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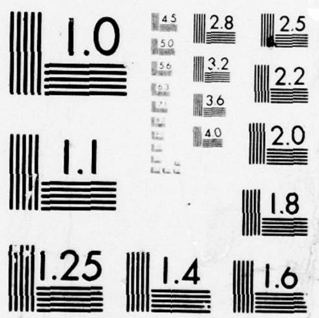

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Predicting The Fatigue Life Of Flexible Airfield Pavements--A Recommended Approach

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JULY 1979

FINAL REPORT FOR PERIOD JULY 1978-JUNE 1979

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The pavement engineer currently has no realistic means of predicting the fatigue life of an existing asphalt pavement or the service of a new asphalt pavement surface. The development of information that would enable engineers to make realistic fatigue life predictions, and thereby to make the best use of the increasingly scarce pavement maintenance dollar, is critically needed. This report reviews current fatigue and routine design test methods and examines the effects of materials and environmental conditions on fatigue

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life. The extensive literature review indicates a possibility that fatigue life may be estimated by correlating known fatigue parameters with results of routine design tests. The repeated-load indirect tensile (fatigue) test and the resilient modulus indirect tensile (routine design) test are recommended for use in U.S. Air Force investigations. For both procedures laboratory and field samples can be easily obtained and transported, and a large amount of data can be generated in a reasonable length of time. It is further suggested that tests on asphalt cement might provide an index that could be correlated with fatigue life data for asphaltic concrete mixtures. The primary research need in the asphalt fatigue area is for the development of a shift factor that would enable researchers to realistically predict actual pavement fatigue life from laboratory test data.

PREFACE

This report documents work performed during the period July 1978 through June 1979 by the University of New Mexico under contract F29601-76-C-0015 with HQ AFESC/RDCF, Tyndall Air Force Base, Florida 32403. Second Lieutenant Richard A. McDonald managed the program.

This report has been reviewed by the Information Officer and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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Project Officer

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Chief, Airbase Facilities Branch

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Chief, Engineering Research Division

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INTRODUCTION

BACKGROUND

Flexible airfield pavements are constructed of layers of various materials placed over a natural subgrade. The surface layer, known as the wearing course, is made up of asphalt cement and aggregates, blended and compacted to provide a smooth, resilient surface for aircraft operations. These pavements are designed to flex, and to do so repeatedly. The repeated flexing ultimately leads to fatigue cracking of the wearing course and thus accelerates the degradation of the pavement system. Fatigue cracking is also accelerated by environmental effects that effectively harden the asphalt cement and reduce the anticipated service life of the pavement.

When asphaltic concrete (AC) airfield pavements are placed in service, the user generally has little or no information concerning their potential service life. Some pavement design procedures are predicated upon a desired service life of, say, 20 years, or upon a given number of aircraft departures. Such predictions, however, are not based upon realistic models. For economic reasons, a method of realistically predicting the service life of both new and existing aircraft pavements is critically needed. With such a tool, pavement engineers could determine more accurately how thick the wearing course for a new pavement should be. In the case of existing pavements, service life predictions could preclude unnecessary upgrading or the over-stressing that can lead to extensive premature repairs.

The U.S. Air Force is currently developing a nondestructive airfield pavement evaluation system that uses the computer code PREDICT to evaluate a pavement's capability to support specific types of aircraft. The system is based on field tests from which the elastic values of pavement materials are determined; a finite-element computer program for predicting stress, strains, and deflections in the pavement; and an AC fatigue algorithm. The fatigue criterion used in PREDICT to evaluate AC wearing courses was originally developed for highway pavements. Because this criterion was considered the best available (in 1976), it was included in the code in an effort to determine whether the code was capable of predicting AC service life. However, the fatigue criterion has been found unsatisfactory for aircraft pavements. This study, which deals solely with the AC material, is a first step in the development of a criterion more applicable to aircraft pavements.

OBJECTIVE

The objective of this study is to evaluate current fatigue prediction criteria and determine their applicability to Air Force aircraft loadings and traffic patterns; to this end, to review fatigue test methods, use of indicator tests, controlling asphalt cement and AC mix properties, and environmental factors that influence fatigue and to recommend a fatigue prediction system that includes the use of extracted AC cores and of procedures that can be used by Air Force personnel.

APPROACH

The study was conducted by means of an extensive literature search, discussions with consultants, and visits with other researchers concerned with the fatigue of AC.

REPORT ORGANIZATION

Section I of this report defines the problem and outlines the approach to the study. Section II provides a discussion of fatigue failure definitions and test loading variables. Section III presents a review of fatigue test procedures that have been used to predict performance and of routine design test methods that might be used to delineate AC fatigue properties. Section IV contains a review of the effects of mixture and environmental variables on fatigue life. A summary of the study is provided in Section V.

