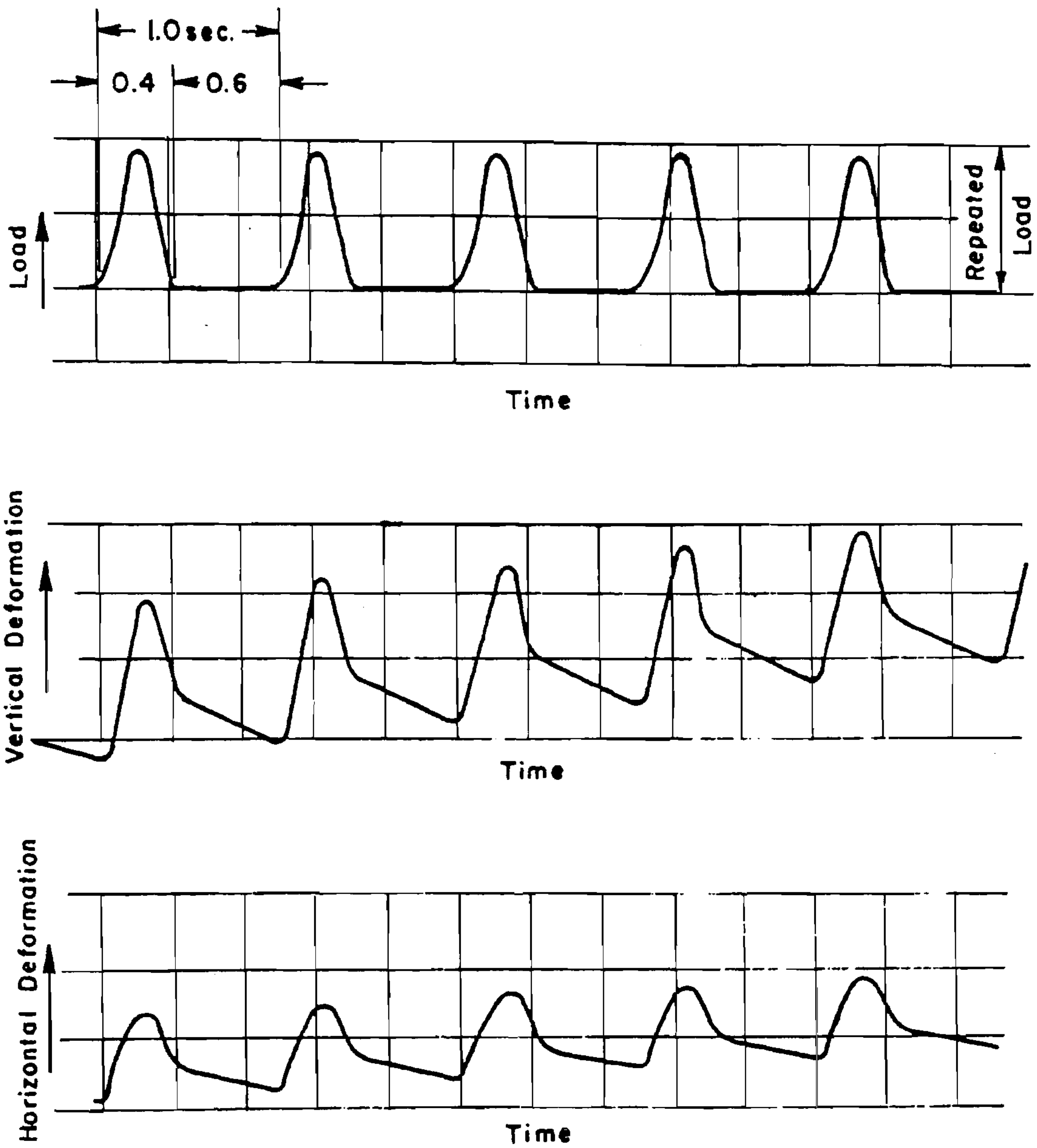


Fig 8. Load pulse and associated deformation data for the repeated-load indirect tensile test.

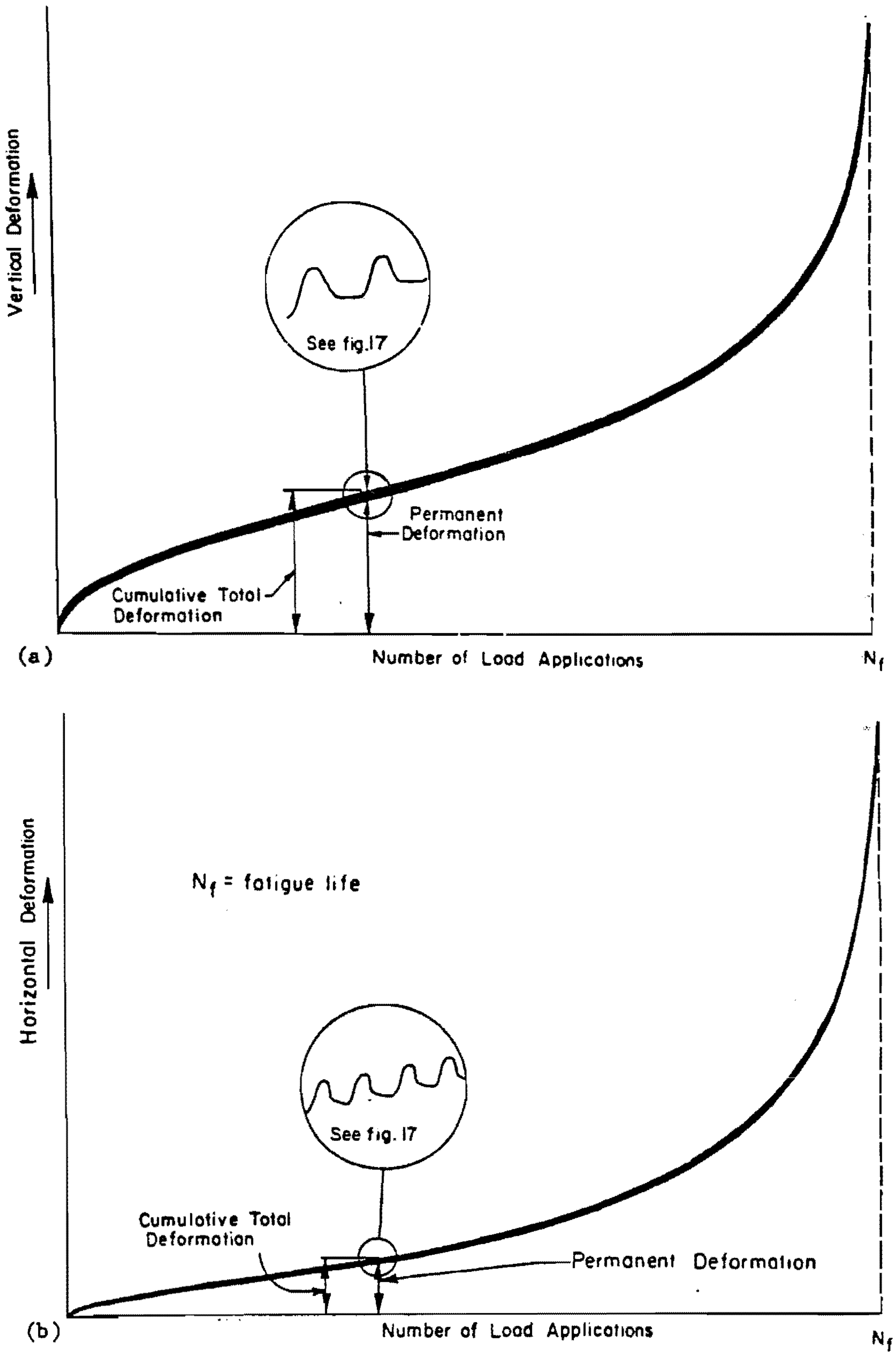


Fig 9. Relationships between number of load applications and vertical and horizontal deformation for the repeated-load indirect tensile test.

then applied to the center of the diaphragm. Tests in which the load was applied by a moving wheel have been performed on outdoor circular test tracks and indoor laboratory tests have been carried out in which the wheel moves back and forth (Refs 3, 18, and 58). Morris et al (Refs 43 and 44) used repeated-load triaxial tests to predict permanent deformation. This triaxial test applied a compressive confining stress and both tensile and compressive axial stresses and was used to a limited extent for fatigue testing (Ref 15). Monismith (Ref 32) in early fatigue testing used a flexure test which had a simulated subgrade. The specimen rested on a rubber mat which covered a bed of springs, simulating the subgrade. The specimen was loaded in the center using a controlled-strain mode of loading.

Comparison of Testing Methods

Basic Test Characteristics. In examining all test methods, it is evident that the repeated-load indirect tensile test is significantly different from the other tests. Table 4 is a summary of the basic characteristics of the flexure, rotating cantilever, repeated-load indirect tensile, and uniaxial fatigue tests. These characteristics involve loading configuration, stress distribution, loading waveform, loading frequency, permanent deformation, and state of stress.

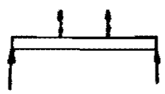
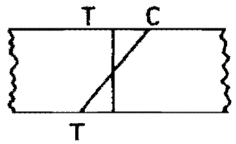
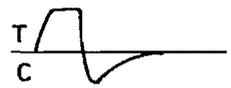
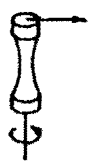
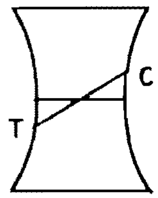
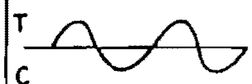
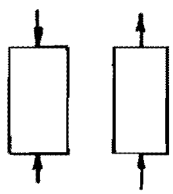
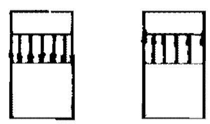
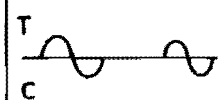
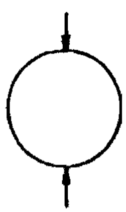
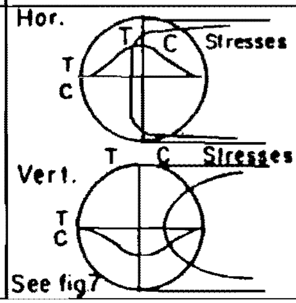
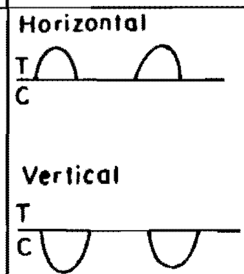
The loading configurations and resulting stresses are different; however, the major difference in stress distribution is whether the state of stress developed is uniaxial or biaxial. The flexure, rotating cantilever, and axial load tests involve a uniaxial state of stress and the indirect tensile test involves a biaxial state of stress.

The loading configuration of the rotating cantilever test produced only a sinusoidal loading waveform. The other types of tests involved a variety of waveforms. The flexure test used a square tensile pulse with a variably-shaped compressive pulse. The axial load test involved a sinusoidal pulse with a rest period and the repeated-load indirect tensile test involved a haversine pulse with and without a rest period.

The loading frequencies of the flexure and repeated-load indirect tensile test were usually lower than those of the rotating cantilever and the axial load tests.

Permanent deformations were not allowed to occur in any test except the repeated-load indirect tensile test.

TABLE 4. SUMMARY OF FATIGUE TEST CHARACTERISTICS

Test	Loading Configuration	Stress Distribution	Loading Waveform	Loading Frequency, cps	Permanent Deformations Allowed ?	State of Stress
Monismith et al / Flexure				1.67	No	Uniaxial
Pell et al / Rotating Cantilever		direction of loading 	 outside fiber at one point	16.67	No	Uniaxial
Raithby & Sterling / Axial Load	 A B	 A B	 for other shapes see Tables 2 & 3	.833-25.0	No	Uniaxial
Kennedy et al / Dynamic Indirect Tension				1.0	Yes	Biaxial

Practicality and Field Simulation. Many differences have been noted between the repeated-load indirect tensile test and the other commonly used fatigue tests, one of the more important being the state of stress, which is biaxial for the repeated-load indirect tensile test. The biaxial state of stress more closely simulates the stress conditions produced at the bottom of a layer by a moving wheel load (Fig 1). The fact that the frequency, load duration, and rest periods can also be changed allows better simulation of actual loading conditions. The fact also allows permanent deformation to occur, which is important and closely related to actual field conditions. Thus, the repeated-load indirect tensile test has loading conditions that more closely resemble field loading conditions than other tests, is practical and easy to perform, and utilizes cylindrical specimens and cores.

TYPICAL FATIGUE RESULTS

In most laboratory fatigue studies repeated loads are applied to a specimen and the number of cycles required to produce failure is determined. These data are often presented in a stress and cycles-to-failure (S-N) diagram. The S-N_f relationship on logarithmic paper (Fig 10) generally is linear and can be expressed in the form

$$N_f = K_2 \left(\frac{1}{\sigma}\right)^{n_2} \qquad (2.3)$$

where

N_f = cycles to failure,
σ = repeated stress,
n_2 = slope of the line,
K_2 = antilog of intercept of the line.

The coefficients K_2 and n_2 completely describe the relationship between fatigue life and stress in Eq 2.3 and can be used to describe the fatigue properties of asphalt mixtures.

In addition, the fatigue characteristics are also expressed in terms of the relationship between the logarithm of strain and the logarithm of fatigue life. In controlled-strain tests, strain is the repeated strain; in controlled-stress tests, strain is usually taken to be the initial strain. This relationship can be expressed in the following manner:

$$N_f = K_1 \left(\frac{1}{\varepsilon}\right)^{n_1} \qquad (2.4)$$

where

N_f = cycles to failure, or fatigue life,
ε = repeated strain or initial strain,
n_1 = slope of the line,
K_1 = antilog of intercept of the line.

Table 5 contains typical values of K_2 and n_2 obtained by Pell et al, Monismith et al, Kennedy et al, and Raithby and Sterling. The values reported for Pell et al and Monismith et al are from Ref 37, and the values for Kennedy et al and Raithby and Sterling were calculated from reported data (Refs 41, 42, 52, and 53).

Figure 10 graphically illustrates typical logarithmic $S\text{-}N_f$ relationships for a variety of mixtures tested under different conditions by a number of investigators using various types of fatigue tests and contains typical values of K_2 and n_2. From an examination of Table 5 and Fig 10, it is obvious that there are large differences in fatigue lives obtained in the various studies, especially for the indirect tensile test. A comparison of K_2 and n_2 values (Table 5) indicates that these differences are primarily reflected by the K_2 values and that the values of n_2 are approximately the same. Values of K_2 ranged from 6.19×10^5 to 2.24×10^{21}, with the lower values associated with the repeated-load indirect tensile test (6.19×10^5 to 2.04×10^{10}) and with higher testing temperatures. Values of n_2 ranged from 2.56 to 7.70.

The differences in the fatigue results obtained by different test methods are due to differences in loading and environmental testing conditions and the composition of the specimen. Therefore, a review of load, environmental, and mixture variables should provide some insight into the differences in fatigue results.

TABLE 5. SUMMARY OF FATIGUE DATA FOR VARIOUS TESTS AND INVESTIGATORS

Test and Investigator		Mixture	Asphalt Content, %	Asphalt Type, Penetration	Temperature, °F	K_2	n_2
Flexure	Monismith et al (Ref 37)	British 594	7.9	40-50	68	1.36×10^{11}	2.87
		California	6.0	85-100	68	1.64×10^{11}	3.69
		California	6.0	85-100	68	1.55×10^{11}	3.51
		California	6.0	85-100	68	2.11×10^{12}	4.04
		California	6.0	60-70	68	7.29×10^{12}	4.21
		California	6.0	40-50	68	1.97×10^{15}	4.93
		California	6.2	60-70	68	6.01×10^{10}	3.24
		Gonzales Lab surface	6.0	85-100	40	1.78×10^{16}	5.09
		Gonzales Lab surface	6.0	85-100	68	6.68×10^{12}	4.48
		Gonzales Lab base	4.7	85-100	68	1.37×10^{13}	3.86
		Folsom Lab surface 1 and 2	4.9	85-100	40	1.16×10^{18}	5.71
		Folsom Lab surface 1 and 2	4.9	85-100	68	3.29×10^{14}	5.72
		Folsom Lab surface 3 and 4	4.9	85-100	40	1.55×10^{16}	4.97
		Folsom Lab surface 3 and 4	4.9	85-100	68	3.97×10^{14}	5.36

(Continued)

TABLE 5. (Continued)

Test and Investigator		Mixture	Asphalt Content, %	Asphalt Type, Penetration	Temperature, °F	K_2	n_2
Rotating Cantilever	Pell et al (Ref 37)	BS 594 - A	8.1	40-50	32	-	6.0
		BS 594 - A	8.1	40-50	50	-	7.7
		BS 594 - A	8.1	40-50	68	-	5.8
		BS 594 - B	7.2	40-50	32	-	6.2
		BS 594 - C	7.2	90-110	32	-	5.3
		BS 594 - D	6.3	40-50	32	-	5.8
		USA - E	5.4	90-100	50	-	5.7
		BS 594 - F	6.0	40-50	50	-	5.9
		BS 594 - G	6.0	40-50	32	-	5.9
		BS 594 - G	6.0	40-50	50	-	5.9
		BS 594 - G	6.0	40-50	68	-	4.6
		BS 594 - G	6.0	40-50	86	-	4.9
		BS 594 - H	6.0	90-110	50	-	4.0
		USA - L	4.2	90-100	50	-	4.0
		Macadam - R	4.7	90-110	50	-	4.1
		Macadam - S	4.3	190-210	50	-	1.4
		Macadam - T	4.7	190-210	50	-	1.9
	Pell and Cooper (Ref 51)	HRA - base course A1	6.0	40-50	50	3.7×10^{16}	5.4
		HRA - base course A13	6.8	40-50	50	1.1×10^{12}	3.5
		AC - wearing course B6	6.0	60-70	50	3.9×10^{15}	4.9
		DBM - base course C5	4.7	90-110	50	3.0×10^{12}	3.9
		DTM - base course D4	6.0	40-60	50	7.5×10^{19}	6.4

(Continued)

TABLE 5. (Continued)

Test	Investigator	Mixture	Asphalt Content, %	Asphalt Type, Penetration	Temperature, °F	K_2	n_2
Repeated-Load Indirect Tension	Kennedy (Refs 41, 42)*	Limestone	7.0	92	75	1.25×10^{9}	4.09
		Gravel	7.0	92	75	2.04×10^{10}	4.74
	Kennedy (Current, unpublished)	Limestone	4.0	88	75	6.19×10^{5}	2.56
		Limestone	5.0	88	75	8.11×10^{6}	2.84
		Limestone	6.0	88	75	6.90×10^{7}	3.23
		Limestone	7.0	88	75	4.76×10^{8}	3.88
		Limestone	8.0	88	75	5.88×10^{7}	3.42
		Gravel	4.0	88	75	2.74×10^{6}	3.24
		Gravel	5.0	88	75	9.40×10^{6}	3.14
		Gravel	6.0	88	75	6.62×10^{7}	3.34
		Gravel	7.0	88	75	3.56×10^{8}	3.80
		Gravel	8.0	88	75	1.90×10^{7}	3.13
Axial Load	Raithby and Sterling (Refs 52, 53)*	Pell's Mix G	6.5	38	50	2.59×10^{13}	4.11
		Pell's Mix G	6.5	38	50	1.72×10^{19}	6.43
		Pell's Mix G	6.5	38	50	2.24×10^{21}	5.97
		Pell's Mix G	6.5	38	50	2.13×10^{17}	5.28
		Pell's Mix G	6.5	38	77	3.65×10^{11}	3.87
		Pell's Mix G	6.5	38	77	5.78×10^{13}	4.76
		Pell's Mix G	6.5	38	77	2.49×10^{13}	4.09

*K_2 and n_2 calculated from data presented in references.

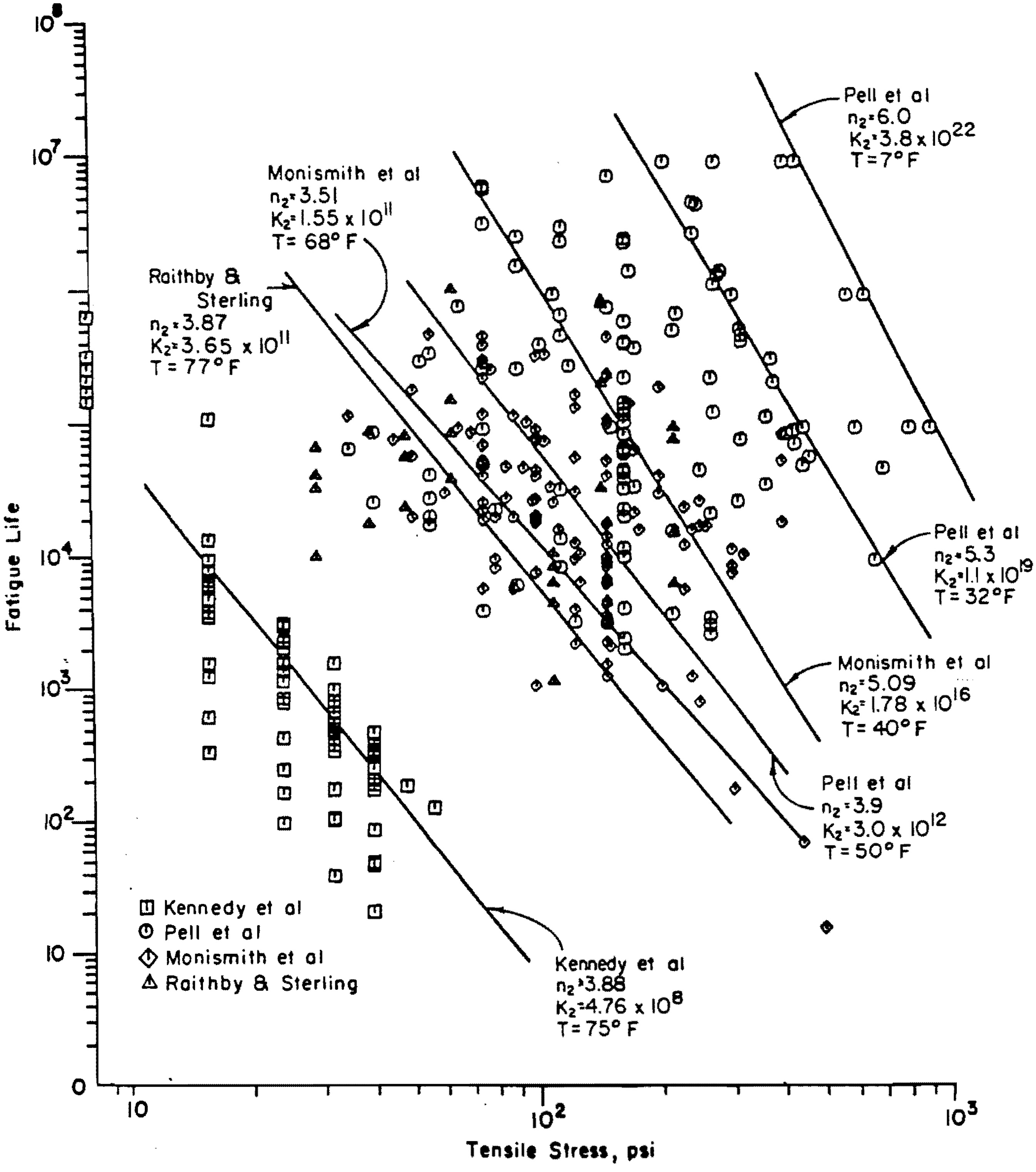


Fig 10. Typical stress-fatigue life relationships for various test methods.

LOAD VARIABLES

Laboratory tests which attempt to obtain information related to the behavior of the material involve a number of load variables, including load history, type of loading, state of stress, loading waveform, rest period, load duration, loading frequency, creep, and other miscellaneous variables.

Load History

For asphaltic mixtures, different fatigue lives are obtained by testing under different loading conditions or by changing the loading conditions during the test. Two basic types of fatigue tests based on load history can be performed, simple loading and compound loading. Simple loading involves constant testing conditions while for compound loading testing conditions change during the test. Compound loading has a varied load history, which must be considered during the evaluation of the test results. Therefore, when differences between tests are being compared only the simple loading case should be considered. Further information on compound loading can be located in the works of Deacon (Ref 6), McElvaney (Ref 31), and Cowher and Kennedy (Ref 5).