SECTION II

FATIGUE FAILURE DEFINITIONS AND LOADING VARIABLES

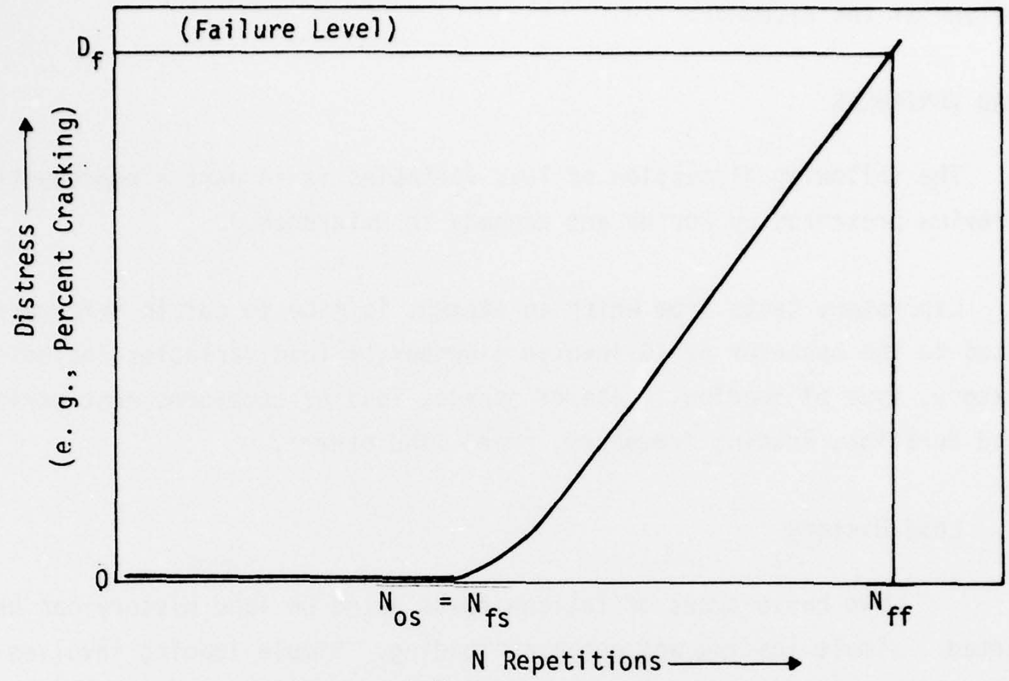
INTRODUCTION

A discussion of fatigue failure definitions and load variables is presented in this section as a preface to the description of test methods in Section III. This background information will help the reader to understand more fully the test methods described.

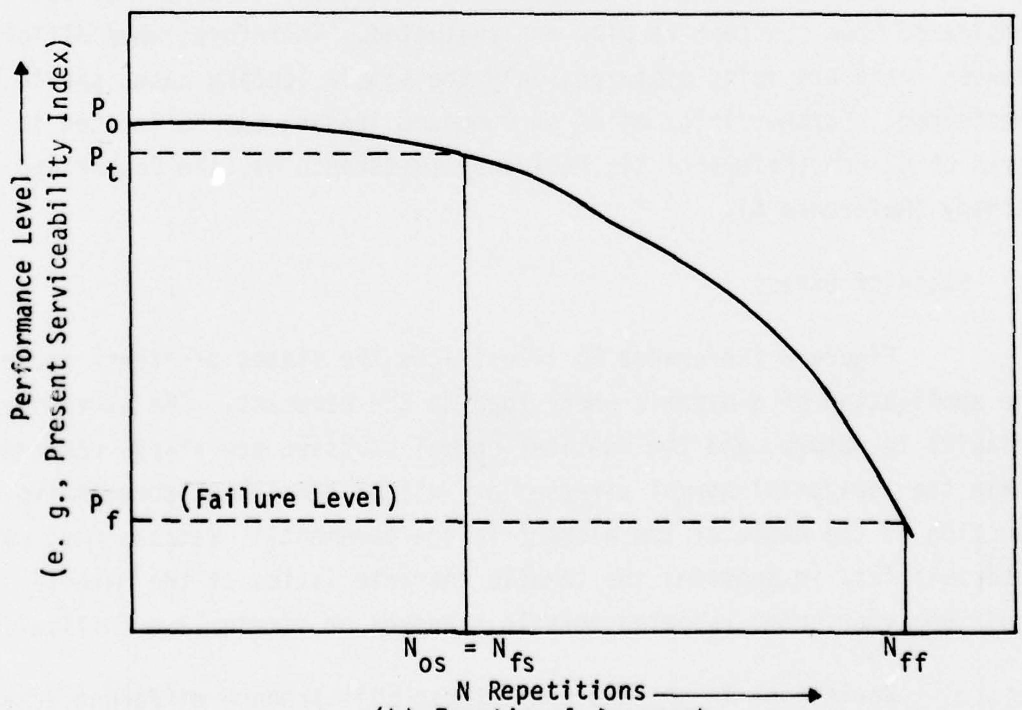
FAILURE DEFINITIONS

Fatigue failure in pavements in service is evidenced by cracking, while laboratory failure is some arbitrarily defined point. Epps and Monismith (Reference 1) describe laboratory fatigue as a point at which a specimen can no longer perform as a load-carrying structure under repetitive loading. Fatigue failure may be assessed by service life, N_s, and fracture life, N_f. N_s is defined as the number of load repetitions required to reduce some characteristic of a test specimen to a critical level, whereas N_f is the number of load repetitions required to cause the specimen to fail completely. Thus, when the service life is defined as complete rupture of the specimen, the two criteria are equal.

Witzcak and Bell (Reference 2) define service life, N_s, as the number of cycles to structural failure and fracture life, N_f, as the functional failure of the pavement. Figure 1 (Reference 2) illustrates distress-based (structural) and performance-based (functional) approaches to pavement life. A specimen undergoing structural distress analysis, as shown in Figure 1-a, may exhibit no distress until a given number of load repetitions, N_{os}, has been reached. That number represents the initiation of cracking in the pavement or incipient structural failure. In contrast, Figure 1-b illustrates that the performance level of a pavement constructed with an initial serviceability of P_0 gradually decreases to a failure level, P_f, after some number of load repetitions, N_{ff}. Thus a given structural failure condition exists (D_f, N_{ff}) that may relate to a functional failure condition (P_f, N_{ff}).



(a) Structural Approach



(b) Functional Approach

Figure 1. Structural- and Performance-Based Design Approaches (after Witczak and Bell, Reference 2)

It should be noted that crack initiation does not constitute functional failure of the pavement.

LOAD VARIABLES

The following discussion of load variables is in part a reproduction of a review presented by Porter and Kennedy in Reference 3.

Laboratory tests from which an attempt is made to obtain information related to the behavior of AC 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 others.

Load History

Two basic types of fatigue tests based on load history can be performed: simple loading and compound loading. Simple loading involves constant testing conditions; in compound loading, test conditions are changed during the test. Compound loading has a varied load history that must be considered when the test results are evaluated. Therefore, when differences between tests are being compared, only the simple loading cases should be considered. Further information on compound loading can be located in the works of Deacon (Reference 4), McElvaney (Reference 5), and Cowher and Kennedy (Reference 6).

State of Stress

Figure 2 (Reference 3) illustrates the states of stress caused by the application of a dynamic wheel load to the pavement. The stresses are triaxial in nature, and the vertical normal stresses are always compressive while the horizontal normal stresses are either tensile or compressive (a function of the depth of the element in the pavement). Because most pavement materials fail in tension, the tensile characteristics of the materials and their behavior under repeated tensile stresses or strains are critical.

Variations in the state of stress will produce different data for the same asphaltic mixtures. Raithby and Sterling have demonstrated that

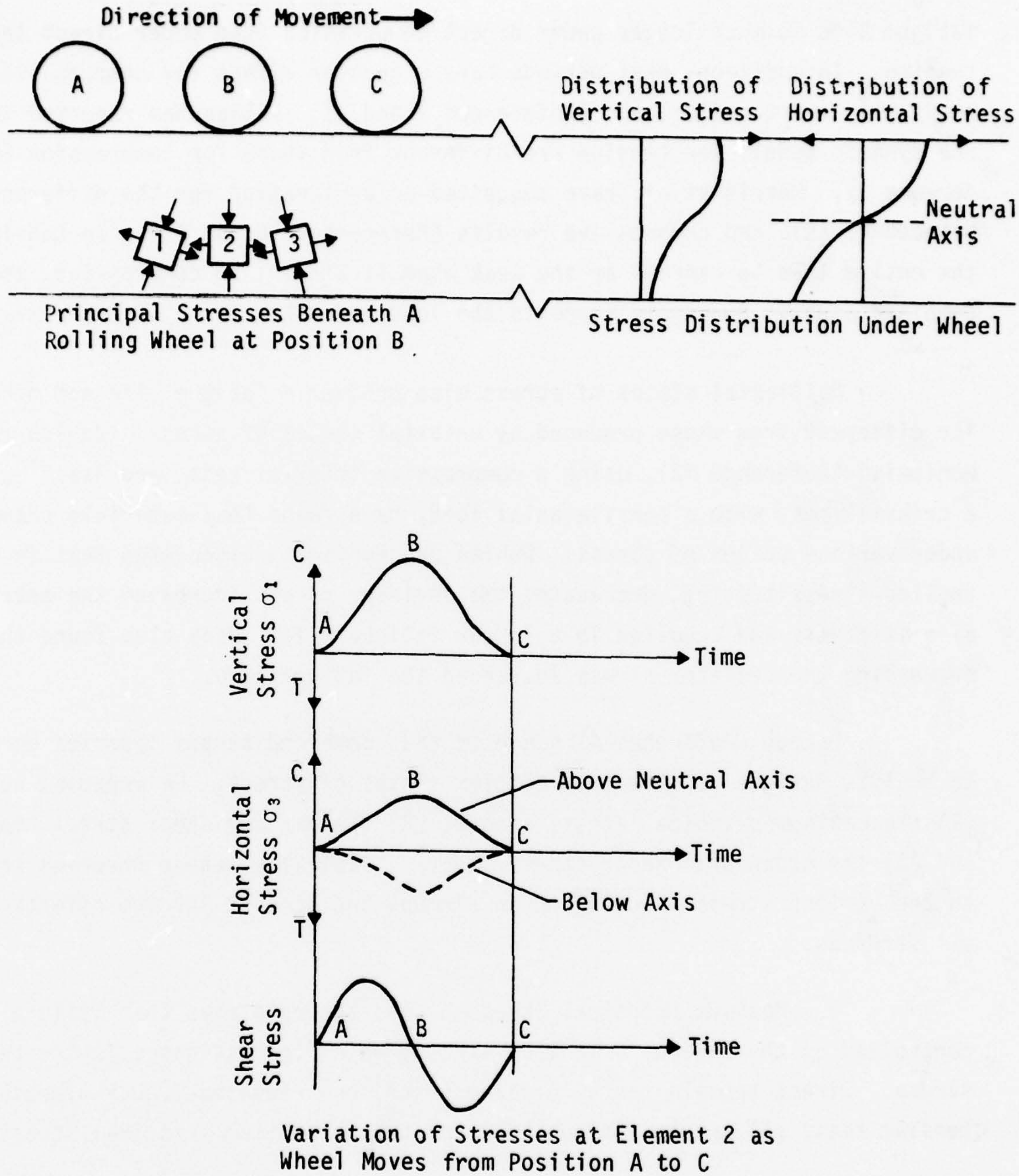


Figure 2. Stresses in Pavement Caused by Moving Wheel (after Porter and Kennedy, Reference 3)

fatigue life is much longer under direct compression than under direct tension testing. In addition, rest periods have a greater effect for compressive loads than for tensile loads (References 7 and 8). Kallas has reported that the dynamic moduli for tension are different from those for compression (Reference 9). Morris et al. have suggested an explanation for the difference between tensile and compressive results (References 10 and 11). In tension, the entire load is carried by the weak asphalt binder; in compression, the combined asphalt aggregate supports the load and makes for a stronger mixture.