State of Stress

The state of stress will produce different results for the same asphaltic mixtures. Raithby and Sterling (Refs 52 and 53) demonstrated that direct compression fatigue lives were much longer than those in direct tension (Table 3). In addition, rest periods had a greater effect for compressive loads than for tensile loads. Kallas (Ref 22) reported that dynamic moduli for tension were different than those for compression. An explanation for the difference between tensile and compressive results was suggested by Morris et al (Refs 43 and 44). In tension, the entire load is carried by the weak asphalt binder; and, in compression, the combined asphalt aggregate supports the load and makes for a stronger mixture.

Multiaxial states of stress also result in different fatigue lives and behavior than those produced by uniaxial states of stress. Dehlen and Monismith (Ref 9) using a compressive triaxial test and Haas (Ref 15) using a triaxial test with a tensile axial load described changes in materials under different states of stress. Dehlen and Monismith discovered that decreasing the deviator stress increased the material's stiffness and resulted in a longer fatigue life in controlled-stress testing. Haas (Ref 15), also, found that decreasing the deviator stress increased fatigue life.

Deacon (Ref 6) suggested the use of combined stress theories to analyze fatigue results for complex states of stress and proposed using the maximum principal stress theory, the maximum shear stress theory, and the octahedral shear stress theory.

These theories basically relate the various stresses acting on an element and account for the effects of all stresses.

Maximum Principal Stress. The maximum principle stress theory states that failure is controlled by the maximum principal stress, which in most cases is the tensile stress. Direct tensile tests, bending tests, and repeated-load indirect tensile tests all relate fatigue behavior to the maximum principal stress.

Maximum Shear Stress Theory. The maximum shear stress theory suggests that failure is controlled by the maximum shear stress developed in the material. Using a Mohr's circle representation of stress, the maximum shear stress is one-half of the difference between the maximum and minimum principal stresses. Thus, this theory considers multiaxial states of stress.

Octahedral Shear Stress Theory. Similarly, this theory considers the effects of multiaxial stresses by stating that failure is controlled by the octahedral shear stress, τ_{oct}, which is defined as

$$\tau_{oct} = 1/3\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}$$

where

σ_1, σ_2, and σ_3 are the principal stresses.

Type of Loading

As previously noted the type of loading employed in laboratory fatigue testing is either controlled-strain or controlled-stress. The controlled-strain testing mode applies a constant deformation or strain to the specimen while the controlled-stress mode applies a constant stress or load. The intermediate cases between controlled-strain are expressed by means of a mode factor. The mode factor MF is defined as

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

where

/A/ = percentage change in stress,

/B/ = percentage change in strain for some fixed percentage reduction of stiffness.

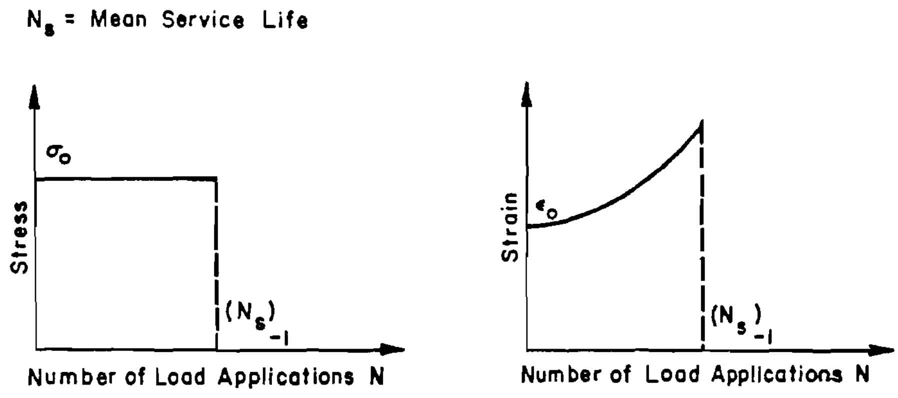
The mode factor is +1 for controlled-strain, -1 for controlled-stress, and somewhere in between +1 and -1 for intermediate modes of loading (Ref 33).

Figure 11(a) shows the relationships between stress and strain and the number of load applications for controlled-stress. As the number of load applications increases, the stress remains constant and the strain increases as the specimen is damaged.

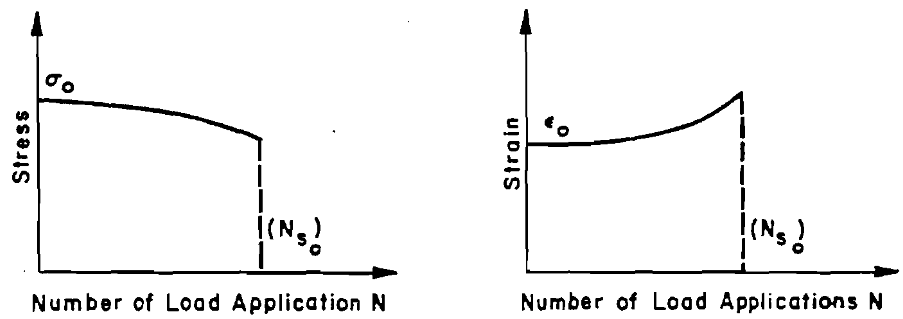
The controlled-strain test is illustrated in Fig 11(c). The figure shows that strain is constant and stress decreases as the number of load applications increases. This resulting decline in stress occurs because the specimen is damaged with each load application and less stress is required to obtain the same strain.

The controlled-stress and controlled-strain test results lead to different conclusions. In controlled-stress tests, stiffer mixtures exhibit longer fatigue lives, while, in controlled-strain tests, the more flexible mixtures have longer fatigue lives. In cases where the specimens are identical, the controlled-stress loading will result in a shorter fatigue life as shown in Fig 12.

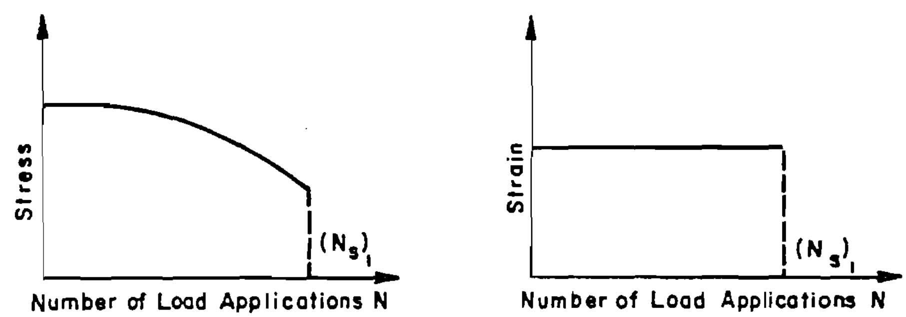
Van Dijk et al (Ref 58) explain the difference between fatigue lives tested under controlled-stress and controlled-strain in terms of total energy dissipation. Figure 13 shows total energy dissipation versus the number of cycles for controlled-stress and controlled-strain tests. For both modes of loading, the total energy dissipated was identical at failure, but the controlled-stress case dissipates energy much faster than the controlled-strain. Figure 14 illustrates that the specimen's bending strength decreased with energy dissipation until the bending strength was equal to the applied load, at which time the specimen failed. In terms of total dissipated energy,



(a) Controlled-stress, mode factor = -1.



(b) Intermediate, mode factor = 0.



(c) Controlled-strain, mode factor = 1.

Fig 11. Schematic representation of fatigue behavior of asphalt paving materials for various modes of loading (Ref 10).

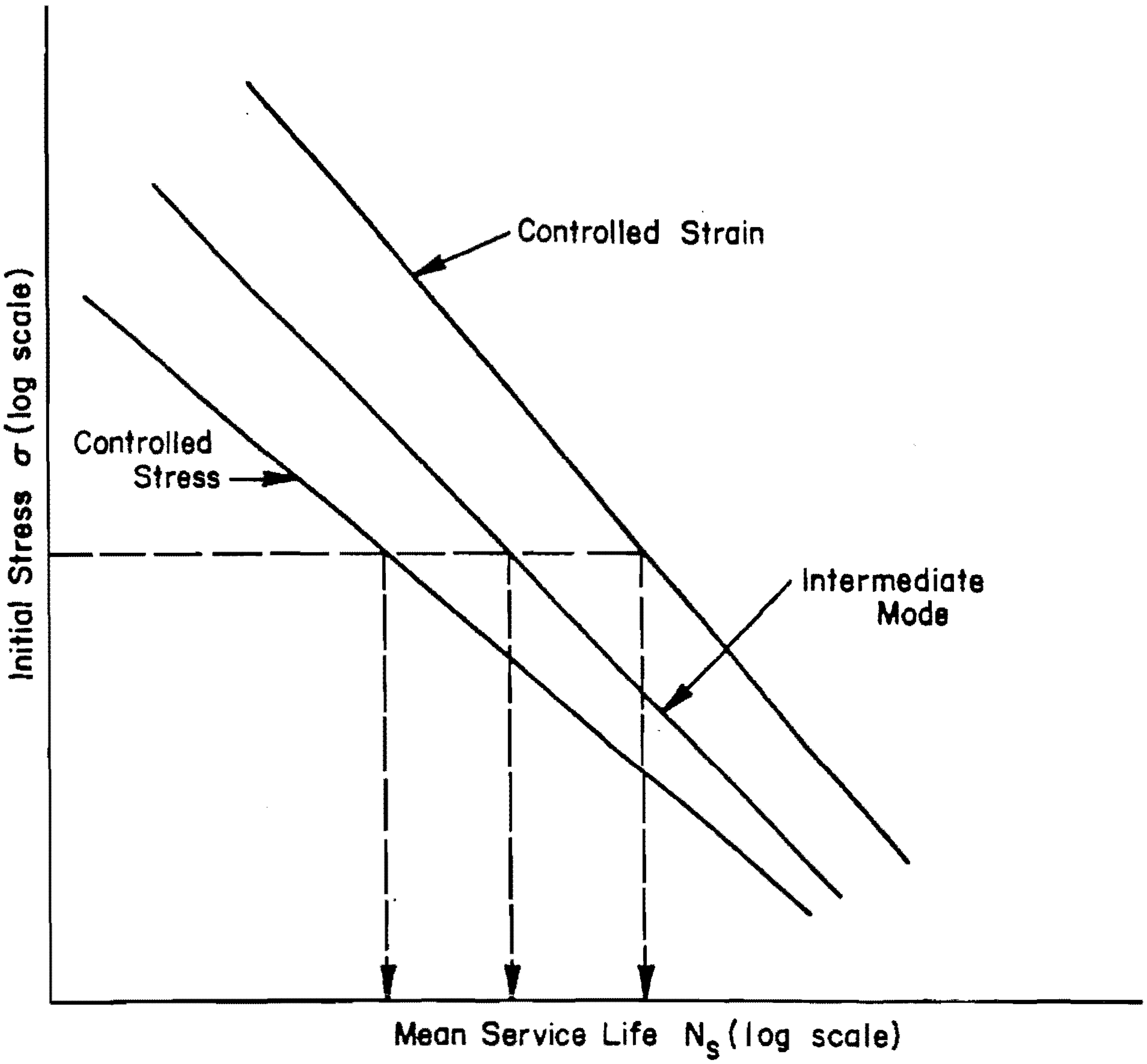


Fig 12. Hypothetical fatigue diagram illustrating effect of mode of loading (Ref 10).

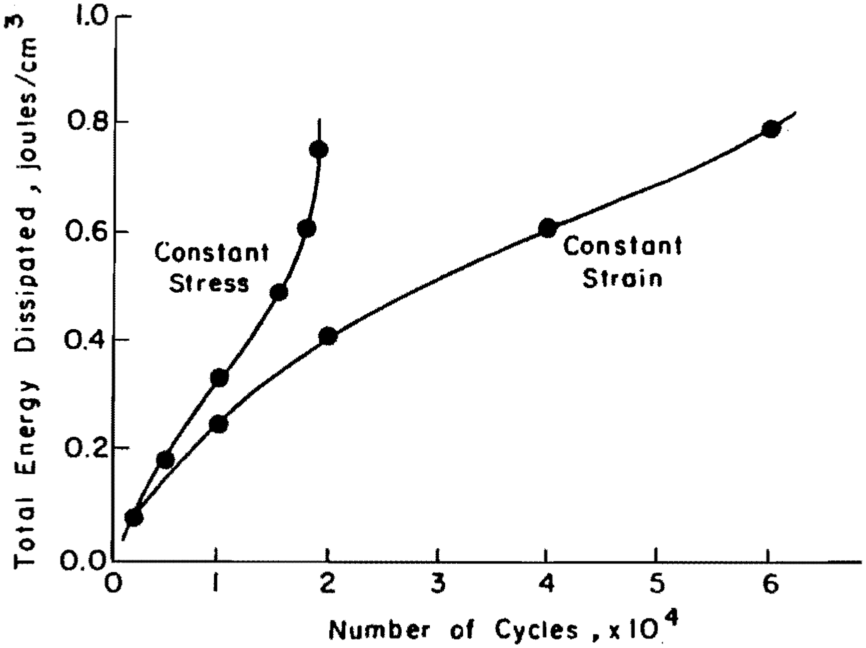


Fig 13. Total energy dissipated as a function of load repetitions for constant stress and constant strain tests (Ref 58).

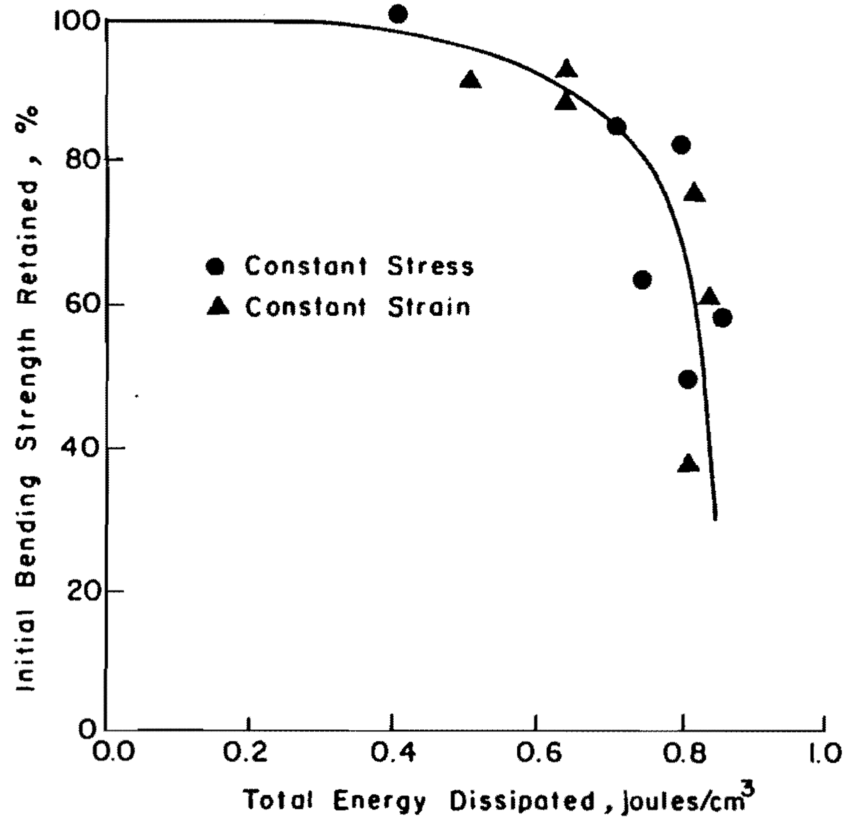


Fig 14. Percentage of retained bending strength as a function of the total energy dissipated for constant stress and strain tests (Ref 58).

fatigue life was independent of the loading mode.

Loading Waveform

Raithby and Sterling (Refs 52 and 53) performed a series of tests to determine the effect of loading waveform on fatigue life. In one series, continuous loading was applied to specimens using three different waveforms: square, sinusoidal, and triangular. A summary of the results is shown in Table 2, p 12. A triangular waveform produced the longest fatigue life and the square waveform produced the shortest.

Rest Period, Load Duration, and Frequency of Loading

The effects of rest period, load duration, and frequency of loading are difficult to determine because these terms are interdependent. The load duration plus rest period determines the frequency of loading. Therefore, a change in any one of these variables will affect the value of at least one other. Even though the variables cannot be varied independently, it is possible to study the general effects of all three.

Rest period. Raithby and Sterling (Refs 52 and 53) studied the effects of rest periods on fatigue life. The results are summarized in Table 3, page 12, and Table 6. A rest period added to any sine wave load pulse increased fatigue life. While rest periods were found to be beneficial, there was a limit above which an additional increase in the rest period did not increase fatigue life significantly (Table 6 and Figure 15), and it was concluded that the length of the maximum beneficial rest period was temperature dependent. In addition, the direction of the stress prior to the rest period was found to be important. A rest period following a compressive stress resulted in a fatigue life which was about 1.5 times that obtained when a tensile stress followed the rest period (Table 3), and Raithby and Sterling concluded that fatigue life is dependent on tensile strains.

Monismith and Epps (Refs 10 and 33) studied the effect of frequency, which also related to rest periods. The loading frequency was varied while the duration of load was held constant, causing the length of the rest period to change. Rest periods caused by frequency variations of 3 to 30 applications of load per minute had no effect on fatigue life. Later testing indicated that decreasing the rest period by increasing the frequencies from 30 to 100 applications per minute decreased the fatigue life. These results also in-

TABLE 6. RESULTS OF REST PERIOD TESTS (REF 52)

Loading Period, ms	Temperature, °C	Alternating Stress, MN/m^2	Rest Period, ms	Number of Tests	Geometric Mean Life, cycles	Std. Dev. of Log Life	Mean Life Ratio*
40	10	1.5 (217 psi)	0	5	6,625	0.192	1.0
			80	6	16,110	0.262	2.4
			400	4	80,870	0.317	12.2
			1000	4	100,500	0.346	15.1
		1.0 (145 psi)	0	7	34,680	0.551	1.0
			80	6	215,400	0.618	6.2
			400	4	896,800	1.015	25.8
			1000	5	843,100	0.637	24.3
40	25	0.76 (110 psi)	0	2	4,690	0	1.0
			80	3	11,190	0.287	2.4
			1000	3	111,400	0.396	23.6
		0.43 (63 psi)	0	6	40,440	0.124	1.0
			40	2	89,130	0.115	2.2
			80	3	158,700	0.042	3.9
			1000	1	1,088,510	-	26.9
40	40	0.20 (29 psi)	0	4	10,360	0.282	1.0
			80	3	34,000	0.052	3.3
			400	4	68,960	0.257	6.7
			1000	4	42,330	0.156	4.1
400	25	0.27 (39 psi)	0	3	18,600	0.268	1.0
			800	2	91,580	0.301	4.9

*Ratio of geometric mean life with rests to geometric mean life under continuous cycling.

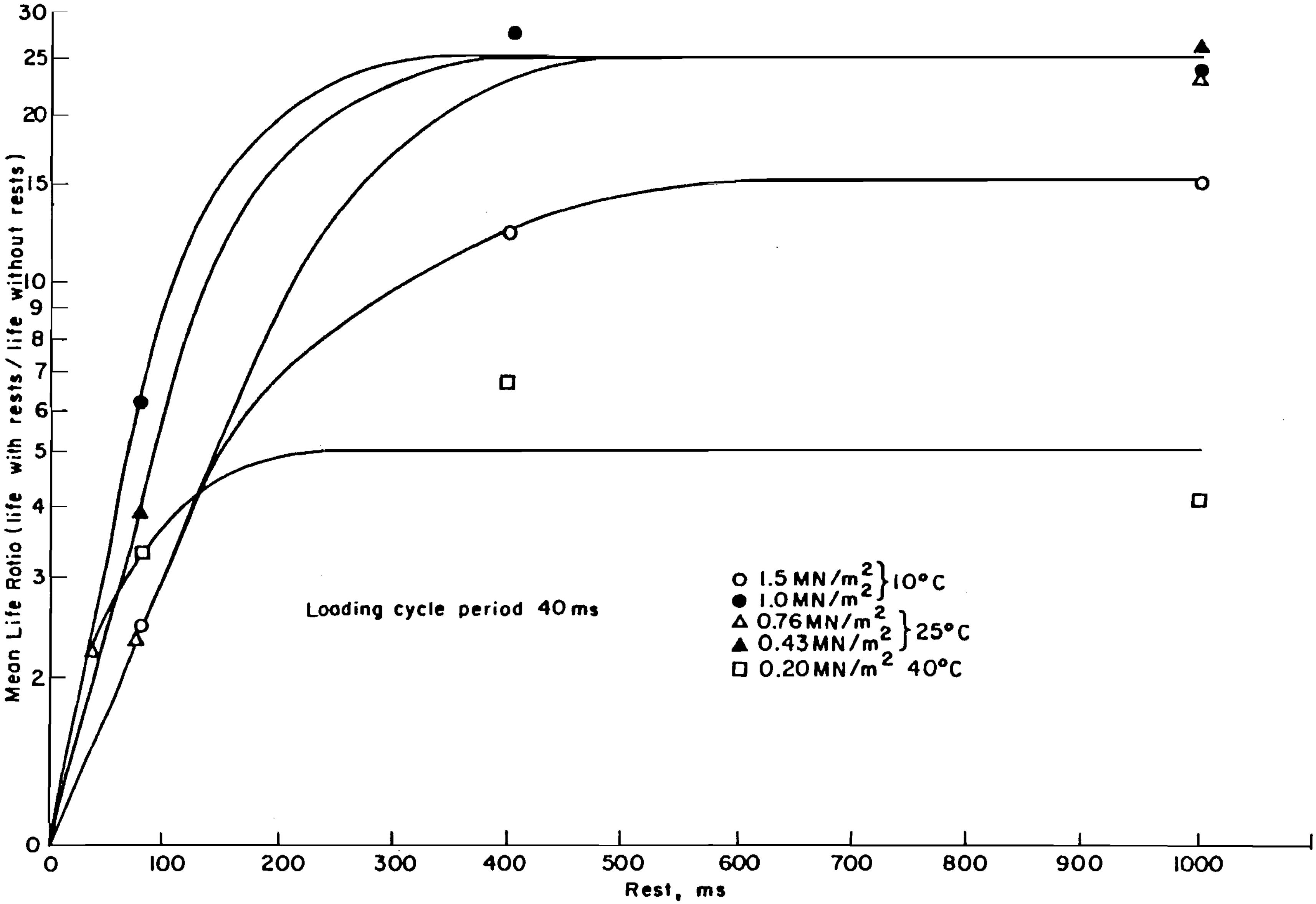


Fig 15. Effect of increasing rest periods on fatigue life (Ref 53).

dicated that there is a point of diminishing return at which an increase in the rest period will not significantly increase fatigue life.

Van Dijk et al (Ref 58) also demonstrated the beneficial effects of rest periods on fatigue life (Fig 16) by adding a rest period to the loading pulse. The S-N_f curve was shifted to the right, i.e., fatigue lives were increased. The interesting feature of their work is the shape of the load pulse, which consists of a large tensile pulse between two small compressive pulses followed by a rest period and more closely simulates the stress pulse caused by a wheel moving across pavement. Van Dijk et al also found evidence which seems to indicate that there is some maximum rest period above which longer rest periods do not increase fatigue life.

Load duration. Deacon (Ref 6) studied the effects of load duration by varying the load duration while holding the frequency constant, which also varied the rest period. Figure 17 illustrates that load duration had a significant effect on fatigue life, with increased load durations producing shorter fatigue lives. However, changes in the length of the rest periods were occuring simultaneously.