Multiaxial states of stress also produce a fatigue life and behavior different from those produced by uniaxial states of stress. Dehlen and Monismith (Reference 12), using a compressive triaxial test, and Haas,[1] using a triaxial test with a tensile axial load, have found that materials change under various states of stress. Dehlen and Monismith discovered that in controlled-stress testing, decreasing the deviator stress increased the material's stiffness and resulted in a longer fatigue life. Haas also found that decreasing the deviator stress increased the fatigue life.

Deacon (Reference 4) suggests that combined stress theories be used to analyze fatigue results from complex states of stress. He proposes using (1) the maximum principal stress theory, (2) the maximum shear stress theory, and (3) the octahedral shear stress theory. Basically, these theories relate to the various stresses acting on an element and account for the effects of all stresses.

1. Maximum Principal Stress. This 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.

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

Footnote

[1]Haas, R. C. G., personal communication of unpublished data to Thomas W. Kennedy, 1974.

3. 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

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

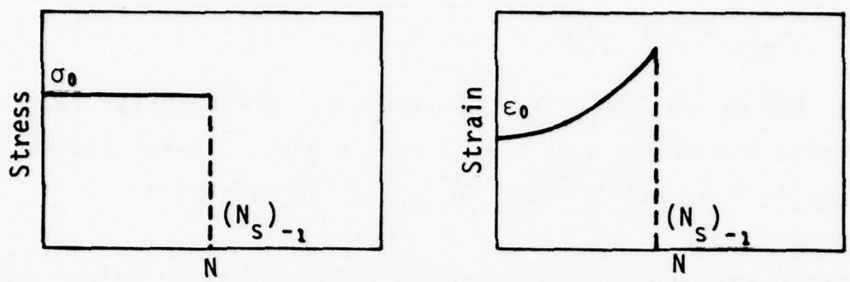
where σ_1, σ_2, and σ_3 are the principal stresses. For uniaxial testing, σ_2 and σ_3 are zero; therefore, $\tau_{oct} = \sqrt{2}/3\ \sigma_1 = 0.47\sigma_1$. In the indirect tensile test, $\sigma_1 = \sigma_t$, $\sigma_2 = 0$, and $\sigma_3 = \sigma_c$, so $\tau_{oct} = \sqrt{26}\sigma_1/3 = 1.7\sigma_1$.

Porter and Kennedy (Reference 3) recommend that fatigue results possibly should be compared in terms of either the maximum shear stress or the octahedral shear stress theory. They suggest that there is very little difference between the two theories for the states of stress developed in most tests. The maximum shear stress theory indicates that the tensile stress in the indirect tensile test is approximately four times the uniaxial tensile stress. The octahedral shear stress theory indicates that 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 choice should be made on the basis of practicality.

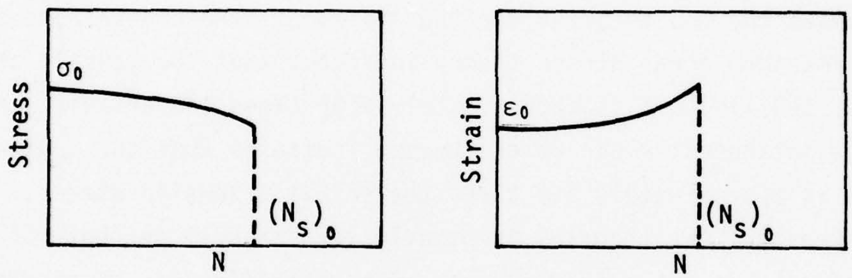
Type of Loading

The type of loading used 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 controlled-strain and controlled-stress procedures are limiting cases of an infinite spectrum of modes of loading.

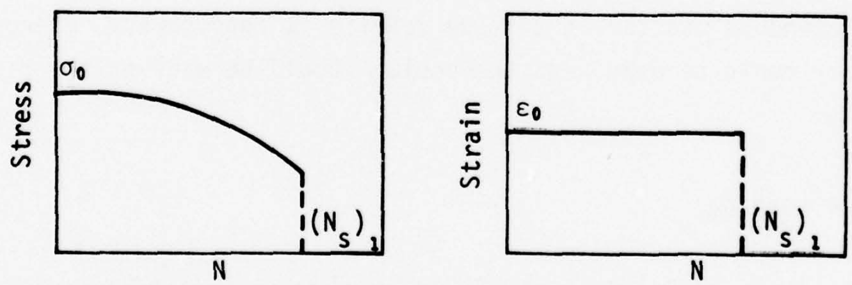
Figure 3-a (Reference 1) shows the relationships between stress and strain and the number of load applications for the controlled-stress mode. As



(a) Controlled Stress; Mode Factor = -1



(b) Intermediate; Mode Factor = 0



(c) Controlled Strain; Mode Factor = 1

Notes: N = Number of Load Applications
N_s = Mean Service Life

Figure 3. Schematic Representation of Fatigue Behavior of Asphalt Paving Materials for Various Modes of Loading (after Epps and Monismith, Reference 1)