Frequency of loading. To determine the effect of frequency, Pell and Taylor (Ref 50) held the ratio of load duration to rest period constant and varied the frequency of a sinusoidal load pulse from 80 to 2500 cycles per minute and discovered that increasing the frequency increased fatigue life, with the most significant change occuring at frequencies below 200 cycles per minute. Figure 18 shows the relationship between loading frequency and cycles to failure. Table 6 summarizes two sets of data obtained by Raithby and Sterling (Refs 52 and 53), from which the effect of frequency can be determined. One set of tests involved a loading period of 40 ms with rest periods of 0 and 80 ms; the second set of data involved a loading period of 400 ms with rest periods of 0 and 800 ms. The specimens having the 400-ms loading period had much shorter fatigue lives, even though they were tested at a lower stress level. Therefore, decreasing the loading period, which increased the frequency, increased fatigue life.

Creep

Creep is a time dependent deformation of a material under constant stress; however, Manson (Ref 29), as the result of a study of high-temperature metal

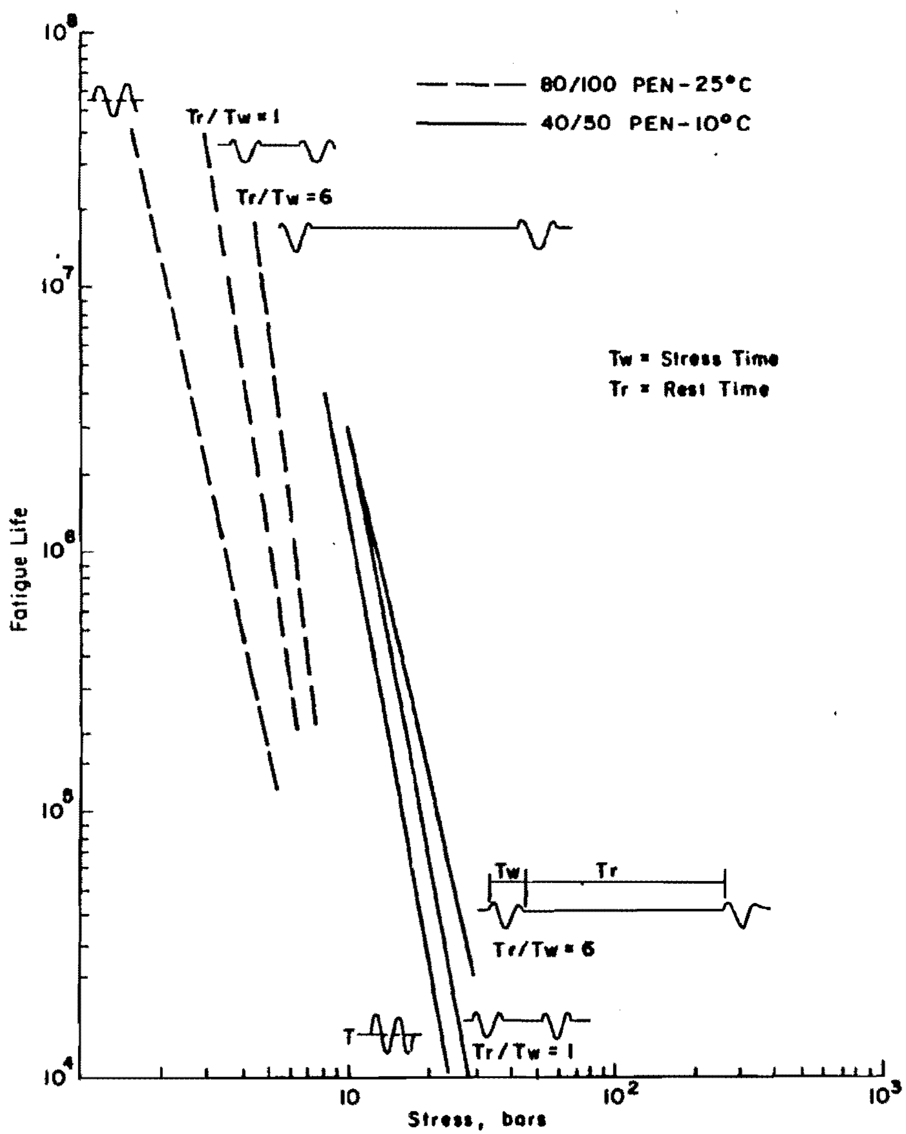


Fig 16. Effect of rest periods on S-N relationships for a cantilever test (Ref 58).

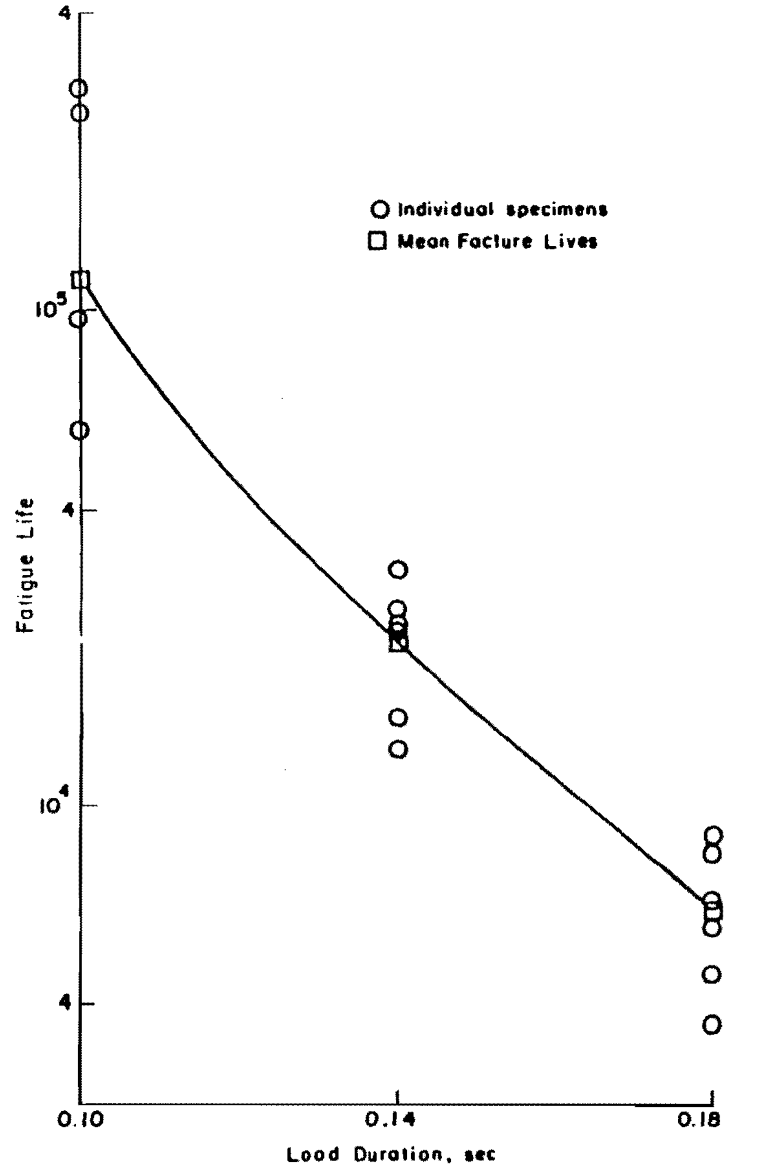


Fig 17. Effect of load duration on fatigue life for a flexure test (Ref 6).

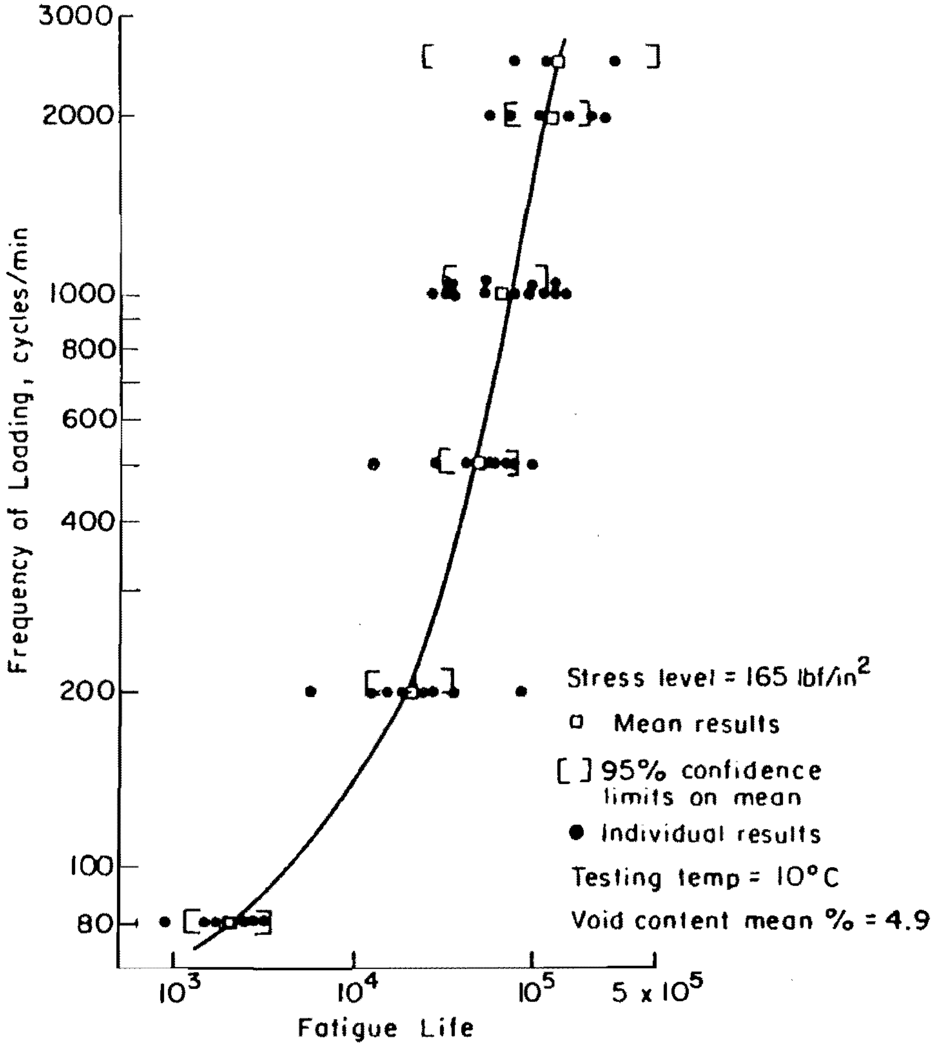


Fig 18. Effect of loading frequency on fatigue life using sinusoidal loading and a rotating cantilever test (Ref 50).

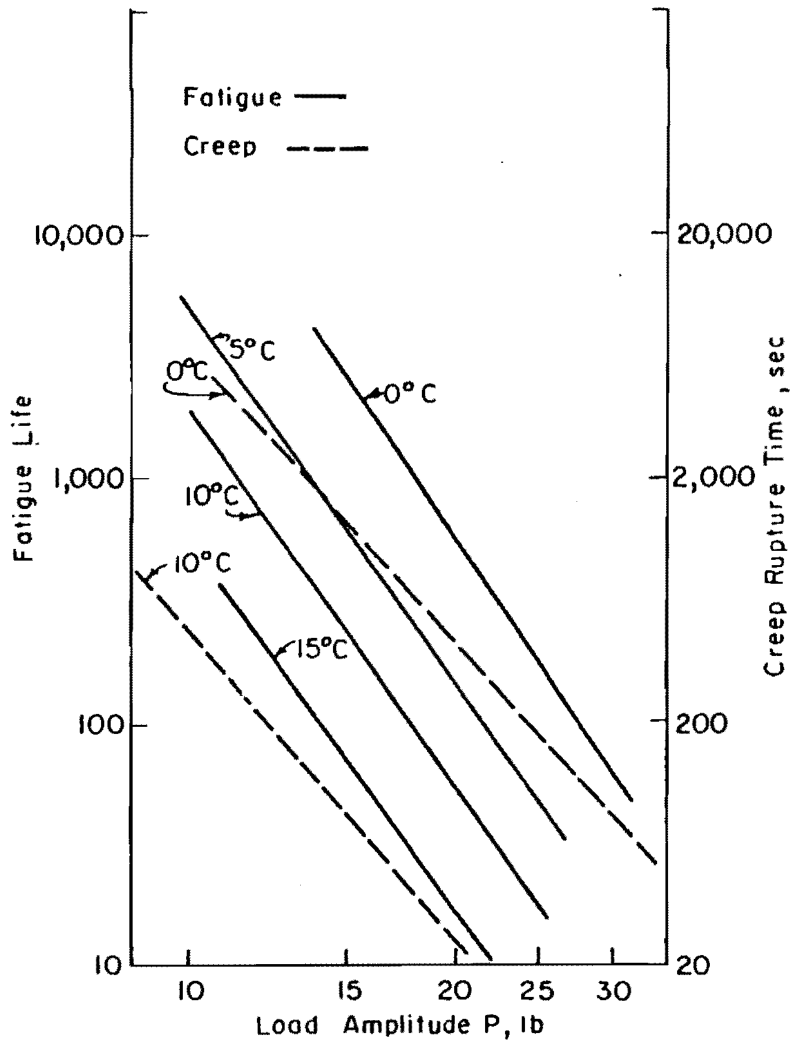


Fig 19. Comparison of creep and fatigue for a flexure test (Ref 28).

fatigue, concluded that since failure of a material is the result of the combined effect of both alternating strain and creep, it follows that the time of exposure to stress, as well as the number of cycles, must enter into the analysis.

Lai and Anderson (Ref 26) performed a series of cyclic creep tests on asphaltic concrete under uniaxial compression. Specimens deformed to various degrees, depending on the duration of loading, which ranged from 10 to 1000 seconds. While these durations are large compared to the load durations used in most fatigue studies, creep deformations still occur in fatigue loading.

Deacon (Ref 6) in the design of his flexural fatigue testing apparatus provided a stress reversal to force the specimen back to its original undeflected position (Fig 3, page 9), which eliminated creep or permanent deformation even though the load duration was only 0.1 second. Raithby and Sterling (Ref 53) also recognized the possibility of creep during testing and did not allow permanent deformations to occur.

To combine fatigue and creep damage, Manson (Ref 29) suggested that at failure the percentage of creep-rupture damage plus the percentage of fatigue damage should equal 100 percent. Based on this theory, Manson predicted high temperature fatigue results using high temperature creep data and normal temperature fatigue data.

Majidzadeh et al (Ref 28) performed fatigue and creep tests on sand asphalt specimens. Load amplitude versus fatigue life and creep time to failure is plotted in Fig 19, which shows a close relationship between creep and fatigue. Guirguis and Majidzadeh (Ref 14) pointed out that fracture is the result of progressive internal damage, which can occur in both fatigue and creep fracture.

Miscellaneous Variables

There are many other load variables which affect fatigue results. Some of these elements are strain rate, stress path, relaxation, resonance, deformability, homogeneity of stresses, and permanent deformation. These variables have not received sufficient investigation to determine their exact influence on fatigue testing; nevertheless, in some cases these factors could be highly significant. The uncertainty caused by the presence of these variables greatly increases the difficulty of evaluating the fatigue results of different investigations (Refs 7 and 10).

ENVIRONMENTAL VARIABLES

Environmental factors influence the fatigue resistance of an asphaltic pavement in two ways. First, there are the immediate effects produced by temperature and moisture. Secondly, there are changes in fatigue characteristics that occur with time due to changes in the material.

Probably the most important environmental factor in laboratory testing is temperature. Several investigators have studied the effect of temperature experimentally and found that fatigue life increases with decreasing temperature in controlled stress tests (Table 7).

Moisture and the change of the material with age have not been studied sufficiently to produce meaningful results, but it is recognized that these variables do affect fatigue life.

MIXTURE VARIABLES

The composition of an asphaltic concrete mixture directly determines fatigue performance. The more important mixture variables are asphalt content, asphalt type, aggregate type, aggregate gradation, and air void content.

The effects of mixture variables are presented in Table 7. Specific examples of changes in mixture variables are described in Table 8. Several investigators (Refs 11, 20, 47, and 50) have presented test results which show an optimum asphalt content with respect to maximum fatigue life. It has also been discovered that viscous asphalts with low penetrations have longer fatigue lives in controlled-stress testing.

The effect of the type of aggregate and aggregate gradation is not totally understood (Ref 10). Mixtures containing aggregate with increased roughness and angularity have a longer fatigue life, and mixtures with aggregate gradation going from coarse to fine tend to have increased fatigue lives when tested in controlled-stress. The aggregate type and gradation have a complex effect on a mixture since they affect air void content, structure, and optimum asphalt content. Air void content, which is a function of mixture composition and compaction, has been shown to affect fatigue life (Refs 11 and 50) and it has been concluded that an increase in the air void content decreases fatigue life, but there is also evidence that the number, size, and shape of the voids are

TABLE 7. FACTORS AFFECTING THE STIFFNESS AND FATIGUE BEHAVIOR OF ASPHALT CONCRETE MIXTURES (REF 10)

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.

TABLE 8. SELECTED RESULTS FROM CONTROLLED STRESS TESTS (REF 10)

Variable	Change in Variable	Change in Fatigue Life[a]	Reference
Asphalt penetration	92-33	500,000 to 1,000,000	11
	120-60	6,000 to 250,000	—
	110-40	no significant change[b]	50
	180-40	250,000 to 1,000,000	52
	85-13	no significant change	—
Asphalt content[c], %	5.3-6.7	2,000 to 20,000	11
	6.0-7.5	6,000 to 40,000	—
	3.5-6.5	6,000 to 2,500,000	50
Aggregate type	Smooth to rough surface texture	800,000 to 1,000,000	11
		8,000 to 40,000	—
		750,000 to 1,000,000	50
	Coarse to fine	450,000 to 1,000,000	11
		450,000 to 1,000,000[d]	11
		150,000 to 1,000,000[d]	48
		350,000 to 1,000,000[d]	52
Aggregate gradation	Addition of filler 0 to 9%	700,000 to 2,500,000	50
Air void content, %	10-3	25,000 to 125,000 (sandsheet)	11
		250 to 15,000 (dense graded)	11
		250 to 5,000 (dense graded)	11
		30,000 to 300,000 (sandsheet)	—
	9-4.5	300,000 to 1,000,000 (sandsheet)	52
Temperature, °F	40-68	200,000 to 1,000,000 (avg. values)	—
		600,000 to 1,000,000 (avg. values)	—
	32-86	No significant change[b]	48
	14-50	No significant change	52

[a] Comparisons based on results from stress-fatigue life relationships.
[b] Little difference was noted on ε-N_f plot provided the mixture did not exhibit nonlinear behavior.
[c] Optimum asphalt content used to establish maximum fatigue life.
[d] Comparison of sheet asphalt mixtures with dense graded mixtures.

also of importance. Moore and Kennedy (Refs 41 and 42), however, pointed out that fatigue life and air void content are both dependent variables whose values are determined by other mixture and construction variables.

Further discussions of mixture variables are presented by Deacon (Ref 7), Epps and Monismith (Ref 10), Pell (Ref 46), and Moore and Kennedy (Refs 41 and 42).

SUMMARY

Up to this time, the study of the fatigue characteristics of asphalt-treated materials has been conducted by investigators using different test methods, test conditions, and materials. Often these investigations report different fatigue characteristics of asphaltic materials. In order for these results to be more meaningful it would be desirable to explain or resolve these differences, especially with respect to the dynamic indirect tensile test, since it is proposed that the Texas Highway Department utilize the indirect tensile test to characterize and evaluate pavement materials because of the simplicity of the test and the fact that cylindrical specimens or cores can be tested.

Any relationships between results from different tests would be helpful when comparing mixtures tested on different machines, relating laboratory tests to field conditions, and providing consistent fatigue information for rational pavement design methods.

Having reviewed fatigue tests and variables, this report is now concerned with the evaluation and comparison of fatigue tests, with special emphasis placed on the results of the repeated-load indirect tensile test compared to other commonly used tests.

CHAPTER 3. METHOD OF ANALYSIS

As stated in Chapter 1, the primary objectives of this study are

(1) to compare fatigue results obtained using the repeated-load indirect tensile test with results obtained using other types of tests to determine whether the results are compatible, and

(2) to make a preliminary comparison of creep behavior and fatigue behavior.

To achieve the first objective, the analysis was divided into two basic parts: (1) consideration of the type of test and the state of stress and (2) consideration of other factors associated with testing and the mixtures tested. The repeated-load indirect tensile test was conducted as a part of this study; other fatigue data were obtained from the literature or from the investigator directly.

The second objective involved a comparison of fatigue and creep behavior obtained using the indirect tensile test and additional comparisons of data obtained from the literature.

EXPERIMENT DESIGNS AND APPROACH

Comparison of Fatigue Results

The evaluation and comparison of fatigue results obtained by various investigators using different tests was broken into consideration of the basic test and consideration of other test and materials factors.

Evaluation of type of test. One of the primary differences between tests is the state of stress produced in the specimen. In all major tests except the repeated-load indirect tensile test, the specimen is subjected to a uniaxial state of stress; in the indirect tensile test a biaxial state of stress is produced.

Since a complex state of stress does exist in the indirect tensile test, one of the combined stress theories should be used in comparing tests. Deacon (Ref 6) suggested the use of the maximum principal stress, the maximum shear stress, or the octahedral shear stress theory to analyze complex states of stress.

The maximum principal stress theory states that failure is caused by the maximum principal stress, which is normally a tensile stress. This theory neglects the effects of stresses on other planes. From a review of the results reported for multiaxial states of stress, it is evident that the maximum principal stress cannot account for the differences observed for uniaxial-stress and multiaxial-stress tests.

In the maximum shear stress theory, failure is related to the maximum shear stress, which is equal to one-half the difference between the maximum and minimum principal stresses. For the uniaxial state of stress, the maximum shear stress is one-half the axial tensile stress; in the case of the indirect tensile test the maximum shear stress is twice the horizontal tensile stress:

$$\sigma_c = -3\sigma_t$$

$$\tau_m = 1/2(\sigma_t - \sigma_c) = 2\sigma_t$$

The octahedral shear stress relates failure to the octahedral shear stress developed in the specimen. The octahedral shear stress is defined as

$$\tau_{oct} = 1/3\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

where

σ_1, σ_2, and σ_3 are the principal stresses.

In the uniaxial case, σ_2 and σ_3 are zero so $\tau_{oct} = \frac{\sqrt{2}}{3}\sigma_1 = .47\sigma_1$. In the case of the indirect tensile test, $\sigma_1 = \sigma_t$, $\sigma_2 = 0$, and $\sigma_3 = \sigma_c$, so $\tau_{oct} = \frac{\sqrt{26}\,\sigma_1}{3} = 1.7\sigma_1$.

Comparison of fatigue results possibly should be in terms of the maximum shear stress or the octahedral shear stress theory; however, there is very little difference between the two theories for the states of stress developed in most tests. The maximum shear stress theory says that the tensile stress in the indirect tensile test is approximately four times the uniaxial tensile stress, while the octahedral shear stress theory says the indirect tensile stress is approximately 3.6 times the uniaxial tensile stress. The difference between the two theories is usually less than 15 percent for most states of stress; in the specific cases of a uniaxial state of stress and the biaxial state of stress developed in the indirect tensile test, the difference is approximately 10 percent. This difference is not significant, especially when the tremendous scatter in fatigue results is considered. Therefore, either theory could be used and the decision as to which to utilize should be based on practicality.

In the triaxial testing of soil and asphaltic mixtures (Refs 9 and 43), the usual practice is to evaluate combined stresses in terms of a Mohr circle theory of stress, which is an application of the maximum shear stress theory. The combined stresses are reported in terms of deviator stress or stress difference, which is the maximum principal stress minus the mimimum principal stress $(\sigma_1 - \sigma_3)$, which is equal to twice the maximum shear stress. Figure 20 illustrates two Mohr circles, one for the case of uniaxial tension and the second for a biaxial state of stress for indirect tension with tension in one axis and compression in the other axis. The maximum shear stress is one-half the stress difference; however, neither the stress difference nor the maximum shear stress is directly related to the maximum tensile stress.

Because stress difference is commonly used for comparisons involving combined stresses, stress difference will be used to evaluate the state of stress for the more commonly used fatigue tests.

Evaluation of Other Factors

Many of the other factors which affect fatigue results have not been explained theoretically and there are limited data available for making an evaluation. Therefore, the selected approach was to conduct a regression analysis on existing fatigue results to quantitatively relate certain factors to the effect on fatigue life produced by these factors.