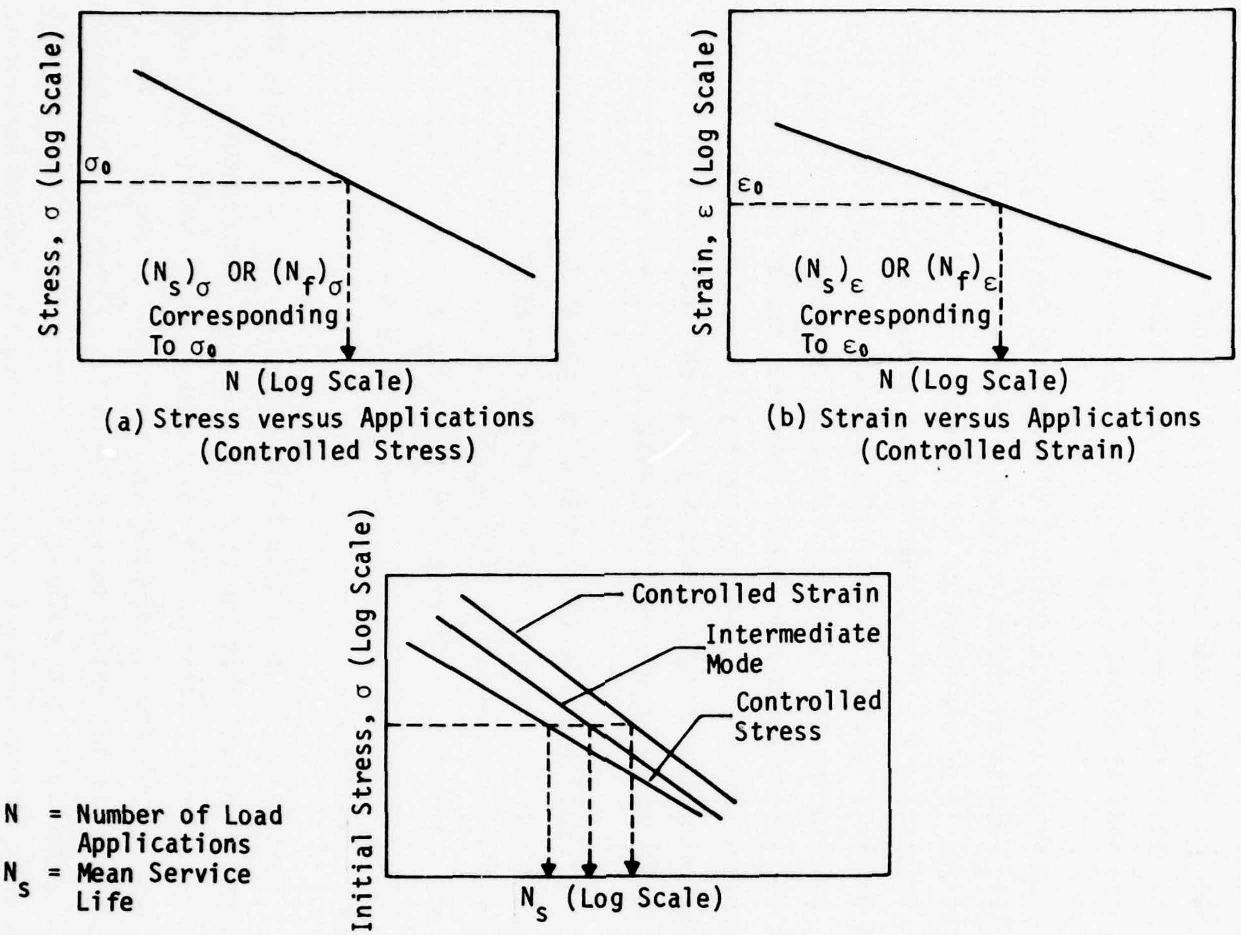
the number of load applications increases, the stress remains constant, and the strain increases as the specimen is damaged.

The controlled-strain test is illustrated in Figure 3-c (Reference 1). The figure shows that strain is constant and stress decreases as the number of load applications increases. The decline in stress occurs because the specimen is damaged with each load application so that less stress is required to obtain the same amount of strain. Note that for all modes of loading, the initial stress (σ_o) and the initial strain (ε_o) are the same.

Controlled-stress and controlled-strain tests produced different fatigue life results as shown in Figure 4 (Reference 1). The stress- and strain-fatigue life relationships are schematically illustrated in Figures 4-a and 4-b, respectively. If one examines the stress-versus-life relationships for both modes of loading, a comparison between modes of loading can be obtained. By assuming that the data have been developed for identical specimens and that the stress and strain levels have been chosen in such a way as to obtain identical values of σ_o and ε_o, one may plot a comparison of controlled stress and controlled strain as shown in Figure 4-c. The controlled-stress mode obviously produces the most conservative fatigue life estimates.

The difference in the locations of the fatigue curves in Figure 4-c may or may not be observed in tests of AC, a variation that is apparently at least partially related to the stiffness of the mixture. The shape of the stress- and strain-versus-service life curve may also be influenced by the mixture's stiffness (Reference 1). (Further discussion of stiffness is presented in Section IV.)

Controlled-stress and controlled-strain modes of loading represent two extreme conditions that can occur in pavements (Reference 4): (1) The AC pavement is generally stiff in the cool spring months, while the subgrade modulus may be much less stiff because of moisture saturation. Thus, the stiffness ratio (relationship of surface to subgrade stiffness) would be high, approaching that of a controlled-stress mode of loading. (2) During the hot summer months, the AC pavement stiffness is greatly reduced because of the pavement's higher temperature, and the subgrade is typically drier and generally stiffer. Therefore, a decrease in stiffness ratio, approximating the



(a) Stress versus Applications (Controlled Stress)

(b) Strain versus Applications (Controlled Strain)

(c) Comparison For Controlled-Stress and Controlled-Strain Tests.

Notes: N = Number of Load Applications

N_s = Mean Service Life

Figure 4. Typical Fatigue Diagrams (after Epps and Monismith, Reference 1)

controlled-strain condition, can be observed. Figure 5 (Reference 4) illustrates this concept.

In controlled-stress tests, stiffer mixes exhibit a longer fatigue life, while in controlled-strain tests, the more flexible mixtures have a longer fatigue life. Pell (Reference 13) reasons that the difference between the modes of failure for the two types of tests causes this phenomenon. In controlled-stress testing, the formation of a crack causes an increase in the stress at the crack tip due to the effect of stress concentration. The crack propagates rapidly, causing complete fracture of the specimen and termination of the test. In the constant-strain test, on the other hand, cracking causes a decrease in crack-tip stress, and the crack grows at a slow rate. Therefore, AC at low stiffness (and hence low stress) has a longer fatigue life because of the considerable length of time it takes for a crack to propagate to a failure condition (Reference 13).

Monismith and Deacon (Reference 14) propose the use of a mode factor (MF) to differentiate between controlled-stress and controlled-strain modes of

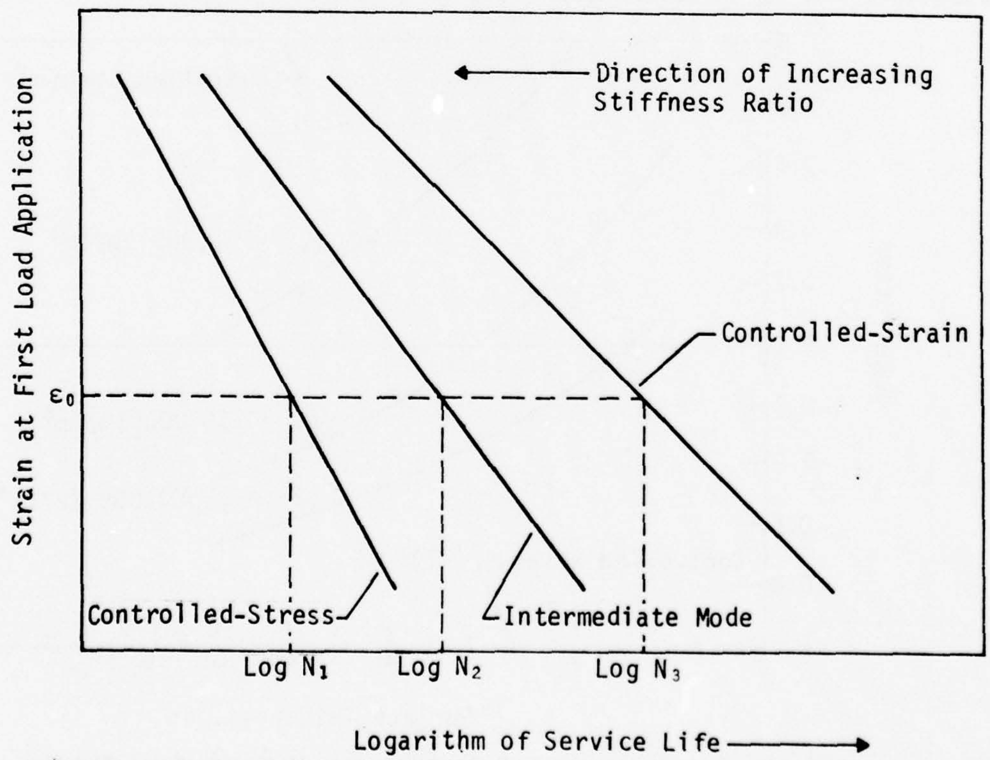


Figure 5. Effect of Mode of Loading (after Deacon, Reference 4)

loading. MF is defined as follows:

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

where

/A/ = percentage change in stress

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

The mode factor has a value of +1 for controlled-strain testing and -1 for controlled-stress testing (Reference 14). Figure 6 (Reference 15) illustrates the change in mode factor as a function of surface-course thickness and stiffness. A controlled-stress condition is approached as the thickness and stiffness of the AC layer increase. The controlled-stress mode is therefore indicated as appropriate for pavement layers that are thick and stiff because such a layer resists load and influences the magnitude of the strains that occur (Reference 15).

Thin, flexible pavements are best simulated by the controlled-strain loading mode. Because a thin layer adds little stiffness to the overall structure, the layer deformation caused by loading is governed by the entire