The intent was not to explain the effects or determine the cause of the observed behavior but to develop a tool which hopefully could be used to relate fatigue results obtained using different tests, test techniques, and materials. The resulting equation was used to predict fatigue behavior for comparison with test results not used in the regression analysis.

As preparation for the regression analysis, the significant factors affecting fatigue were determined from a review of the literature, and a list of important factors was compiled. From this list the following factors were chosen for evaluation in the regression analysis: asphalt content, asphalt penetration (viscosity), temperature, percent air voids, principal stresses, load duration, rest periods, frequency and loading wave shape. Factors such as aggregate type, aggregate gradation, which could not be easily quantified, were not included. Only data which involved all the selected factors were used in the analysis.

A stepwise multiple linear regression program (The University of Texas Center for Highway Research Program STEP01) was used to analyze the data. In the analysis, log N_f was the dependent variable and the relevant factors and combinations of factors were independent variables. The program examines all independent variables and enters the variable which is the most highly correlated with log N_f. The remaining variables are then examined and the next most highly correlated variable is entered into the equation and all previously entered variables are checked to determine whether the newly entered variable has reduced their significance. If the significance of a previously entered variable is reduced below a certain value it is removed from the equation. This process is continued until the addition of a new variable does not significantly improve the equation. By using the regression program only the highly relevant factors which adequately described fatigue life were used in the regression equation.

To evaluate the resulting regression equation, an independent set of data was compared with values predicted using the regression equation.

Comparison of Creep and Fatigue Behavior

The investigation and evaluation of the relationships between creep and fatigue behavior were conducted in two parts.

(1) The creep behavior and fatigue behavior of duplicate specimens tested in indirect tension were compared and evaluated.

(2) The creep behavior and fatigue behavior of specimens tested in flexure by Majidzadeh et al (Ref 28) were compared and related to the behavior in indirect tension.

Indirect tensile creep and fatigue behavior. Eight identical specimens were prepared and subjected to constant indirect tensile stresses. Two specimens were subjected to each of the following tensile stresses: 16, 24,

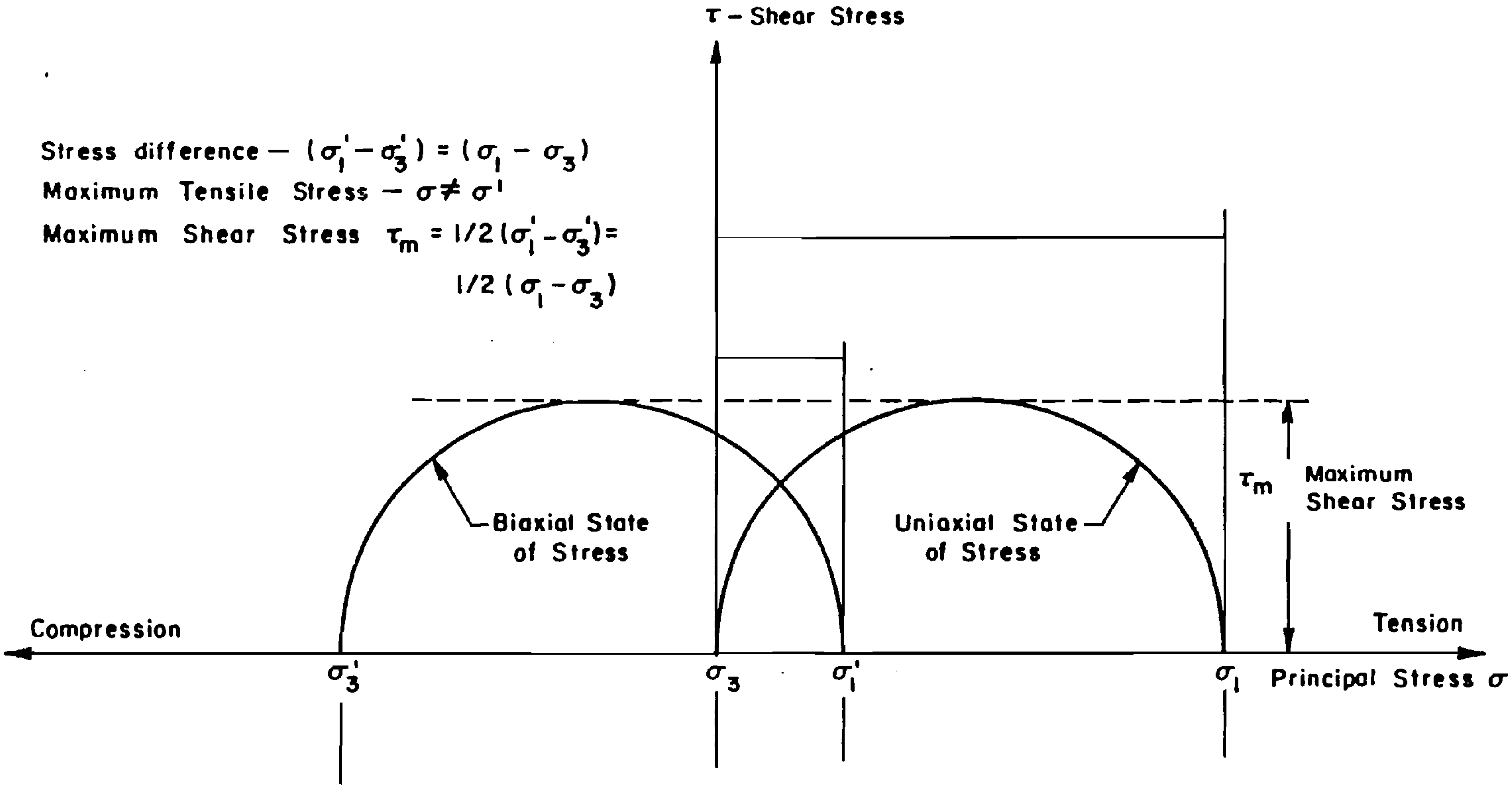


Fig 20. Mohr circle states of stress.

32, and 40 psi. These correspond to stress differences of 64, 96, 128, and 160 psi. Deformations with respect to time were recorded until the specimens failed.

The resulting indirect tensile creep deformation relationships and the times to failure were compared to the repeated indirect tensile test deformation relationships and the fatigue life relationships $(S-N_f)$ in order to develop techniques for estimating fatigue behavior from creep relationship. The basic design of the experiment is shown in Fig 21.

Indirect tensile and flexural creep and fatigue behavior. An additional evaluation was conducted to compare the indirect tensile fatigue and creep behavior with the flexural fatigue and creep behavior reported by Majidzadeh. This evaluation was made to provide additional knowledge as to whether a meaningful relationship exists between fatigue and creep.

METHODS OF TEST

Fatigue Tests

The study was limited to controlled-stress tests which had been used extensively and, therefore, for which large quantities of data were available for comparison with the results of the repeated-load indirect tensile test (Refs 41 and 42). These tests were the uniaxial test (Refs 52 and 53), the flexural test (Refs 33, 37, and 38), and the rotating cantilever test (Refs 48 and 50).

Repeated-Load Indirect Tensile Test

The repeated-load indirect tensile test involves loading a right cylindrical specimen along two opposite diametral generators with repeated compressive loads as shown in Fig 5. A rigid stainless steel loading strip which is curved at the interface with the specimen and has a 2-inch radius was employed to transmit the compressive load to the specimen in order to maintain a constant loading area. This loading configuration develops a relatively uniform tensile stress perpendicular to the directions of loading and along the vertical diametral plane through the center of the loading strips. Hondros (Ref 17) analyzed a circular specimen subjected to loading through a narrow strip, assuming that the body forces were negligible, and developed equations for the resulting stresses. Based on these equations, the tensile stress in the center of the specimen is given by

Tensile Stress, psi	Stress Difference, psi	Number of Specimens	
		Creep	Fatigue
16	64	2	8
24	96	2	5
32	128	2	5
40	160	2	5

Fig 21. Summary of experiment to compare creep and fatigue behavior using the indirect tensile test.

$$\sigma_t = \frac{2P}{\pi ah} (\text{Sin } 2\alpha - \frac{a}{2R}) \qquad (2.1)$$

where

σ_t = indirect tensile stress, in psi;

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

a = width of the loading strip, in inches;

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

2α = angle at the center of the specimen subtended by the width of the loading strip, in radians;

R = radius of the specimen, in inches.

The basic testing apparatus was a closed-loop electrohydraulic loading system operating in the controlled-stress mode. The actual loading device was a commercially available die-set modified to accept the loading strips in the upper and lower platens (Fig 6, p 13). The data were recorded using a two-channel strip chart recorder, an analog-digital recorder, and a digital voltmeter.

The load pulse was controlled with a strain-gage type load cell and was varied in magnitude pulsewise by combining the signals from two frequency generators. A frequency of 1 Hz was selected, with a 0.4-second pulse time and a 0.6-second rest time. Figure 8 (p 16) shows a representative load pulse with the associated vertical and horizontal deformations. The data which were recorded with the analog-digital device can be reproduced graphically to give the plots shown in Fig 9 (p 17) if the individual cyclic deformation is superimposed on the permanent deformation information. Although both individual cyclic information and total or permanent data were recorded for all specimens tested, only fatigue life data are considered in this investigation.

Other Tests

This section provides a brief description of the fatigue tests used in the regression analysis. Further information concerning these tests can be found in Chapter 2 and the cited references.

Uniaxial test. Raithby and Sterling (Refs 52 and 53) performed fatigue tests using direct tension and compression axial loading. Load was applied through loading caps epoxied to the ends of the specimen.

Flexural test. Monismith et al (Refs 33, 37, and 38) used the controlled-stress flexure apparatus developed by Deacon (Ref 6). Two-point loading (Fig 2, p 7) was employed and the pneumatic type loading system applied a return load to force the specimen back to its original undeflected position.

Rotating cantilever. A rotating cantilever test was used by Pell et al (Refs 48 and 50). The necked cylindrical specimens were fixed to a rotating shaft at the bottom and load was applied through a wire at the top (Fig 4, p 10).

Creep Tests

The loading configuration for the indirect tensile creep test was identical to the configuration for the indirect tensile fatigue test except that a constant load was used in the creep test.

The flexural creep test of Majidzadeh et al (Ref 28) applies a constant load to the center of a simply supported beam.

MATERIALS AND SPECIMEN PREPARATION

A variety of mixtures and specimen preparation techniques were involved since the majority of the data was obtained from the literature. The materials and preparation techniques are briefly summarized below. Further information concerning mixture compositions can be found in Appendix A.

Fatigue and Creep Indirect Tensile Tests

In the fatigue study, two different aggregate types were used, a crushed limestone and a smooth river gravel. Each aggregate was separated and recombined to produce the gradation curve shown in Fig 22. The aggregate-asphalt mixtures were prepared with various asphalt contents using an AC-10 (88 pen) asphalt cement from the Cosden Refinery, Big Spring, Texas . Table 9 gives the pertinent physical information on this asphalt cement. The aggregates and asphalt cement were combined by a mechanical mixer at a temperature of 300°F with a mixing time of three minutes (Appendix C). The mixture was then compacted, using the Texas Gyratory-Shear Compactor, into specimens nominally 2 inches in height and 4 inches in diameter. The specimens were then cured for two days at room temperature, 75°F.

TABLE 9. CHARACTERISTICS OF COSDEN ASPHALT CEMENT AC-10

Water, %	Nil
Viscosity at 275°F, stokes	2.45
Vixcosity at 140°F, stokes	940
Solubility in CCl_4, %	—
Flash point C.O.C., °F	585
Ductility, 77°F, 5 cm/min., cm	—
Pen at 77°F, 100 g, 5 sec.	88
Tests on residues from thin film oven test:	
Viscosity at 140°F, stokes	2052
Ductility at 77°F, 5 cm/min., cms.	141+
Res. pen 77°F	52
Original specific gravity 77°F	1.031

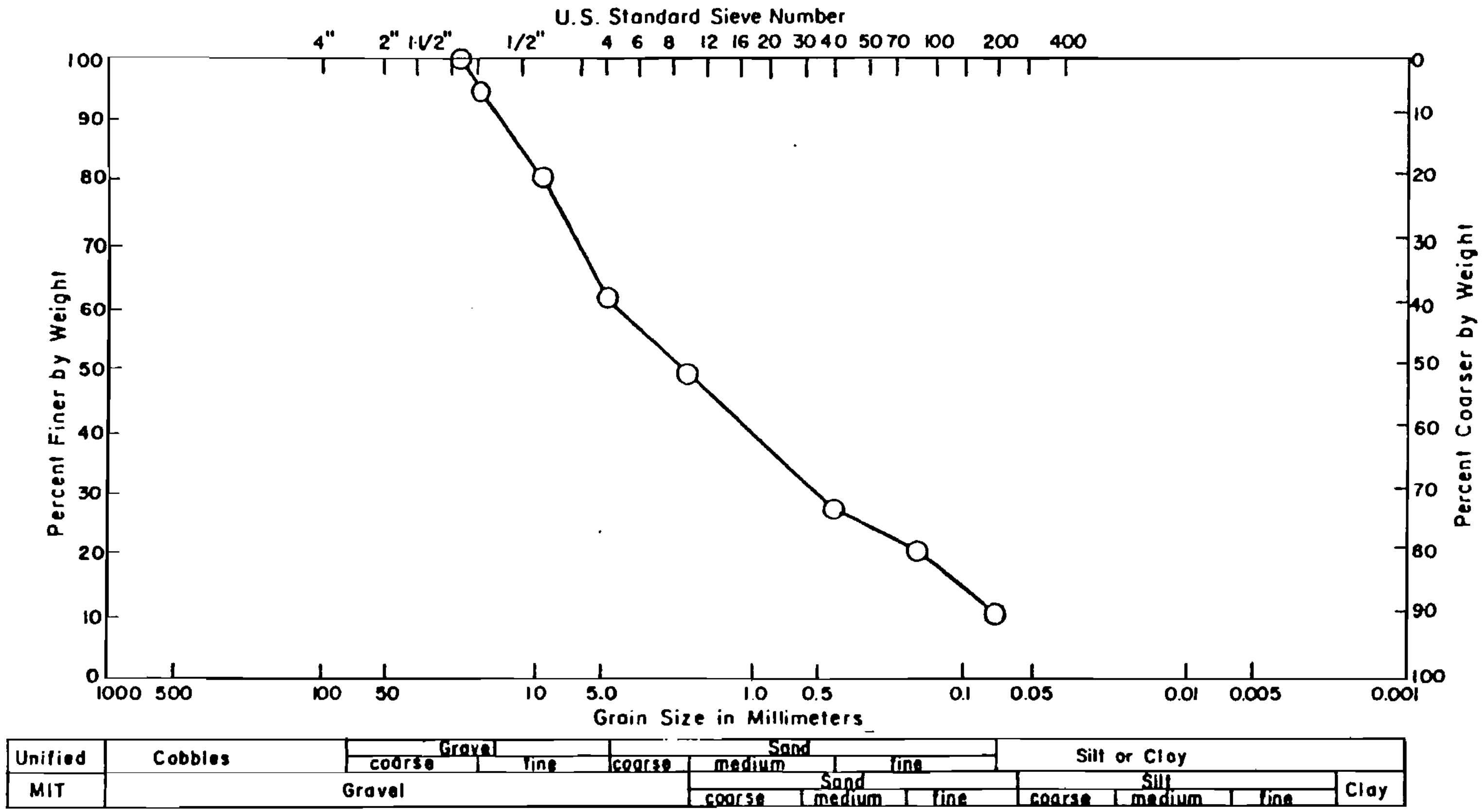


Fig 22. Gradation of aggregate used in the indirect tensile experiment.

The creep tests used specimens identical to the fatigue specimens except that only one mixture was compared. The creep specimens were composed of limestone aggregate and had an asphalt content of 7 percent.

Uniaxial Fatigue Tests

The uniaxial tests were conducted by Raithby and Sterling (Refs 52 and 53) and involved a mixture containing crushed porphyry aggregate. The specimens were sawed out of a layer constructed using a full-scale mixing plant, paver, and road roller.

Flexural Fatigue Tests

A variety of crushed basalt, limestone, granite, and gravel aggregate, each of fine, medium, and coarse gradation, was used by Monismith et al (Refs 6, 33, 37, and 38) in the preparation of flexural test specimens. These specimens were prepared using a kneading compactor and then sawed to final shape.

Rotating Cantilever Fatigue Tests

The mixtures used by Pell et al (Refs 48 and 50) in the rotating cantilever test usually conformed to British Standard 594 and contained siliceous river gravel or crushed porphyry rock. The specimens were shaped in a split mold by hand tamping and then compressing the hot mixture in a hydraulic press.

Flexural Fatigue and Creep Tests

Majidzadeh et al (Ref 28) used an asphalt with a penetration value of 63. The specimens contained 6 percent asphalt and a well-graded Ottawa sand. The specimens were compacted into a mold using a drop hammer.

Other Fatigue Data

Fatigue data not used in the fatigue analysis were used to check the regression equation. The test methods used are reported in Appendix B and are a four-point flexure test (Ref 23), a cantilever test (Ref 58), a triaxial test (Ref 15), and a flexural mid-span load test (Ref 28). The data were derived from tests using different asphalt mixtures, testing temperatures, and testing methods. Much of the variation in the data is due to the fact that several of the data points are single fatigue test results and not averages of several tests. The additional data in some cases had significant parameters in terms of the regression equation which were not reported in the same detail as the original data. For example, the type of asphalt would be reported as an 80-100 penetration asphalt; in lieu of an accurately measured value, the penetration value was considered to be 90.

CHAPTER 4. DISCUSSION OF RESULTS

The results and findings of the comparison of fatigue tests and the preliminary study of the relationships between fatigue behavior and creep behavior are discussed in this chapter.

COMPARISON OF FATIGUE RESULTS

Evaluation of Type of Test

The review of the more important tests used for fatigue studies indicated that one of the major differences between the indirect tensile test and other fatigue tests is the state of stress developed in the specimen, suggesting that if the biaxial state of stress in the indirect tensile test is considered the differences in results can be explained. The chosen method of accounting for the biaxial state of stress is to express the applied stress in terms of stress difference.

Figure 23 contains the data from Fig 10 except that the applied tensile stress is expressed in terms of stress difference. For the indirect tensile tests, stress difference is approximately equal to $4\sigma_T$ while the stress difference for the uniaxial stress is equal to the applied stress. As seen in Fig 23, the differences in the results were greatly reduced. Expressing the applied indirect tensile stress in terms of stress difference merely shifts the position of the stress-fatigue life relationship and does not change the slope. Therefore, the values of K_2 are significantly increased while the values of n_2 are not affected. The K_2 values for the repeated-load indirect tensile test, which had ranged from 6.19×10^5 to 2.04×10^{10}, were increased to a range of 2.15×10^7 to 1.46×10^{13}, which more closely lies within the range of the other tests in Table 1 (6.01×10^{10} to 2.24×10^{21}). Nevertheless, relatively large differences still exist. However, the relationships from the results of Raithby and Sterling and from the indirect tensile test results, both obtained at about 75°F, are essentially the same. Thus, it appears that a large portion of the differences in fatigue results can be explained

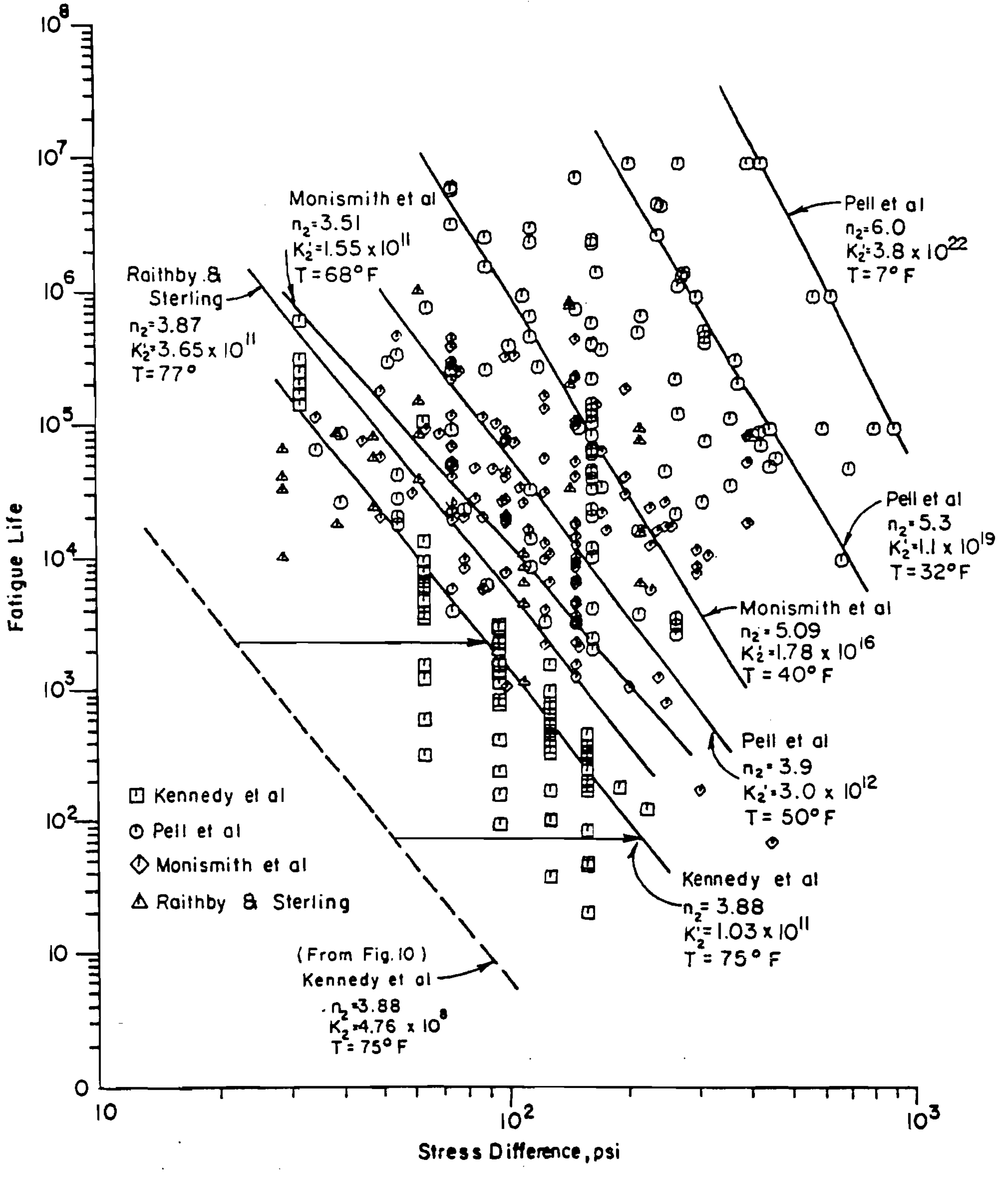


Fig 23. Typical stress difference-fatigue life relationships for various test methods.

in terms of stress difference and that the results from the indirect tensile test are compatible with the results from other commonly used uniaxial tests. The remaining differences would probably be reduced if other factors (temperature, load pulse, mixture variables, etc.) were the same.

It has been theorized by Pell (Ref 46) that much of the variation caused by state of stress, temperature, and mixture can be explained by considering strains. Strain-fatigue-life relationships have been shown to be fairly independent of mixture and temperature factors but Pell and Cooper (Ref 51) have shown that strain-fatigue-life relationships are not the same for different test methods. Therefore strain-fatigue-life relationships were not evaluated in this study. However, as more data become available it may be possible to use these relationships to compare fatigue testing methods.

Evaluation of Other Factors

Since many of the factors affecting fatigue behavior cannot be theoretically explained because there are limited data available for evaluating their effects, a regression analysis was performed on existing fatigue data in an attempt to provide a means of relating the fatigue results obtained using different test methods and materials.

Regression analysis. A multiple linear regression analysis was performed using the previously reported fatigue data in order to develop a regression equation capable of transforming the data from one set of conditions to another or for predicting fatigue life. The factors used in the analysis were selected because they have been shown to affect fatigue behavior (Chapter 2). The tests were the uniaxial, flexure, rotating cantilever, and repeated-load indirect tension fatigue tests. All data are compiled in Appendix A. Most factors were considered to vary linearly except where previous investigators had shown nonlinear effects or interactions. The resulting equation was

$$\begin{aligned}\log \hat{N}_f = {} & 13.2424 - 3.4190 \log SD - .07899T + \\ & .9226(PCA) - .04795(PCA^2) - .02616(AP) + \\ & .0003621T(AP) - 1.4325(TD + TR) \end{aligned} \qquad (4.1)$$

where

$\hat{N}_f$ = estimated fatigue life,

SD = stress difference = applied stress for uniaxial tests,
T = testing temperature, °F,
PCA = percent asphalt cement,
AP = penetration of asphalt cement,
TD = duration of tensile stress, seconds,
TR = rest period after a tensile stress, seconds.

The above regression equation had a multiple correlation coefficient R of 0.90, a coefficient of determination R^2 of 0.81, and a standard error of residuals of 0.52. The relationship between the measured values and the estimated value of fatigue life is shown in Fig 24.

Assuming that the regression equation is valid, it would be possible to compare fatigue tests for the same conditions. Figure 25 illustrates the relationship between stress difference and estimated fatigue life for the standard set of conditions shown. Naturally, the scatter in Fig 23 was greatly reduced in Fig 25 since a regression analysis generates an equation which reduces variation as much as possible. The scatter which does exist could possibly be explained by the fact that aggregate type and aggregate gradation could not be quantified and therefore were not included in the analysis and in the regression equation.

Evaluation of regression equation. A regression analysis forces an equation to conform to a set of data. Therefore, it is possible for the equation to closely describe the data used in its derivation but not necessarily follow the trends in the population from which the data were taken. The data used in the regression analysis were not selected in a random, or a representative, manner. For example, only 26 data points were obtained from the axial load test while 110 data points were used from the rotating cantilever test. Obviously, the rotating cantilever test influenced the regression equation more than the axial load test. In addition, it is necessary to compare values estimated, or predicted, by the regression equation with measured values from an independent set of data not used to derive the equation in order to provide limited verification of the equation.

Fatigue data (Fig 26), which were obtained from a cantilever test, a centerpoint loading flexure test, and a triaxial test and which were not used to develop the regression equation, were corrected to the same set of conditions, using the regression equation (Fig 27). Much of the scatter in the

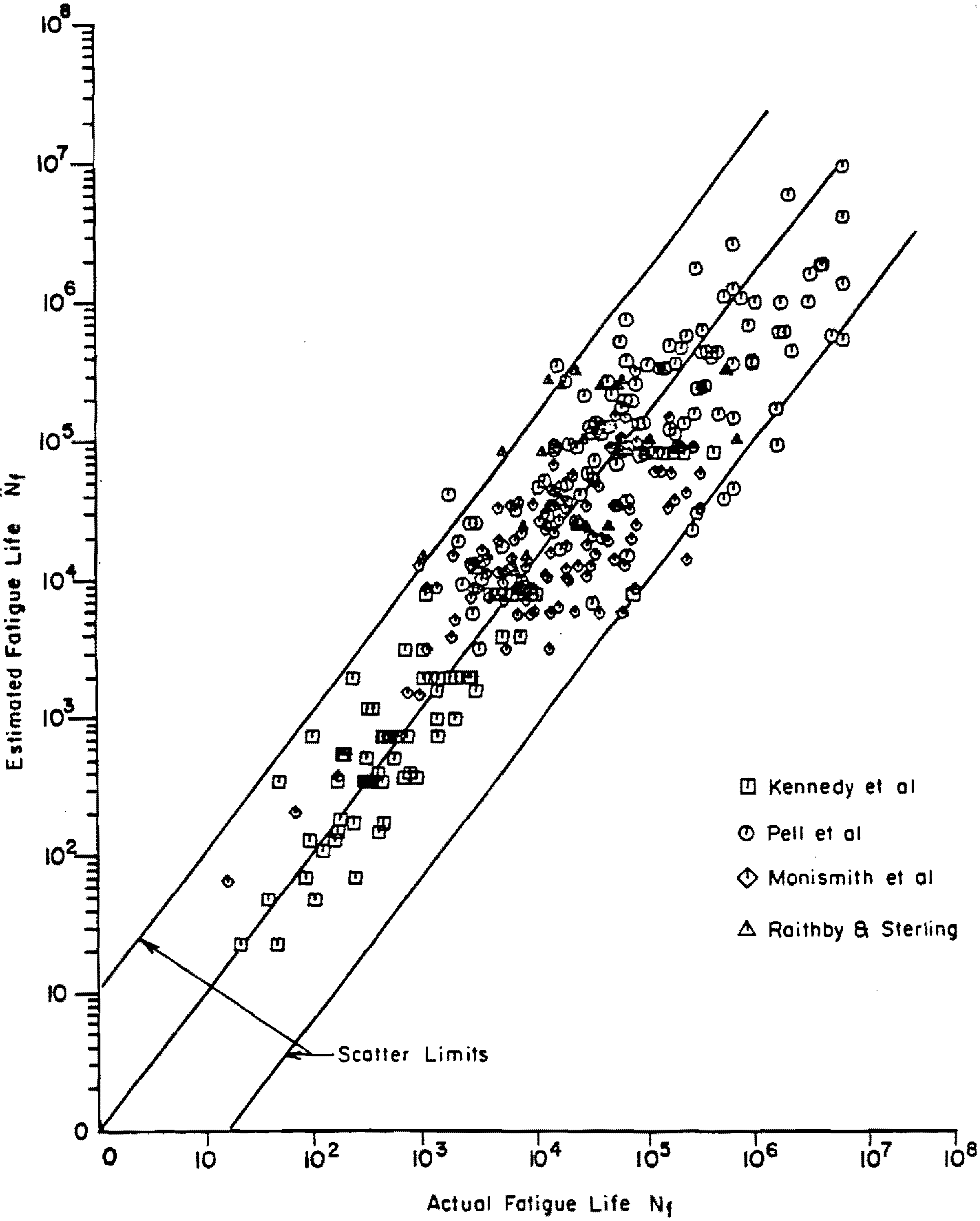


Fig 24. Comparison of actual and estimated fatigue lives.

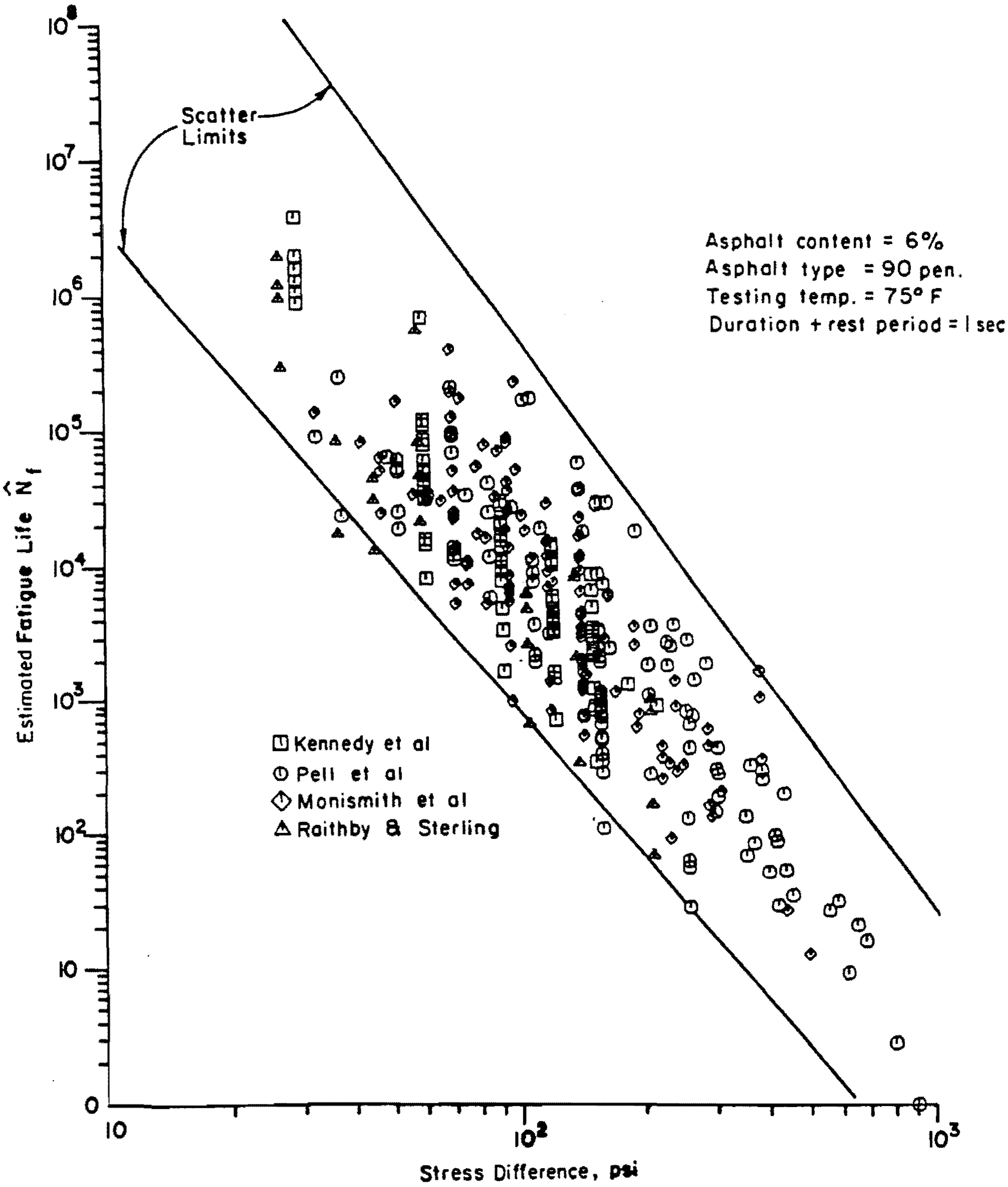


Fig 25. Relationship between stress differences and fatigue lives corrected to a standard set of conditions.

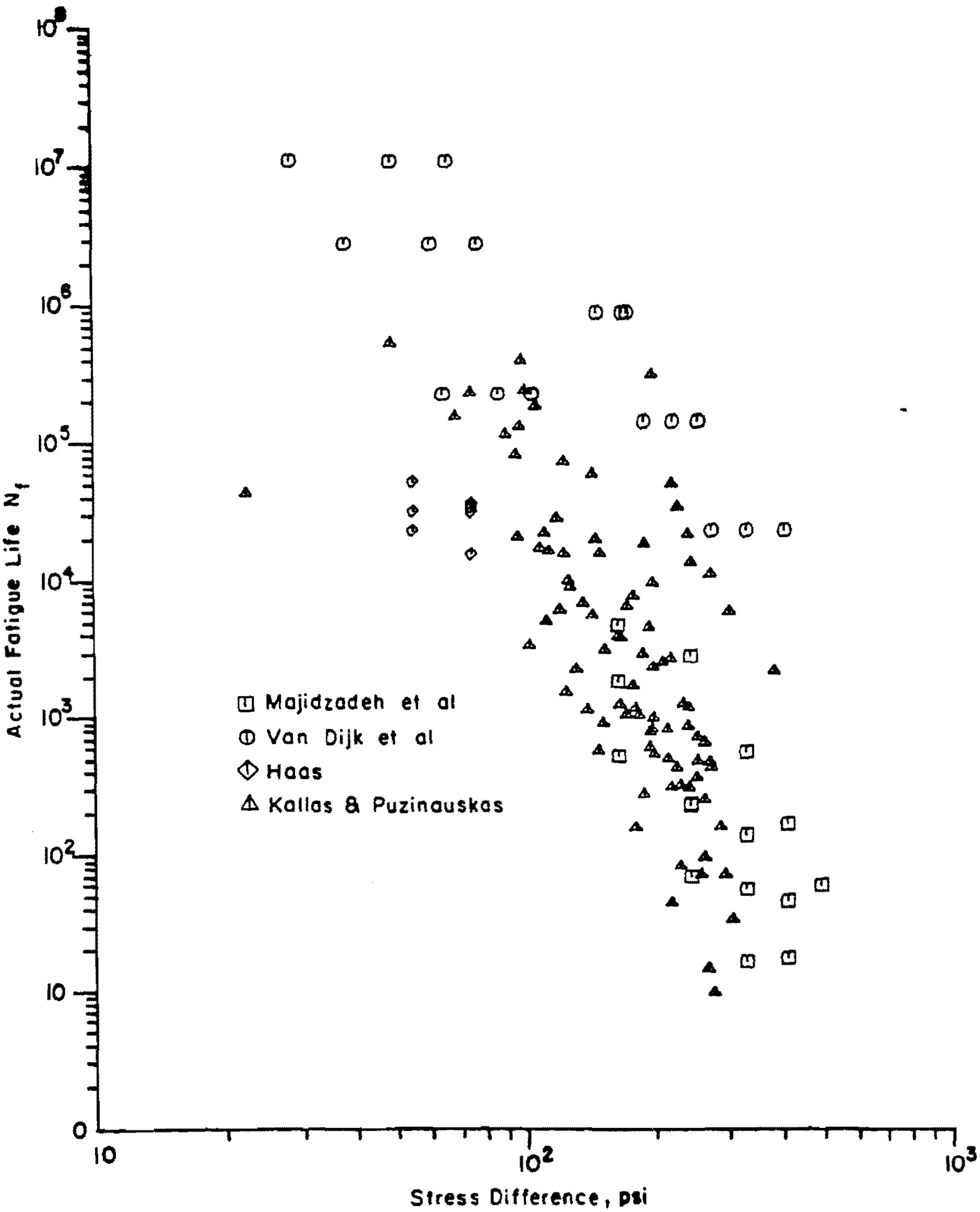


Fig 26. Relationship between stress differences and fatigue lives for data used to evaluate the regression equation.

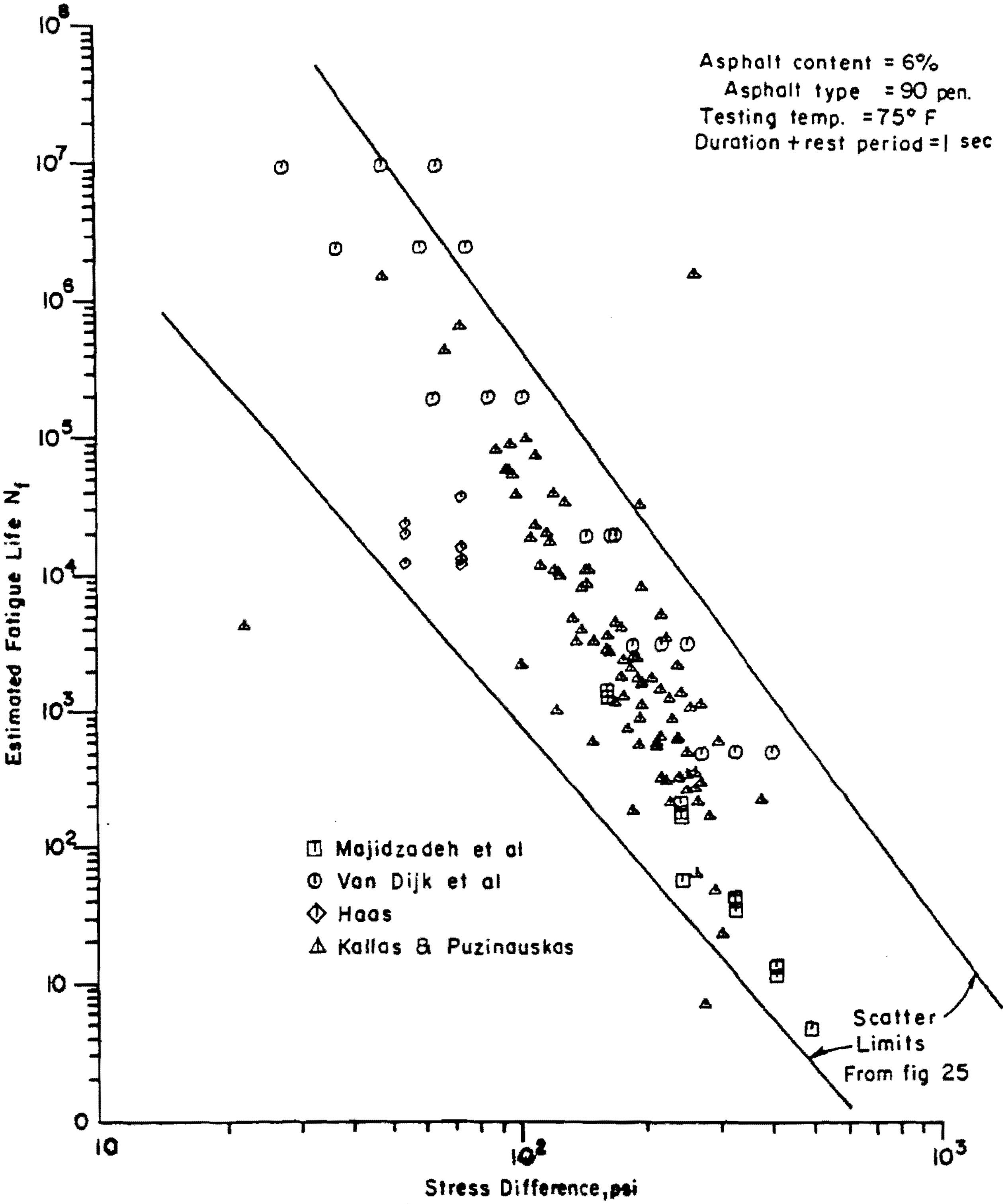


Fig 27. Relationship between stress difference and estimated fatigue life for independent data corrected to the same set of conditions.

data has been reduced and the independent data points lie within the scatter band derived from the original data in Fig 25. Figure 28 shows the actual versus the estimated fatigue life. The data in Fig 28 seem to have a slope a little different than that predicted by the regression equation. However, the predicted data are within limits of the lines taken from the original data in Fig 24.

Since the regression equation reasonably models this independent set of data, the analysis seems to be free of major defects. The regression equation has therefore provided a quantitative measure of the effect of the factors contained in the regression equation.

Effects of temperature, asphalt content, and asphalt penetration. The effects of temperature, percent asphalt, and asphalt penetration were found to follow trends previously established by other investigators. For controlled-stress loading, decreasing temperature increased fatigue life; increasing asphalt penetration decreased fatigue life; and increasing asphalt content causes fatigue life to increase up to a point and then decrease. The nonlinear effect of asphalt content is denoted by the percent asphalt squared term (PCA^2) in the regression equation.

An interaction between temperature and asphalt penetration was found in the analysis. This interaction indicates that the effects of temperature and the viscosity of the asphalt are dependent on the level of the other factor.

Effect of load factors. A great many loading variables were considered in the regression analysis. Such factors as frequency, load duration, rest period, and shape of the loading pulse and many combinations of these variables were included in the study. The regression analysis indicated that a single variable was the best predictor of fatigue life for the data analyzed. This variable was the sum of the tensile load duration and the length of the rest after the tensile load (TD + TR). This variable is related to load duration, rest period, and frequency. The only test used in the analysis which consistently had a rest period after a tensile load was the dynamic indirect tensile test. The other test methods either applied a compressive load without a rest period or applied a compressive load to eliminate creep deformation prior to the rest period.

Effect of air void content. The air void content was not a significant variable in the regression equation, indicating that the effect of air voids

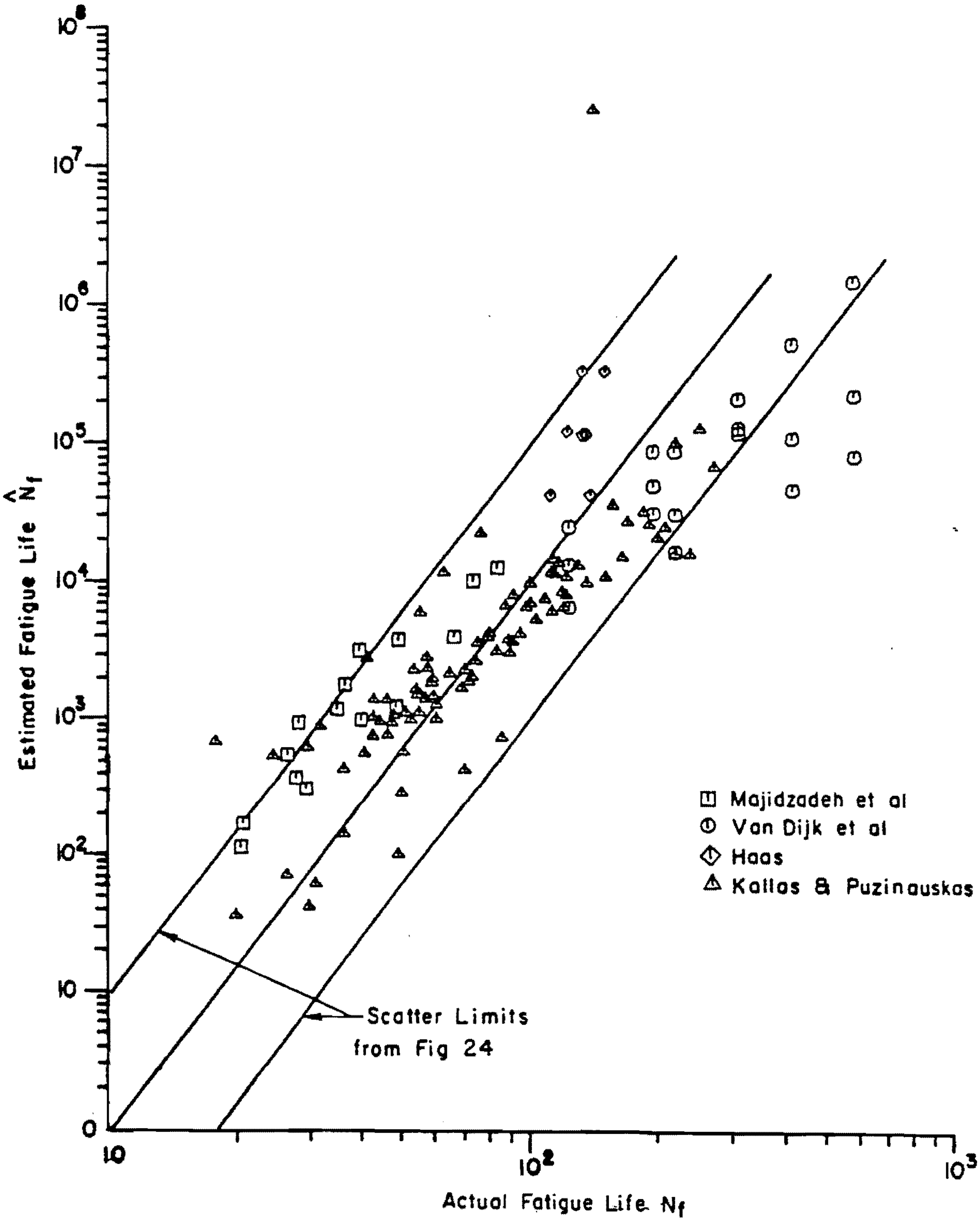


Fig 28. Comparison of actual and estimated fatigue lives of the independent data.

was not as important as the effects of other variables in the regression equation.

Previous investigators have shown that decreasing air void content increases fatigue life (Table 7). However, Moore and Kennedy (Refs 41 and 42) found no relationship between air void content and fatigue life and concluded that for the same basic mix a relationship might exist but that for a variety of mixes other factors are more important and that air void content and fatigue life are dependent on other mixture variables already included in the regression equation. It is also possible that the lack of significance in the regression analysis may be due to the fact that different investigators measured and calculated voids using different methods so that different results could have been derived for the same void content.