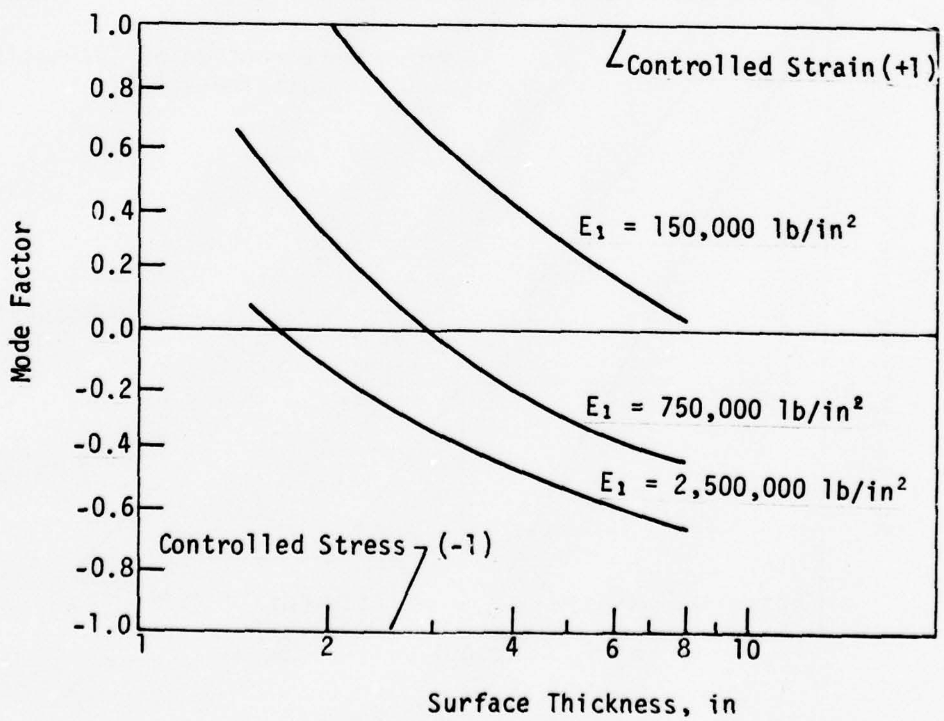


Figure 6. Variation of Mode Factor With Surface Thickness (after Pell, Reference 15)

structure; therefore, the stiffness of the entire pavement, rather than just the stiffness of the thin layer, determines the resultant stress (Reference 16).

Van Dijk et al. (Reference 17) explain the difference between controlled-stress and controlled-strain fatigue life test results in terms of total energy dissipation. A relationship of the form $W_{fat} = AN^z$ exists, where W_{fat} is the total dissipated energy per unit volume, N is the number of load applications, and A and z are constants dependent upon mix properties.

Figure 7 (Reference 17) shows total energy dissipation versus the number of loading cycles for controlled-stress and controlled-strain tests. The total energy dissipated at failure was found to be essentially identical for both modes of loading; however, energy was dissipated much more quickly in the controlled-stress test than in the controlled-strain test. In the controlled-strain mode, the stress on the sample decreases with increasing repetitions of load; in the controlled stress mode, however, the strain increases from its initial level. The product of stress and strain (which represents work) therefore increases in the controlled-stress test and decreases in the controlled-strain test. It therefore follows that work (or energy) is expended more quickly in the controlled-stress test and that fatigue life is shortened (References 17 and 18).

Figure 8 (Reference 17) illustrates the retained bending strength of the mixture as a function of the total energy dissipated. As energy dissipates, the bending strength decreases regardless of the mode of loading. At some point the retained bending strength becomes equal to the applied stress and fatigue failure occurs.

Loading Waveform

The most commonly used loading waveforms are repeated-block, sinusoidal, and haversine patterns. As will be described later in this section, many types of testing machines are used to generate these waveforms. However, only limited data are available for the purpose of comparing the effects of waveforms for similar AC mixtures (Reference 1).

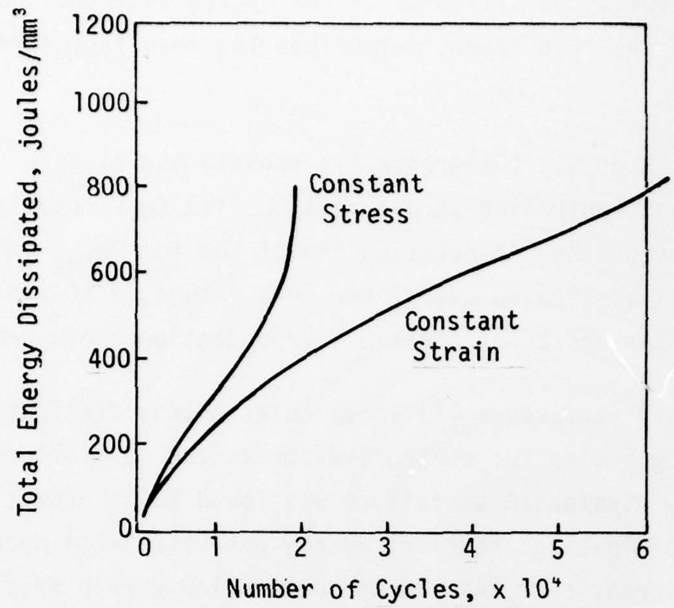


Figure 7. Total Energy Dissipated as a Function of Load Repetitions for Constant-Stress and Constant-Strain Tests (after Van Dijk et al., Reference 17)