COMPARISON OF CREEP AND FATIGUE

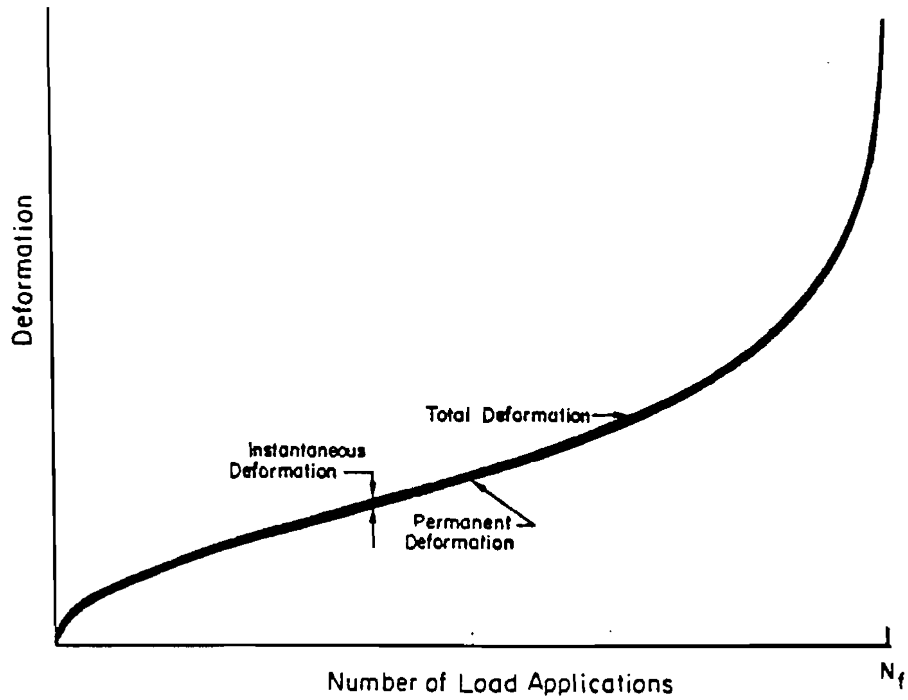
Creep and fatigue tests performed in indirect tension were compared and evaluated. The results for a similar flexural experiment performed by Majidzadeh et al were then compared.

Indirect Tension

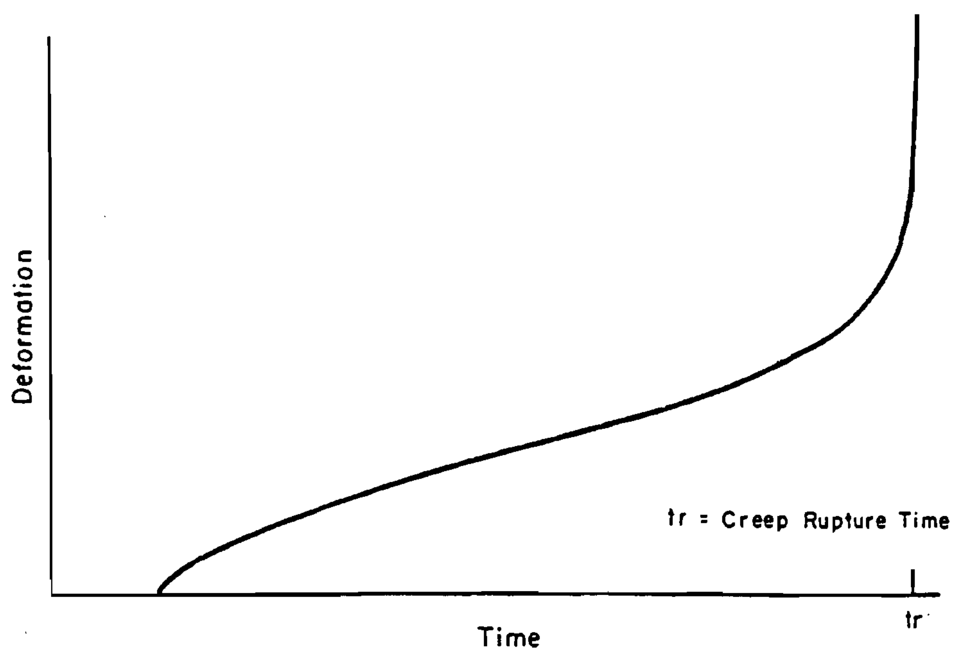
In this study, duplicate specimens were tested at the same stress levels using the repeated-load indirect tensile test and creep indirect tensile test. Repeated-load performance deformations, creep deformations, creep rupture times, and fatigue life were measured.

Deformations. Typical creep and fatigue permanent deformation curves are shown in Fig 29 and the actual relationships are contained in Appendix D. The deformation curves are very similar, the only major difference being the initial instantaneous deformations occurring due to repeated loading. The similar shapes of the curves indicate the possibility of a relationship between fatigue and creep. A comparison of the fatigue and creep deformations did not yield a relationship or a definite conclusion, possibly due to the scatter in the data and the small number of specimens tested. While this brief initial study did not result in any deformation relationships, it is believed that further investigation could result in a relationship between creep and fatigue deformations and that additional study is warranted.

Creep rupture time and fatigue life. The creep rupture times and fatigue



(a) Permanent deformation for repeated loading.



(b) Creep deformation.

Fig 29. Comparison of creep and fatigue deformations in indirect tension.

lives from the indirect tensile creep and fatigue experiment are shown in Table 10. The relationship between fatigue life and creep rupture time was linear (Fig 30) and indicated that fatigue life was approximately 6.5 times the creep rupture time in seconds.

Flexure of Majidzadeh et al and Indirect Tension

Figure 19 shows the fatigue and creep data reported by Majidzadeh et al (Ref 28). These data were taken from Fig 19 and are listed in Table 11. It was found, Fig 31, that two relationships between fatigue life and creep rupture time existed, one for 32°F and one for 50°F. The scatter was greater in these relationships than in the indirect tensile test comparison. Also, the slopes of the lines were different, with 2.3 for 32°F and 4.3 for 50°F as compared to 6.5 at 75°F for the indirect tensile tests.

When comparing the creep and fatigue results between the indirect tensile and flexure tests two problems were encountered. First, the tests were conducted at different temperatures and, second, the loading frequencies and waveforms were different. Since the difference between creep, indirect tensile fatigue, and flexural fatigue is the method of loading, it was hoped that all three tests could be explained in terms of a loading variable. The previous repeated-load regression analysis indicated that the only significant loading variable was tensile load duration and rest after a tensile load (TD + TR). Since TD + TR cannot be determined directly for creep, a creep equivalent of TD + TR, designated TC, was developed. Since the difference between the creep equivalent TC and the fatigue parameter TD + TR would be proportional to the difference between the logarithm of creep rupture time and the logarithm of fatigue life, the following relationship can be expressed:

$$\log N'_f - \log (tr) = C\ (TD + TR) - TC \qquad (4.2)$$

where

N'_f = fatigue life,

tr = creep rupture time,

TD + TR = fatigue tensile load duration plus rest period after the tensile load duration,

TC = creep equivalent of TD + TR,

C = coefficient,

TABLE 10. INDIRECT TENSILE CREEP AND FATIGUE RESULTS

Tensile Stress, psi	Stress Difference, psi	Creep Rupture Time tr, sec	Log Average of Creep Rupture Time tr	Fatigue Life N_f	Log Average of Fatigue Life N_f	Fatigue Life N'_f Estimated Using Eq 4.5
16	64	1177 1344	1258	8909 8441 7172 6498 6041 6800 11801 11093	8117	8352
24	96	279 221	248	1942 1645 1405 1812 1412	1629	1647
32	128	87 124	104	569 695 612 488 512	571	690
40	160	52 48	50	475 273 287 333 315	330	332

TABLE 11. FLEXURE CREEP AND FATIGUE RESULTS FOR MAJIDZADEH ET AL (REF 28)

Tensile Stress*	Temperature, °F	Creep Rupture Time tr, sec	Fatigue Life N_f	Fatigue Life N'_f Estimated Using Eq 4.5
248	32	1384	3020	1868
330		428	602	578
413		174	178	235
495		81	62	109
165	50	480	1995	1262
248		87	251	229
330		25	58	66

*Tensile Stress = Stress Difference

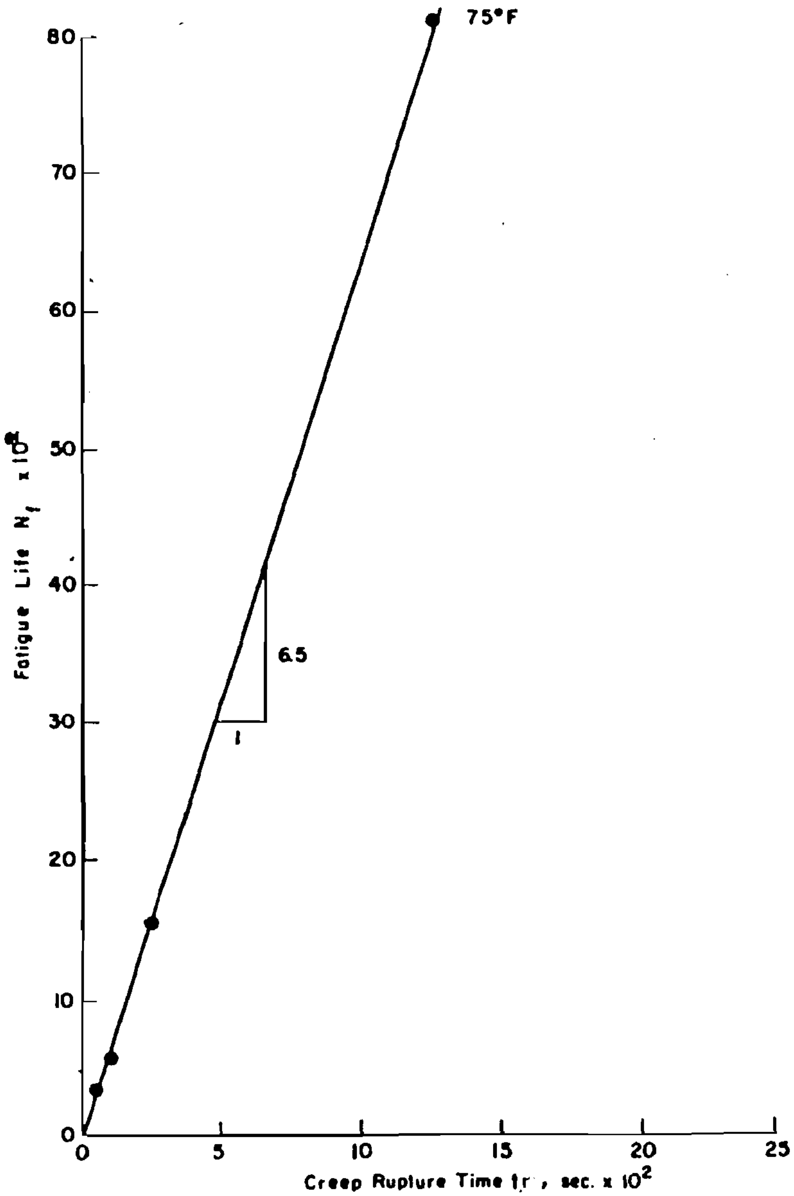


Fig 30. Relationship between fatigue life and creep rupture time for indirect tensile test.

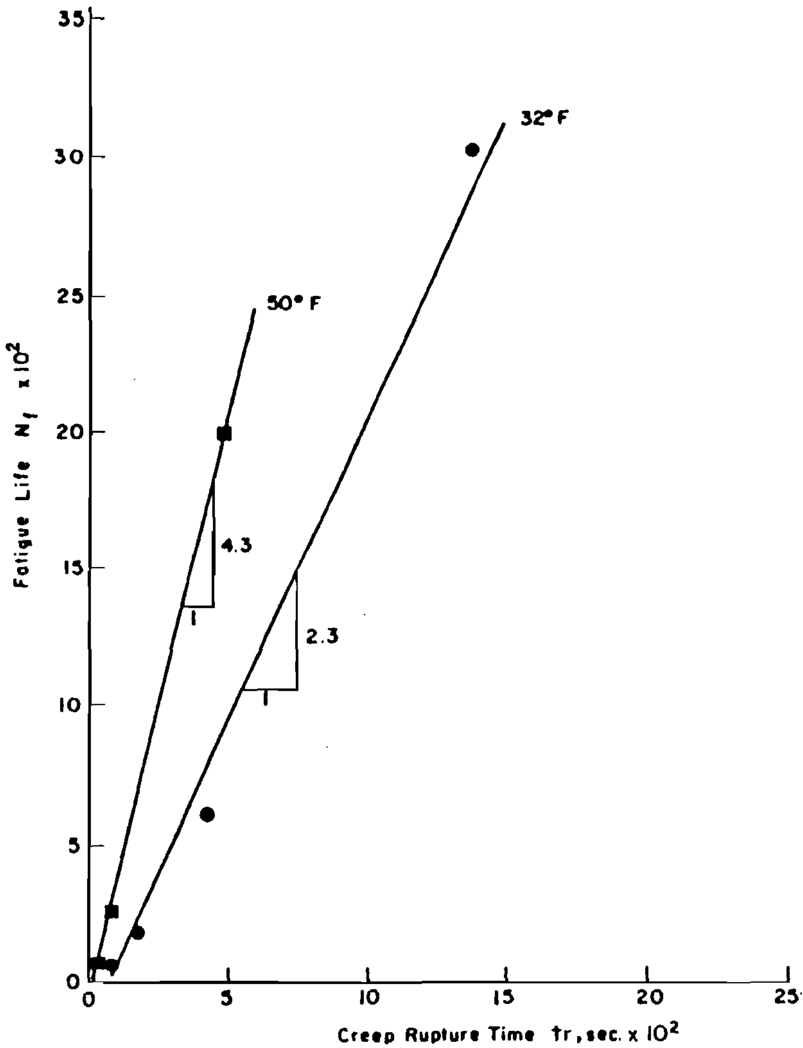


Fig 31. Relationship between fatigue life and creep rupture time for flexure test.

Since the effect of TD + TR was included as the last term in Eq 4.1, the coefficient for this term was substituted for C, yielding a modification of Eq 4.2:

$$\log N'_f = \log tr - 1.4325\ (TD + TR) - TC \tag{4.3}$$

Using Eq 4.3 and the data in Tables 10 and 11, a creep equivalent (TC) was computed for each temperature and it was found that TC was temperature dependent and could be expressed as follows:

$$TC = .7315 + 0.1123T \tag{4.4}$$

where

T = temperature in °F

Thus, a value of TC was developed which related creep rupture time to fatigue life for both flexural and indirect tensile loadings.

By combining Eqs 4.3 and 4.4, an equation to predict fatigue life from creep rupture time was developed:

$$\log N'_f = \log tr - 1.4325(TD + TR) + .01609T + 1.0478 \tag{4.5}$$

where

N'_f = predicted fatigue life for a given load impulse characterized by TD + TR and

tr = creep rupture time.

A comparison of measured fatigue lives and fatigue lives predicted using Eq 4.5 is shown in Fig 32. While this equation produced remarkable results, other factors could influence the prediction of fatigue life. Nevertheless, the ability of the creep equivalent TC to predict fatigue indicates a close relationship between fatigue and creep and suggests the need for additional study.

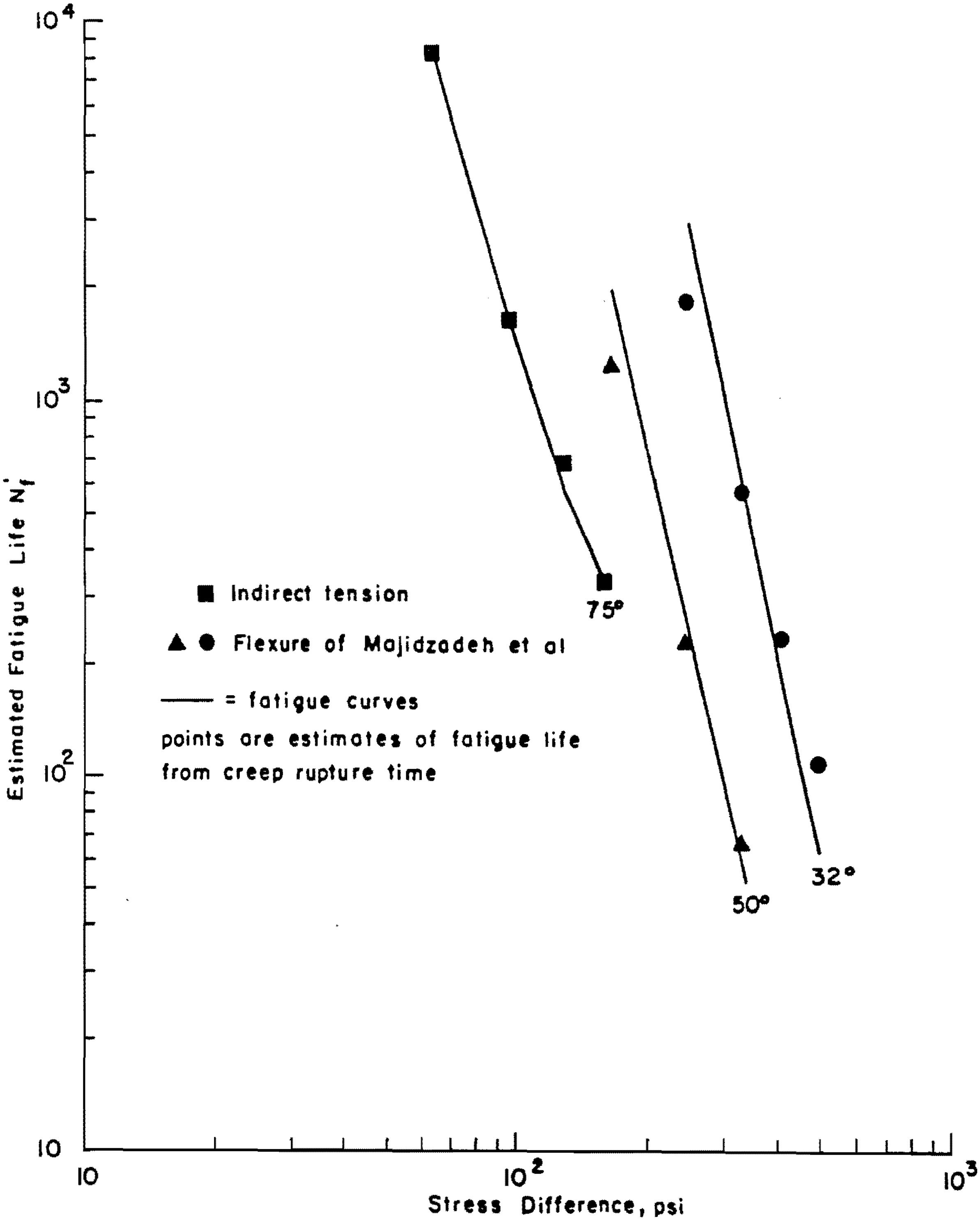


Fig 32. Stress difference-fatigue life relationships estimated from creep rupture times.

This brief preliminary study of the comparison of creep and fatigue provides evidence of a relationship between creep and fatigue behavior.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Comparison of Fatigue Results

(1) The repeated-load indirect tensile test provides fatigue results which are comparable to other commonly used test methods.

(2) Stress difference can be used to explain a large portion of the fatigue life differences observed between the repeated-load indirect tensile test and other commonly used fatigue tests.

Regression Equation

(1) The following regression equation relating fatigue life to some of the more important mixture, construction, and testing variables was developed:

$$\log \hat{N}_f = 13.2424 - 3.4190 \log SD - .07899T + .9226(PCA) - .04795(PCA^2) - .02616(AP) + .0003621T(AP) - 1.4325(TD + TR) \quad (4.1)$$

where

$\hat{N}_f$ = estimated fatigue life,

SD = stress difference = applied stress for uniaxial tests,

T = testing temperature, °F

PCA = percent asphalt cement,

AP = penetration of asphalt cement,

TD = duration of tensile stress, seconds,

TR = rest period after a tensile stress, seconds.

(2) A comparison of results estimated using the regression equation with an independent set of measured data indicated that the equation could be used to relate fatigue results for a variety of mixtures tested by different methods.

(3) The factors testing temperature, asphalt content, asphalt penetra-

tion, and tensile stress duration plus rest after a tensile stress are included in the equation and the nature of their effects is compatible with previously observed behavior. Other qualitative factors such as aggregate type and gradation were not considered in the analysis.

Creep and Fatigue Comparison

(1) A preliminary relationship was developed between fatigue life and creep rupture time which indicates that fatigue life can possibly be estimated from creep tests:

$$\log N'_f = \log tr - 1.4325(TD + TR) + .01609T + 1.0478 \qquad (4.5)$$

where

N'_f = predicted fatigue life for a given load impulse characterized by TD + TR,

tr = creep rupture time,

TD + TR = fatigue tensile load duration plus rest period after the tensile load duration,

T = temperature in °F.

(2) The preliminary relationship between creep rupture time and fatigue life appears to be temperature dependent.

(3) The differences between indirect tensile fatigue and creep were compatible with the differences between flexural fatigue and creep of Majidzadeh et al.

(4) Even though a relationship between creep and fatigue deformations could not be developed, it is believed that further investigation should be devoted to a detailed study of the relationship between creep and fatigue.

RECOMMENDATIONS

Additional Research

(1) Stress difference should be considered in the analysis of laboratory and field indirect tensile fatigue studies. In addition, consideration should be given to possibly more sophisticated theories involving states of stress.

(2) The regression equation for estimating fatigue life should be evaluated using additional fatigue data.

(3) The relationship between creep and fatigue should be investigated in more detail with respect to fatigue and creep deformations, fatigue life, and creep rupture time.

Implementation

(4) The Texas Highway Department should begin to use the repeated-load indirect tensile test to obtain information and to obtain estimates of the modulus of elasticity and Poisson's ratio under repeated loads.

(5) The Texas Highway Department should develop the capability to make and record deformation measurements in order to estimate the load-deformation characteristics of pavement materials. This is necessary regardless of the type of test used.

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APPENDIX A

FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE REGRESSION ANALYSIS

TABLE A1. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE REGRESSION ANALYSIS, KENNEDY ET AL (REFS 41 AND 42) AND CURRENT RESEARCH

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	STRESS MAGINTUDES MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
7.00	92	75	1.50	8.0	.0	24.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	648755
7.00	92	75	1.50	16.0	.0	48.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	111652
7.00	92	75	1.50	24.0	.0	72.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	3074
7.00	92	75	1.50	32.0	.0	96.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	1600
7.00	92	75	1.50	40.0	.0	120.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	478
7.00	92	75	1.33	8.0	.0	24.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	265604
7.00	92	75	1.33	16.0	.0	48.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	13650
7.00	92	75	1.33	24.0	.0	72.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	3233
7.00	92	75	1.33	32.0	.0	96.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	822
7.00	92	75	1.33	40.0	.0	120.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	355
7.00	92	75	1.33	8.0	.0	24.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	150055
7.00	92	75	1.33	16.0	.0	48.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	6669
7.00	92	75	1.33	24.0	.0	72.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	2095
7.00	92	75	1.33	32.0	.0	96.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	678
7.00	92	75	1.33	40.0	.0	120.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	317
7.00	92	75	1.50	8.0	.0	24.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	181333
7.00	92	75	1.50	16.0	.0	48.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	4942
7.00	92	75	1.50	24.0	.0	72.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	2369
7.00	92	75	1.50	32.0	.0	96.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	556
7.00	92	75	1.50	40.0	.0	120.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	177
7.00	88	75	1.33	24.0	.0	72.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	1172
7.00	88	75	1.33	32.0	.0	96.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	476
7.00	88	75	1.33	40.0	.0	120.0	1.0000	0.0000	0.0000	0.0000	1.00	.5000	.3750	344
7.00	88	75	1.33	8.0	.0	24.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	214536
7.00	88	75	1.33	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	8117
7.00	88	75	1.33	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1629
7.00	88	75	1.33	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	571
7.00	88	75	1.33	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	330
7.00	88	75	1.33	48.0	.0	144.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	187
7.00	88	75	1.33	56.0	.0	168.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	129
4.00	88	75	9.60	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	618
4.00	88	75	9.60	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	165
4.00	88	75	9.60	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	107
4.00	88	75	9.60	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	47
5.00	88	75	6.80	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	3576
5.00	88	75	6.80	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	870
5.00	88	75	6.80	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	433
5.00	88	75	6.80	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	255
6.00	88	75	3.30	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	9595
6.00	88	75	3.30	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	2321

(Continued)

TABLE A1. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	COMP.	MINOR AXIS	LOAD DURATION TENSION	COMP.	REST PERIODS AFTER TENSION	COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	CENTROID FACTOR	FATIGUE LIFE
6.00	88	75	3.30	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1015
6.00	88	75	3.30	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	480
8.00	88	75	.77	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	3926
8.00	88	75	.77	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1170
8.00	88	75	.77	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	382
8.00	88	75	.77	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	194
4.00	88	75	10.00	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	333
4.00	88	75	10.00	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	97
4.00	88	75	10.00	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	39
4.00	88	75	10.00	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	21
5.00	88	75	7.20	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1576
5.00	88	75	7.20	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	430
5.00	88	75	7.20	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	176
5.00	88	75	7.20	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	88
6.00	88	75	3.50	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	6313
6.00	88	75	3.50	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1583
6.00	88	75	3.50	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	762
6.00	88	75	3.50	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	253
7.00	88	75	1.50	8.0	.0	24.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	329035
7.00	88	75	1.50	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	5956
7.00	88	75	1.50	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	1395
7.00	88	75	1.50	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	503
7.00	88	75	1.50	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	383
8.00	88	75	.42	16.0	.0	48.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	3619
8.00	88	75	.42	24.0	.0	72.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	800
8.00	88	75	.42	32.0	.0	96.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	344
8.00	88	75	.42	40.0	.0	120.0	.4000	0.0000	.6000	0.0000	1.00	.5000	.3750	208

TABLE A2. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE REGRESSION ANALYSIS, MONISMITH ET AL (REFS 6, 33, 37, AND 38)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
7.90	33	68	5.19	175.0	131.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	67385
7.90	33	68	5.42	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	104923
7.90	33	68	5.50	125.0	94.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	175032
6.00	92	68	5.48	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	1605
6.00	92	68	5.80	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	7885
6.00	92	68	5.85	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	23017
6.00	92	68	5.72	450.0	338.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	72
6.00	92	68	5.62	250.0	188.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	836
6.00	92	68	5.64	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	3800
6.00	92	68	5.82	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	19277
6.00	92	68	5.73	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	72059
6.00	92	68	4.60	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	3509
6.00	92	68	4.30	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	21193
6.00	92	68	4.57	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	73310
6.00	67	68	4.83	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	6592
6.00	67	68	4.68	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	28812
6.00	67	68	4.87	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	123936
6.00	33	68	4.78	175.0	131.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	22944
6.00	33	68	4.55	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	42818
6.00	33	68	5.55	125.0	94.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	58921
6.00	33	68	4.63	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	346538
5.70	67	68	7.65	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	4978
6.20	67	68	6.17	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	6645
6.20	67	68	7.00	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	21512
6.20	67	68	7.00	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	54968
6.70	67	68	5.20	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	19136
7.70	67	68	4.05	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	14953
8.70	67	68	1.60	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	9573
5.30	67	68	8.77	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	2387
5.70	67	68	8.10	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	3298
6.20	67	68	7.20	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	4605
5.20	92	68	7.06	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	19925
4.70	92	68	6.40	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	23556
4.60	92	68	8.20	75.0	56.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	42474
6.00	92	40	5.46	320.0	240.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	11000
6.00	92	40	5.46	260.0	195.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	18000
6.00	92	40	5.46	230.0	172.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	25000
6.00	92	40	5.46	200.0	150.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	200000
6.00	92	68	5.00	125.0	93.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	4200
6.00	92	68	5.00	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	20000

(Continued)

TABLE A2. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	STRESS MAGINTUDES MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIOUE LIFE
6.00	92	68	5.00	65.0	48.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	98000
4.70	92	68	5.34	80.0	60.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	10000
4.70	92	68	5.34	60.0	45.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	32000
4.70	92	68	5.34	45.0	33.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	80000
4.70	92	40	6.03	230.0	172.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	6000
4.70	92	40	6.03	200.0	150.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	43000
4.70	92	40	6.03	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	56000
5.90	92	40	7.63	300.0	225.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	8000
5.90	92	40	7.63	240.0	180.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	17000
5.90	92	40	7.63	170.0	127.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	150000
5.90	92	68	7.93	125.0	93.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	2300
5.90	92	68	7.93	80.0	60.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	21000
5.90	92	68	7.93	50.0	37.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	190000
4.60	92	68	8.66	80.0	60.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	8500
4.60	92	68	8.66	50.0	37.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	21000
4.60	92	68	8.66	35.0	26.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	120000
4.60	92	40	8.62	240.0	180.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	1300
4.60	92	40	8.62	180.0	135.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	17000
4.60	92	40	8.62	125.0	93.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	140000
5.90	92	40	8.12	230.0	172.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	13000
5.90	92	40	8.12	200.0	150.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	32000
5.90	92	40	8.12	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	240000
5.90	92	68	8.40	85.0	63.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	50000
5.90	92	68	8.40	70.0	52.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	90000
5.90	92	68	8.40	55.0	41.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	500000
4.90	92	68	8.18	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	231375
4.90	92	68	8.18	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	47470
4.90	92	68	8.18	125.0	93.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	13276
4.90	92	68	8.18	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	7093
4.90	92	68	7.01	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	479254
4.90	92	68	7.01	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	94685
4.90	92	68	7.01	125.0	93.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	32684
4.90	92	68	7.01	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	18507
4.20	92	68	8.00	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	52441
4.20	92	68	8.00	85.0	63.8	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	28887
4.20	92	68	8.00	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	18947
4.90	92	40	6.60	300.0	225.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	12000
4.90	92	40	6.60	250.0	187.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	28000
4.90	92	40	6.60	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	490000
4.90	92	68	7.00	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	1100

(Continued)

TABLE A2. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIQUE LIFE
4.90	92	68	7.00	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	6000
4.90	92	68	7.00	50.0	37.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	60000
4.90	92	40	7.30	300.0	225.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	9000
4.90	92	40	7.30	250.0	187.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	18000
4.90	92	40	7.30	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	250000
4.90	92	68	7.30	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	1300
4.90	92	68	7.30	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	8000
4.90	92	68	7.30	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	27000
6.00	92	68	4.50	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	318357
6.00	92	68	4.60	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	42615
6.00	92	68	4.40	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	9459
6.00	92	68	4.40	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	415638
6.00	92	68	4.50	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	83532
6.00	92	68	4.40	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	10373
6.00	92	68	4.90	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	297195
6.00	92	68	4.80	100.0	75.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	78653
6.00	92	68	4.80	150.0	112.5	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	8852
6.00	92	68	4.60	75.0	56.3	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	406666
6.00	92	68	4.60	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	114809
6.00	92	68	4.50	150.0	113.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	12965
6.00	92	75	4.53	507.2	380.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	16
6.00	92	75	4.53	303.5	228.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	180
6.00	92	75	4.53	203.5	153.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	1100
6.00	92	75	4.53	153.5	115.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	2200
6.00	92	75	4.53	128.5	96.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	6700
6.00	92	75	4.53	113.5	85.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	17000
6.00	92	75	4.53	98.5	74.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	28000
6.00	92	75	4.53	88.5	66.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	120000
6.00	92	75	4.53	78.5	59.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	270000
6.00	92	75	4.53	93.5	70.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	48975
6.00	92	75	4.53	95.0	71.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	107827
6.00	92	75	4.53	108.5	81.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	35500
6.00	92	75	4.53	110.0	83.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	27103
6.00	92	75	4.53	125.0	94.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	10075
6.00	92	75	4.53	128.5	96.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	11050
6.00	92	40	4.53	400.0	300.0	0.0	.1000	.0500	0.0000	1.7500	2.00	.8333	.4700	88942
6.00	92	40	4.53	400.0	300.0	0.0	.1000	.0500	0.0000	.8500	1.00	.8333	.4700	56127
6.00	92	40	4.53	400.0	300.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	19264
6.00	92	75	4.53	105.0	79.0	0.0	.1000	.0500	0.0000	1.7500	2.00	.8333	.4700	355700
6.00	92	75	4.53	105.0	79.0	0.0	.1000	.0500	0.0000	.4500	1.67	.8333	.4700	77577

(Continued)

TABLE A2. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	COMP.	MINOR AXIS	LOAD DURATION TENSION	COMP.	REST PERIODS AFTER TENSION	COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	CENTROID FACTOR	FATIGUE LIFE
6.00	92	75	4.53	88.5	66.0	0.0	.1400	.0500	0.0000	.4100	1.67	.8333	.4700	21000
6.00	92	75	4.53	88.5	66.0	0.0	.1800	.0500	0.0000	.3700	1.67	.8333	.4700	6000

TABLE A3. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE REGRESSION ANALYSIS, PELL ET AL (REFS 47, 48 AND 50)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
9.50	45	7	3.50	910.0	910.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	100000
9.50	45	7	3.50	630.0	630.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1000000
9.50	45	7	3.50	430.0	430.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	10000000
9.50	45	15	3.50	810.0	810.0	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	100000
9.50	45	15	3.50	570.0	570.0	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	1000000
9.50	45	15	3.50	400.0	400.0	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	10000000
9.50	45	32	3.50	700.0	700.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	50000
9.50	45	32	3.50	600.0	600.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	100000
9.50	45	32	3.50	400.0	400.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	1000000
9.50	45	32	3.50	270.0	270.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	10000000
9.50	45	45	3.50	670.0	670.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	10000
9.50	45	45	3.50	450.0	450.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	100000
9.50	45	45	3.50	300.0	300.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	1000000
9.50	45	45	3.50	205.0	205.0	0.0	.0130	.0130	0.0000	0.0000	38.33	.6366	.3927	10000000
9.50	45	77	3.50	153.0	153.0	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	100000
9.50	45	77	3.50	110.0	110.0	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	1000000
8.10	43	32	4.20	430.0	430.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	75000
8.10	43	32	4.20	380.0	380.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	220000
8.10	43	32	4.20	315.0	315.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	500000
8.10	43	32	4.20	270.0	270.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1200000
8.10	43	32	4.20	240.0	240.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	5000000
8.10	43	50	4.20	310.0	310.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	28000
8.10	43	50	4.20	270.0	270.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	130000
8.10	43	50	4.20	220.0	220.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	720000
8.10	43	50	4.20	170.0	170.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1500000
8.10	43	50	4.20	150.0	150.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	7800000
8.10	43	68	4.20	175.0	175.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	36000
8.10	43	68	4.20	120.0	120.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	290000
8.10	43	68	4.20	102.0	102.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	420000
8.10	43	68	4.20	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3400000
7.20	43	32	3.30	465.0	465.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	60000
7.20	43	32	3.30	410.0	410.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	90000
7.20	43	32	3.30	365.0	365.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	120000
7.20	43	32	3.30	312.0	312.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	550000
7.20	43	32	3.30	275.0	275.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1400000
7.20	43	32	3.30	245.0	245.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	4800000
7.20	98	32	4.60	365.0	365.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	37400
7.20	98	32	4.60	315.0	315.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	80800
7.20	98	32	4.60	265.0	265.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	239000
7.20	98	32	4.60	215.0	215.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	541000

(Continued)

TABLE A3. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
7.20	98	32	4.60	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2640000
6.30	43	32	3.00	450.0	450.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	52000
6.30	43	32	3.00	425.0	425.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	95000
6.30	43	32	3.00	375.0	375.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	330000
6.30	43	32	3.00	315.0	315.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	450000
6.30	43	32	3.00	280.0	280.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1500000
6.30	43	32	3.00	240.0	240.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2900000
5.40	98	50	4.00	250.0	250.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	48000
5.40	98	50	4.00	175.0	175.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	400000
5.40	98	50	4.00	150.0	150.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	800000
5.40	98	50	4.00	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2500000
6.00	43	50	5.80	265.0	265.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3230
6.00	43	50	5.80	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	46100
6.00	43	50	5.80	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	490000
6.00	43	50	5.80	90.0	90.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	1630000
6.00	43	50	5.80	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	6510000
6.00	43	32	5.20	265.0	265.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	22700
6.00	43	32	5.20	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	433000
6.00	43	32	5.20	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3230000
6.00	43	50	5.20	265.0	265.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3660
6.00	43	50	5.20	215.0	215.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	16700
6.00	43	50	5.20	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	70400
6.00	43	50	5.20	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	704000
6.00	43	50	5.20	90.0	90.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2710000
6.00	43	50	5.20	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	6180000
6.00	43	68	5.20	150.0	150.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3360
6.00	43	68	5.20	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	8790
6.00	43	68	5.20	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	52800
6.00	43	68	5.20	52.0	52.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	313000
6.00	43	86	5.20	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	4110
6.00	43	86	5.20	55.0	55.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	18400
6.00	43	86	5.20	40.0	40.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	91300
6.00	98	50	4.80	265.0	265.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2740
6.00	98	50	4.80	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	24500
6.00	98	50	4.80	90.0	90.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	275000
6.00	98	50	4.80	65.0	65.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	815000
4.20	98	50	6.20	215.0	215.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3920
4.20	98	50	6.20	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	12400
4.20	98	50	6.20	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	34000
4.20	98	50	6.20	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	277000

(Continued)

TABLE A3. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	STRESS MAGINTUDES MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
4.10	43	50	9.80	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2550
5.60	43	50	5.70	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	35000
6.00	43	50	4.50	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	67100
6.60	43	50	3.50	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	110000
7.70	43	50	.90	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	154000
10.10	43	50	0.00	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	88900
12.50	43	50	0.00	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	41500
6.00	43	50	5.20	165.0	165.0	0.0	.3750	.3750	0.0000	0.0000	1.33	.6366	.3927	2120
6.00	43	50	5.20	165.0	165.0	0.0	.1500	.1500	0.0000	0.0000	3.33	.6366	.3927	21400
6.00	43	50	5.20	165.0	165.0	0.0	.0600	.0600	0.0000	0.0000	8.33	.6366	.3927	48600
6.00	43	50	5.20	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	63900
6.00	43	50	5.20	165.0	165.0	0.0	.0150	.0150	0.0000	0.0000	33.33	.6366	.3927	125000
6.00	43	50	5.20	165.0	165.0	0.0	.0120	.0120	0.0000	0.0000	41.67	.6366	.3927	139000
3.50	43	50	5.40	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	10500
4.50	43	50	2.80	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	443000
6.40	43	50	.40	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	2470000
8.00	43	50	0.00	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	630000
10.50	43	50	0.00	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	239000
4.70	98	50	6.80	165.0	165.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	4290
4.70	98	50	6.80	115.0	115.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	14500
4.70	98	50	6.80	75.0	75.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	95900
4.70	98	50	6.80	55.0	55.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	357000
4.70	98	68	6.80	55.0	55.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	29100
4.30	197	50	6.50	80.0	80.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	23700
4.30	197	50	6.50	55.0	55.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	43900
4.30	197	50	6.50	35.0	35.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	68200
4.70	197	50	6.10	125.0	125.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	3380
4.70	197	50	6.10	90.0	90.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	6360
4.70	197	50	6.10	55.0	55.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	21200
4.70	197	50	6.10	40.0	40.0	0.0	.0300	.0300	0.0000	0.0000	16.67	.6366	.3927	27200

TABLE A4. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE REGRESSION ANALYSIS, RAITHBY AND STERLING (REFS 52 AND 53)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
6.50	38	50	3.00	217.0	217.0	0.0	.0200	.0200	0.0000	0.0000	25.00	.6366	.3927	6675
6.50	38	50	3.00	217.0	217.0	0.0	.0200	.0200	0.0000	.0800	8.33	.6366	.3927	16110
6.50	38	50	3.00	217.0	217.0	0.0	.0200	.0200	0.0000	.4000	2.27	.6366	.3927	80870
6.50	38	50	3.00	217.0	217.0	0.0	.0200	.0200	0.0000	1.0000	.96	.6366	.3927	100500
6.50	38	50	3.00	145.0	145.0	0.0	.0200	.0200	0.0000	0.0000	25.00	.6366	.3927	34680
6.50	38	50	3.00	145.0	145.0	0.0	.0200	.0200	0.0000	.0800	8.33	.6366	.3927	215400
6.50	38	50	3.00	145.0	145.0	0.0	.0200	.0200	0.0000	.4000	2.27	.6366	.3927	896800
6.50	38	50	3.00	145.0	145.0	0.0	.0200	.0200	0.0000	1.0000	.96	.6366	.3927	843100
6.50	38	77	3.00	110.0	110.0	0.0	.0200	.0200	0.0000	0.0000	25.00	.6366	.3927	4690
6.50	38	77	3.00	110.0	110.0	0.0	.0200	.0200	0.0000	.0800	8.33	.6366	.3927	1190
6.50	38	77	3.00	110.0	110.0	0.0	.0200	.0200	0.0000	1.0000	.96	.6366	.3927	11140
6.50	38	77	3.00	62.3	62.3	0.0	.0200	.0200	0.0000	0.0000	25.00	.6366	.3927	40440
6.50	38	77	3.00	62.3	62.3	0.0	.0200	.0200	0.0000	.0400	12.50	.6366	.3927	89130
6.50	38	77	3.00	62.3	62.3	0.0	.0200	.0200	0.0000	.0800	8.33	.6366	.3927	158700
6.50	38	77	3.00	62.3	62.3	0.0	.0200	.0200	0.0000	1.0000	.96	.6366	.3927	1088510
6.50	38	104	3.00	29.0	29.3	0.0	.0200	.0200	0.0000	0.0000	.96	.6366	.3927	10360
6.50	38	104	3.00	29.0	29.3	0.0	.0200	.0200	0.0000	.0800	8.33	.6366	.3927	34000
6.50	38	104	3.00	29.0	29.3	0.0	.0200	.0200	0.0000	.4000	2.27	.6366	.3927	68960
6.50	38	104	3.00	29.0	29.3	0.0	.0200	.0200	0.0000	1.0000	.96	.6366	.3927	42330
6.50	38	77	3.00	39.1	39.1	0.0	.2000	.2000	0.0000	0.0000	2.50	.6366	.3927	18600
6.50	38	77	3.00	39.1	39.1	0.0	.2000	.2000	0.0000	.8000	.83	.6366	.3927	91580
6.50	38	77	3.00	47.8	47.8	0.0	.0200	.0200	0.0000	0.0000	25.00	1.0000	.5000	24690
6.50	38	77	3.00	47.8	47.8	0.0	.0200	.0200	0.0000	0.0000	25.00	.6366	.3927	58950
6.50	38	77	3.00	47.8	47.8	0.0	.0200	.0200	0.0000	0.0000	25.00	.5000	.3333	85570
6.50	38	77	3.00	110.0	110.0	0.0	.0200	.0200	.0800	0.0000	8.33	.6366	.3927	6649
6.50	38	77	3.00	110.0	.0	0.0	.0200	0.0000	.0800	0.0000	1.00	.6366	.3927	8748

APPENDIX B

FATIGUE DATA AND MIXTURE CHARACTERISTICS USED IN THE EVALUATION OF THE REGRESSION EQUATION

TABLE B1. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED FOR EVALUATION OF THE REGRESSION EQUATION, HAAS (REF 15)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	COMP.	MINOR AXIS	LOAD DURATION TENSION	COMP.	REST PERIODS AFTER TENSION	COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	CENTROID FACTOR	FATIGUE LIFE
5.80	84	70	10.00	40.0	0.0	35.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	16950
5.80	84	61	2.00	40.0	0.0	15.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	57500
5.80	84	61	10.00	40.0	0.0	35.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	34250
5.80	84	70	10.00	40.0	0.0	15.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	25000
5.80	84	70	2.00	40.0	0.0	35.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	40000
5.80	84	61	2.00	40.0	0.0	35.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	37500
5.80	84	61	10.00	40.0	0.0	15.0	.0400	0.0000	.2100	0.0000	4.00	.6366	.3927	35000

TABLE B2. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED FOR EVALUATION OF THE REGRESSION EQUATION, KALLAS AND PUZINAUSKAS (REF 23)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	STRESS MAGINTUDES MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
5.60	57	70	5.20	278.0	27.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	10
5.60	57	70	4.80	254.0	25.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	390
5.60	57	70	5.20	228.0	22.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	460
5.60	57	70	5.00	197.0	19.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	840
5.60	57	70	5.00	185.0	18.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1110
5.60	57	70	4.90	165.0	16.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	4275
5.60	57	70	5.10	137.0	13.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	7320
5.60	57	70	5.20	115.0	11.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	17580
5.60	57	70	5.20	91.0	9.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	127500
5.60	57	70	5.00	255.0	25.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	510
5.60	57	70	4.70	243.0	24.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	925
5.60	57	70	4.50	217.0	21.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	875
5.60	57	70	4.70	189.0	18.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	3140
5.60	57	70	4.90	168.0	16.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	4115
5.60	57	70	4.90	144.0	14.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	6010
5.60	57	70	4.70	119.0	11.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	30625
5.60	57	70	4.80	96.0	9.6	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	89970
8.60	57	70	5.00	191.0	19.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	20040
8.60	57	70	6.10	144.0	14.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	64900
8.60	57	70	6.10	99.0	9.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	439800
8.00	57	70	8.80	200.0	20.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	10450
8.00	57	70	7.40	101.0	10.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	263600
5.70	84	70	4.30	274.0	27.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	462
5.70	84	70	4.30	255.0	25.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	769
5.70	84	70	4.00	237.0	23.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1345
5.70	84	70	4.00	212.0	21.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	2715
5.70	84	70	4.30	200.0	20.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	2505
5.70	84	70	4.10	174.0	17.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	7015
5.70	84	70	3.70	150.0	15.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	17050
5.70	84	70	4.20	124.0	12.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	16965
5.70	84	70	4.10	98.0	9.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	144391
5.70	65	70	16.40	306.0	30.6	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	35
5.70	65	70	15.80	294.0	29.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	75
5.70	65	70	16.00	265.0	26.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	100
5.70	65	70	15.60	233.0	23.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	340
5.70	65	70	16.00	190.0	19.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	294
5.70	65	70	16.00	152.0	15.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	970
5.70	65	70	16.50	125.0	12.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1630
5.70	65	70	16.10	103.0	10.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	3573
5.20	65	70	8.20	265.0	26.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	269

(Continued)

TABLE B2. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
5.20	65	70	7.90	287.0	28.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	169
5.20	65	70	7.60	244.0	24.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	328
5.20	65	70	8.50	222.0	22.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	332
5.20	65	70	8.30	199.0	19.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	891
5.20	65	70	8.50	179.0	17.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1820
5.20	65	70	7.70	154.0	15.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	3335
5.20	65	70	8.40	127.0	12.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	10675
5.20	65	70	9.00	112.0	11.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	23700
5.20	90	70	8.10	217.0	21.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	530
5.20	90	70	8.70	200.0	20.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1065
5.20	90	70	8.80	181.0	18.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1245
5.20	90	70	8.70	172.0	17.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1125
5.20	90	70	8.60	128.0	12.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	9610
5.20	90	70	8.70	109.0	10.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	18460
3.00	59	70	10.90	270.0	27.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	15
3.00	59	70	10.90	260.0	26.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	75
3.00	59	70	10.90	233.0	23.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	87
3.00	59	70	11.40	222.0	22.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	46
3.00	59	70	10.70	201.0	20.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	572
3.00	59	70	10.90	181.0	18.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	168
3.00	59	70	10.70	148.0	14.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	616
3.00	59	70	10.90	132.0	13.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	2426
3.00	59	70	10.60	113.0	11.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	5356
6.00	84	55	3.40	383.0	38.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	2330
6.00	84	55	3.20	302.0	30.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	6380
6.00	84	55	3.40	274.0	27.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	12000
6.00	84	55	3.40	248.0	24.8	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	14630
6.00	84	55	3.40	230.0	23.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	37080
6.00	84	55	3.50	244.0	24.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	23415
6.00	84	55	3.20	22.4	24.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	40500
6.00	84	55	3.70	223.0	22.3	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	55140
6.00	84	55	3.20	200.0	20.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	349500
0.00	84	70	3.20	272.0	27.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	504
6.00	84	70	3.40	265.0	26.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	697
6.00	84	70	3.30	244.0	24.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1267
6.00	84	70	3.50	222.0	22.2	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	2900
6.00	84	70	3.70	196.0	19.6	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	4945
6.00	84	70	3.40	180.0	18.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	8355
6.00	84	70	3.00	147.0	14.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	21660
6.00	84	70	3.50	124.0	12.4	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	80350

(Continued)

TABLE B2. (Continued)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
6.00	84	70	3.20	107.0	10.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	204200
6.00	84	85	3.20	196.0	19.6	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	648
6.00	84	85	3.00	167.0	16.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1344
6.00	84	85	3.40	140.0	14.0	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	1224
6.00	84	85	3.60	121.0	12.1	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	6590
6.00	84	85	3.50	97.0	9.7	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	22380
6.00	84	85	3.40	69.0	6.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	170900
6.00	84	85	3.20	75.0	7.5	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	255300
6.00	84	85	3.60	49.0	4.9	0.0	.1000	.0500	0.0000	.3500	2.00	.5000	.3750	594000

TABLE B3. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED FOR EVALUATION OF THE REGRESSION EQUATION, MAJIDZADEH ET AL (REF 28)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	STRESS MAGINTUDES MAJOR AXIS COMP.	MINOR AXIS	LOAD DURATION TENSION	LOAD DURATION COMP.	REST PERIODS AFTER TENSION	REST PERIODS AFTER COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	WAVEFORM SHAPE CENTROID FACTOR	FATIGUE LIFE
6.00	63	32	17.00	247.5	247.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	3020
6.00	63	32	17.00	330.0	330.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	602
6.00	63	32	17.00	412.5	412.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	178
6.00	63	32	17.00	495.0	495.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	62
6.00	63	41	17.00	165.0	165.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	5129
6.00	63	41	17.00	247.5	247.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	245
6.00	63	41	17.00	330.0	330.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	148
6.00	63	41	17.00	412.5	412.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	48
6.00	63	50	17.00	165.0	165.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	1995
6.00	63	50	17.00	247.5	247.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	251
6.00	63	50	17.00	330.0	330.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	58
6.00	63	50	17.00	412.5	412.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	13
6.00	63	59	17.00	165.0	165.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	562
6.00	63	59	17.00	247.5	247.5	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	72
6.00	63	59	17.00	330.0	330.0	0.0	1.0000	1.0000	0.0000	0.0000	.50	.6366	.3927	17

TABLE B4. SUMMARY OF FATIGUE DATA AND MIXTURE CHARACTERISTICS USED FOR EVALUATION OF THE REGRESSION EQUATION, VAN DIJK ET AL (REF 58)

PERCENT ASPHALT	ASPHALT PEN.	TEMP.	PERCENT VOIDS	STRESS MAGINTUDES MAJOR AXIS TENSION	COMP.	MINOR AXIS	LOAD DURATION TENSION	COMP.	REST PERIODS AFTER TENSION	COMP.	FREQUENCY	WAVEFORM SHAPE AREA FACTOR	CENTROID FACTOR	FATIGUE LIFE
6.00	90	77	6.00	64.7	10.8	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	251188
6.00	90	77	6.00	38.1	6.3	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	3162277
6.00	90	77	6.00	28.2	4.7	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	12589254
6.00	90	77	6.00	87.3	14.6	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	251188
6.00	90	77	6.00	60.4	10.1	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	3162277
6.00	90	77	6.00	49.1	8.2	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	12589254
6.00	90	77	6.00	105.0	17.5	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	251188
6.00	90	77	6.00	77.8	13.0	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	3162277
6.00	90	77	6.00	66.2	11.0	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	12589254
6.00	45	50	6.00	148.3	24.7	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	1000000
6.00	45	50	6.00	191.0	31.8	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	158489
6.00	45	50	6.00	276.1	46.8	0.0	.0100	.0100	0.0000	0.0000	50.00	.6366	.3927	25118
6.00	45	50	6.00	170.2	28.3	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	1000000
6.00	45	50	6.00	224.4	37.3	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	158489
6.00	45	50	6.00	331.9	55.3	0.0	.0175	.0050	0.0000	.0225	22.22	.6366	.3927	25118
6.00	45	50	6.00	174.2	29.0	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	1000000
6.00	45	50	6.00	257.6	42.8	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	158489
6.00	45	50	6.00	408.3	68.1	0.0	.0175	.0050	0.0000	.1355	6.35	.6366	.3927	25118

APPENDIX C

BATCHING AND MIXING, COMPACTION, AND CURING PROCEDURES

APPENDIX C. SPECIMEN PREPARATION

BATCHING AND MIXING PROCEDURES

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

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

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

COMPACTION PROCEDURES

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

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

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

CURING PROCEDURES

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

APPENDIX D

CREEP AND PERMANENT DEFORMATION RELATIONSHIPS FOR INDIRECT TENSILE TESTING

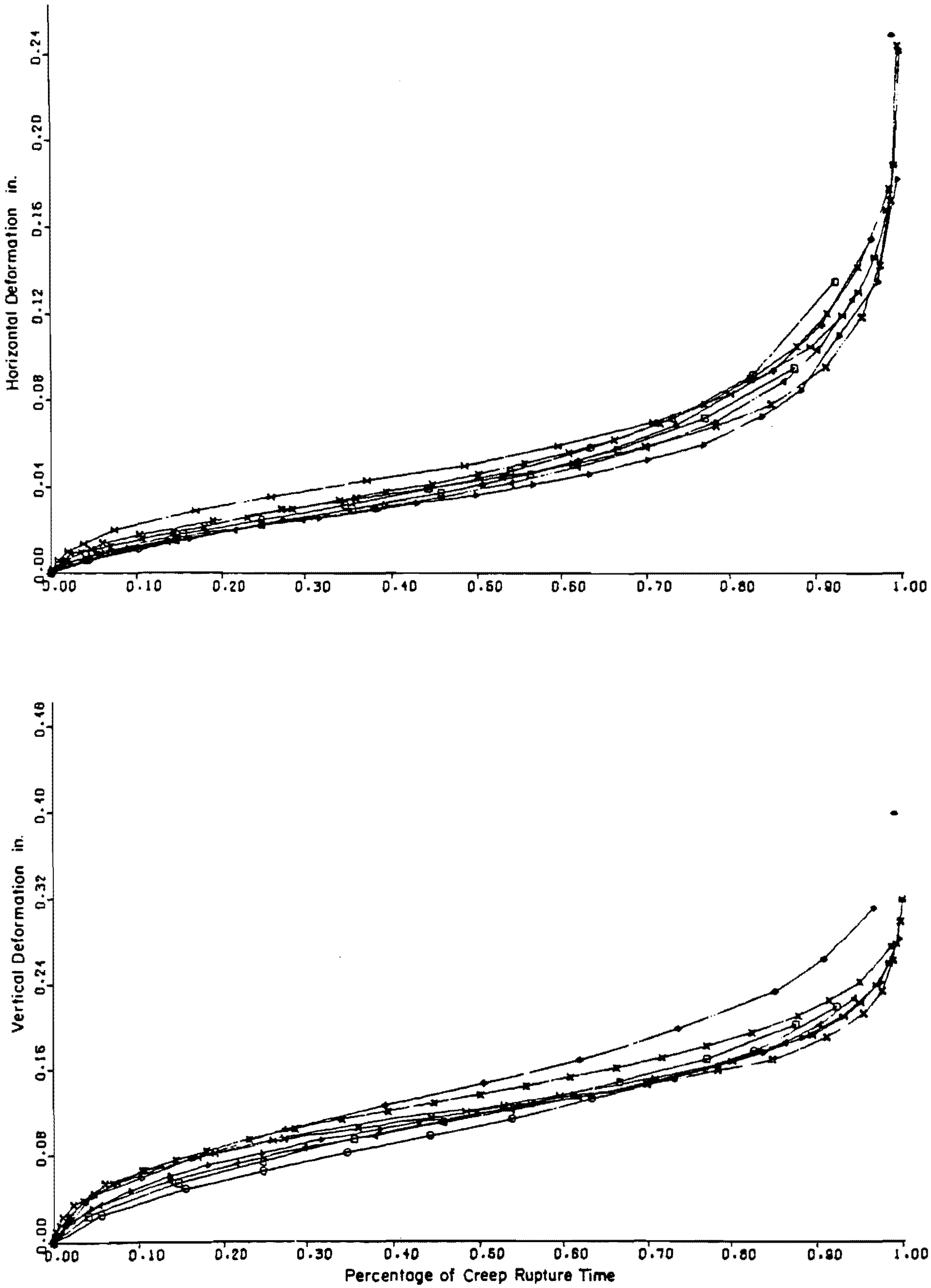

Fig D1. Horizontal and vertical creep deformations for creep indirect tension.

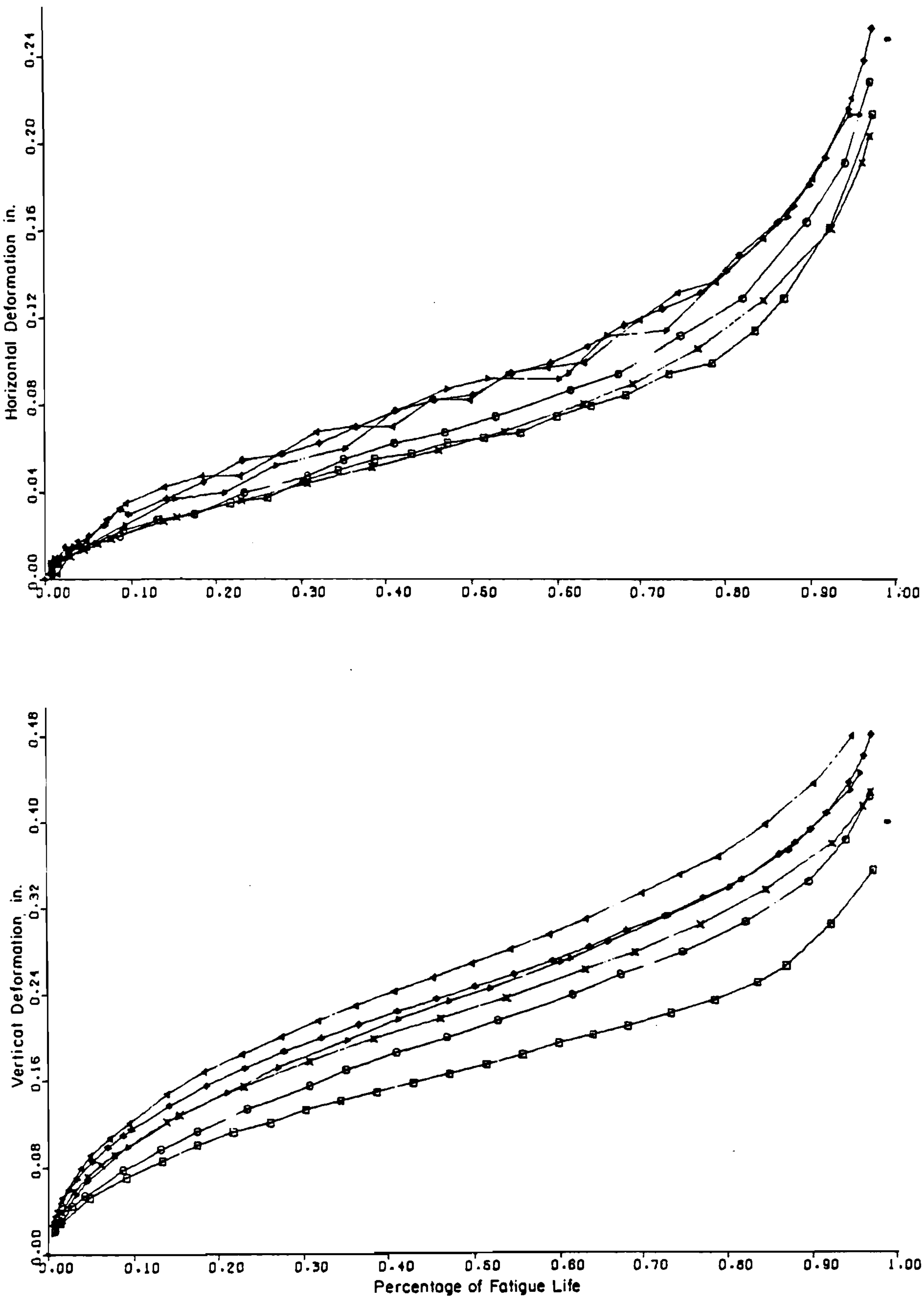

Fig D2. Horizontal and vertical permanent deformations for repeated-load indirect tension with a stress difference of 64 psi.

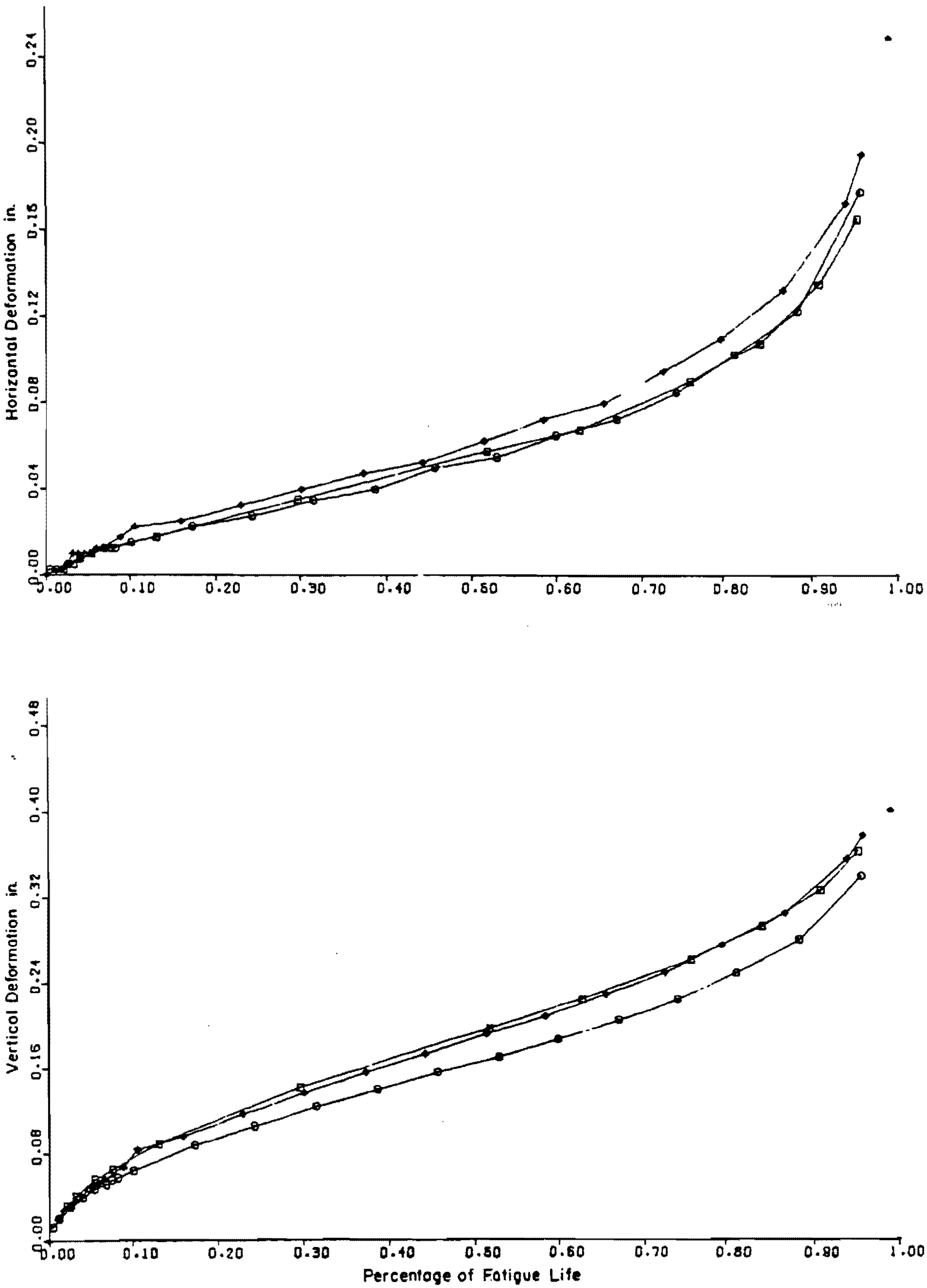

Fig D3. Horizontal and vertical permanent deformations for repeated-load indirect tension with a stress difference of 90 psi.

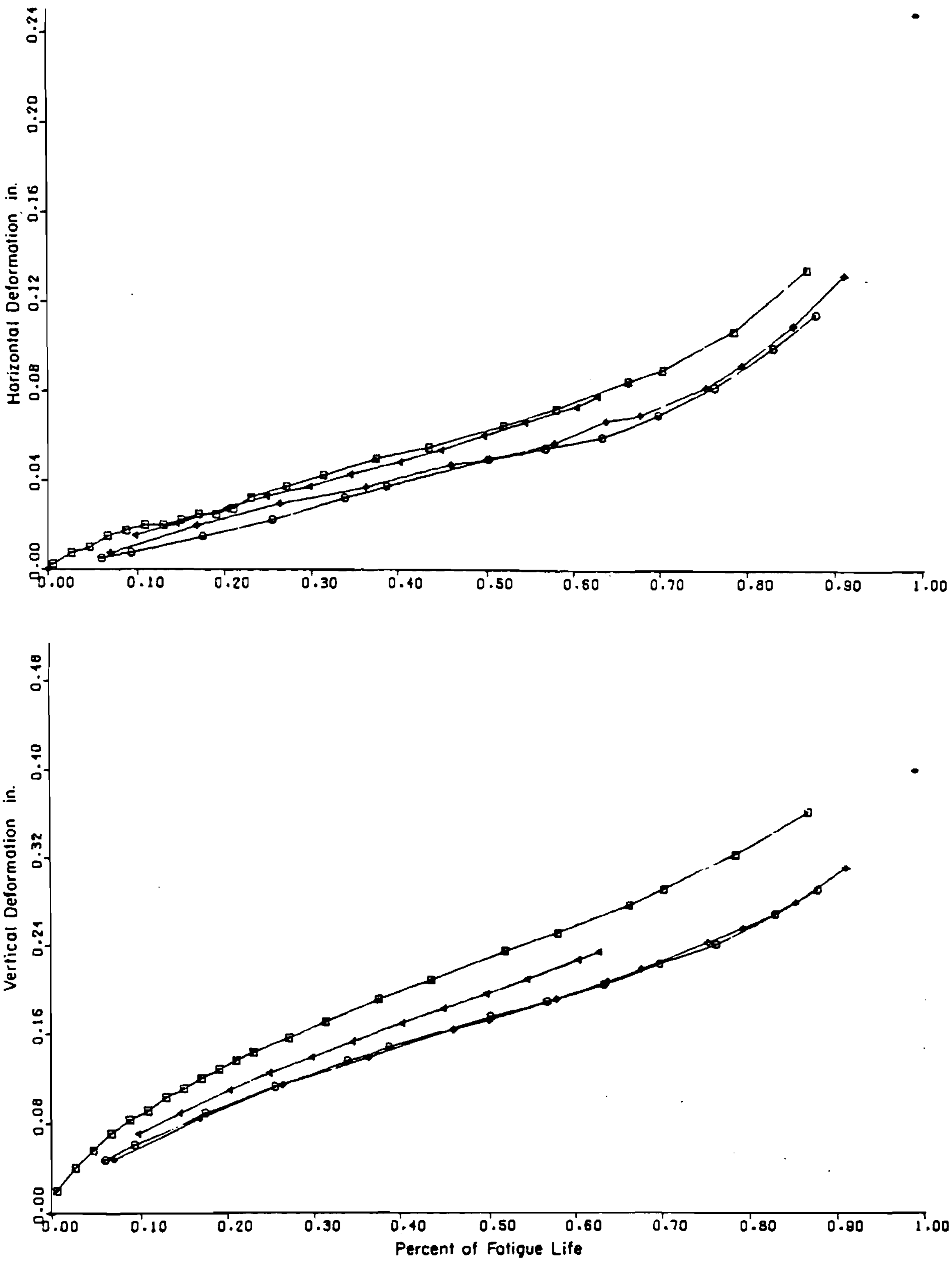

Fig D4. Horizontal and vertical permanent deformations for repeated-load indirect tension with a stress difference of 128 psi.

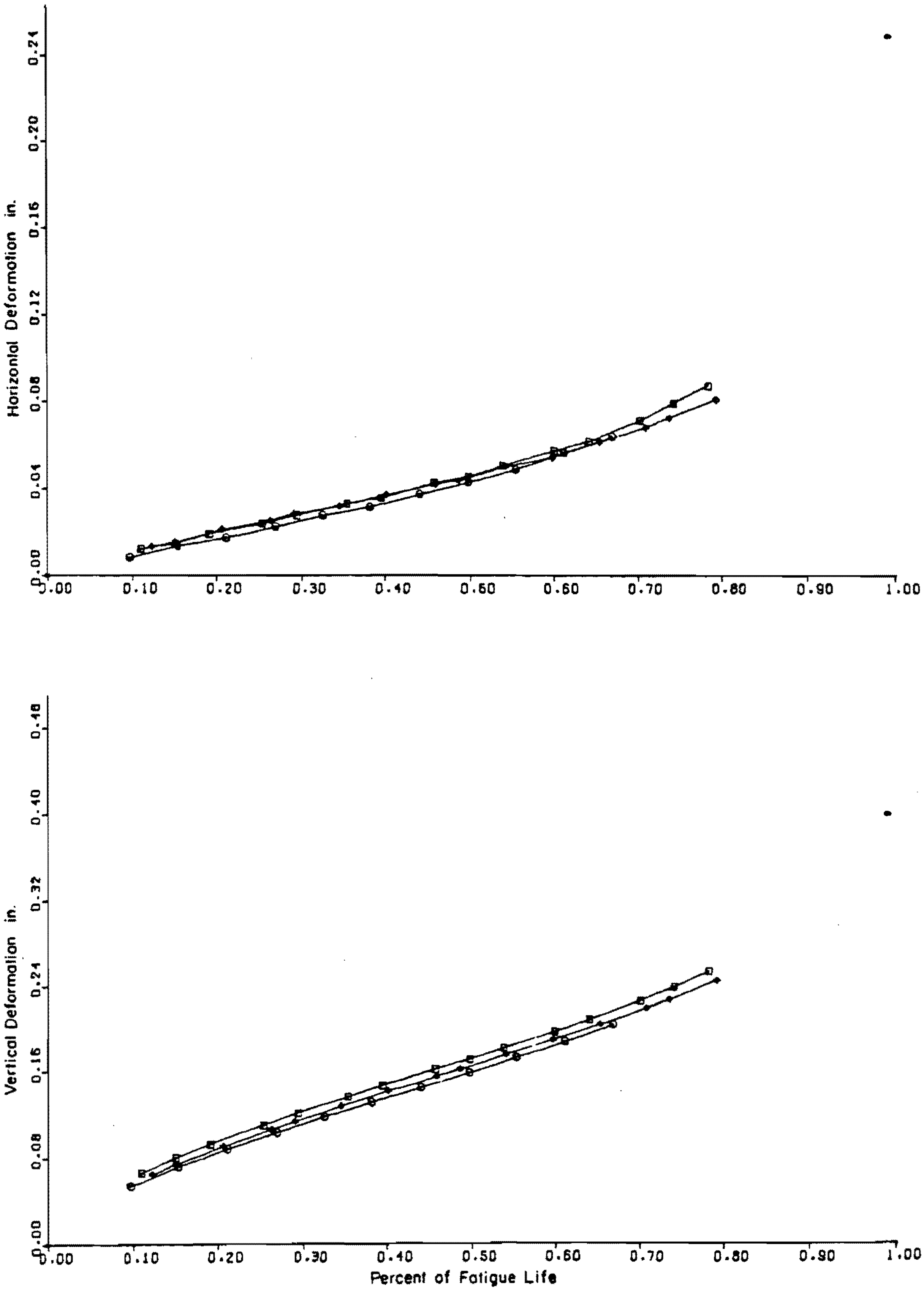

Fig D5. Horizontal and vertical permanent deformations for repeated-load indirect tension with a stress difference of 160 psi.