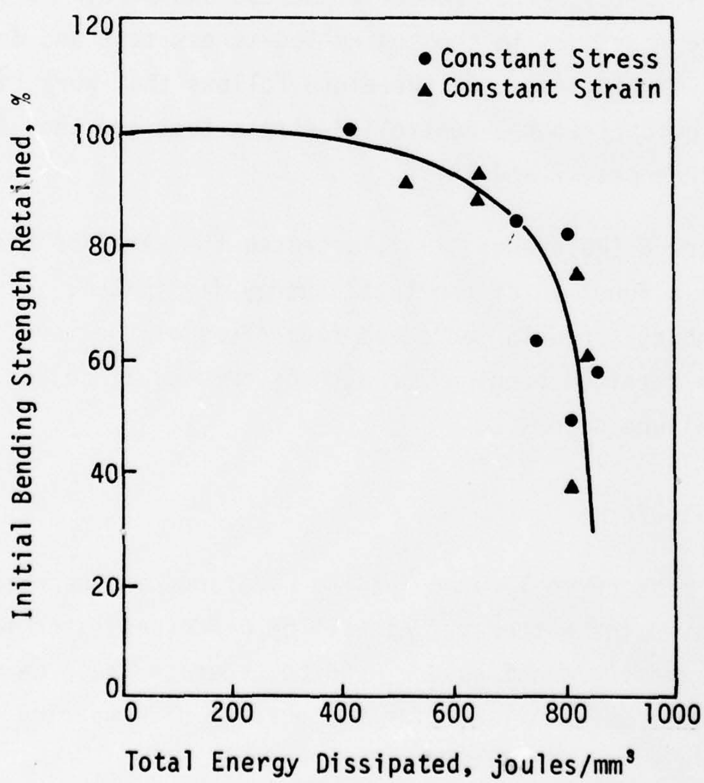


Figure 8. Percentage of Retained Bending Strength as a Function of Total Energy Dissipated for Constant-Stress and Constant-Strain Tests (after Van Dijk et al., Reference 17)

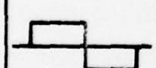
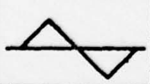
Raithby and Sterling (References 7 and 8) performed a series of tests to determine the effect of loading waveform on fatigue life. In one test series, continuous loading was applied to specimens. Three different waveforms were used: square, sinusoidal, and triangular. A summary of the results is shown in Table 1 (Reference 8). The triangular waveform produced the longest fatigue life, and the square waveform produced the shortest. This author could find no documentation to indicate which of these waveforms most closely simulates field loading conditions.

Rest Period, Load Duration, and Frequency of Loading

The precise effects of rest period, load duration, and frequency of loading are difficult to determine because these conditions are interdependent in that the load duration plus the rest period defines the loading cycle. Because the three variables are interdependent, they cannot be varied independently; however, it is possible to study the general effects of each.

1. Rest Period. Raithby and Sterling (References 7 and 8) studied the effects of rest periods on fatigue life. The results are summarized in Tables 2 and 3 (References 7 and 8). A rest period added to any sine wave load pulse was found to increase fatigue life. While rest periods were found to be beneficial, there was a maximum beyond which an additional increase in the rest period did not significantly increase fatigue life (Table 3

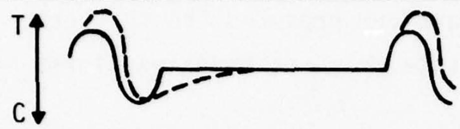
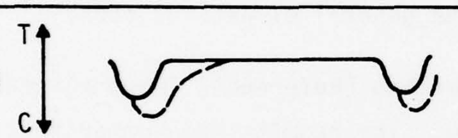
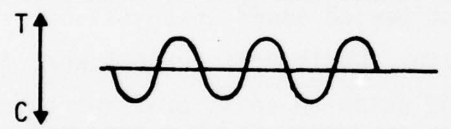
TABLE 1. EFFECT OF SHAPE OF WAVEFORM ON FATIGUE LIFE

Waveform	Temperature, °C	Stress Amp., MN/m^2	Initial Strain Amp.[a]	Geometric Mean Fatigue Life, Cycles	Relative Lives
	25		1.70×10^{-4}	24,690	0.42
	25	±0.33 ($48\ lb/in^2$)	1.20×10^{-4}	58,950	1.00
	25		0.67×10^{-4}	85,570	1.45

(Reference 8)

[a]These represent values after approximately 200 cycles.

TABLE 2. VARIOUS UNIAXIAL LOADING WAVEFORM SHAPES USED BY RAITHBY AND STERLING

Waveform ——— = Stress ------ = Strain	Geometric Mean Fatigue Life, Cycles[a]
1) 	11,190
2) 	6,649
3) 	8,748
4) 	196,200
5) 	4,690

(Reference 8)

[a]Peak stress = 110 lb/in^2; temperature = 25°C

and Figure 9 [Reference 8]). The authors also conclude that the length of the maximum beneficial rest period is dependent upon the temperature at which the test is performed. In addition, the direction of the stress imposed prior to the rest period was found to be important. A rest period following a compressive stress (C) resulted in a fatigue life significantly longer than that obtained when a tensile stress (T) preceded the rest period (Table 2). Thus, Raithby and Sterling conclude that fatigue life is dependent on tensile strains.

Monismith and Epps (References 1 and 16) studied the effects of frequency of loading, including the effect of rest periods, on fatigue life. The frequency of loading was varied, while the duration of the load was held constant, causing the length of the rest period to change. Rest periods

TABLE 3. RESULTS OF REST-PERIOD TESTS

Loading Period, ms	Temperature, °C	Alternating Stress, MN/m² (lb/in²)	Rest Period, ms	Number of Tests	Geometric Mean Life, cycles	Std. Dev. of Log Life	Mean Life Ratio[a]
40	10	1.50 (217)	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
		1.00 (145)	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)	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)	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)	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)	0	3	18,600	0.268	1.0
			800	2	91,580	0.301	4.9

(Reference 7)

[a]Ratio of geometric mean life with rests to geometric mean life under continuous cycling.

caused by frequency variations of 3 to 30 applications of load per minute had no effect on fatigue life. Later testing indicated that when the rest period was decreased by an increase in frequency of from 30 to 100 applications per minute, fatigue life was also decreased. These results indicate that there

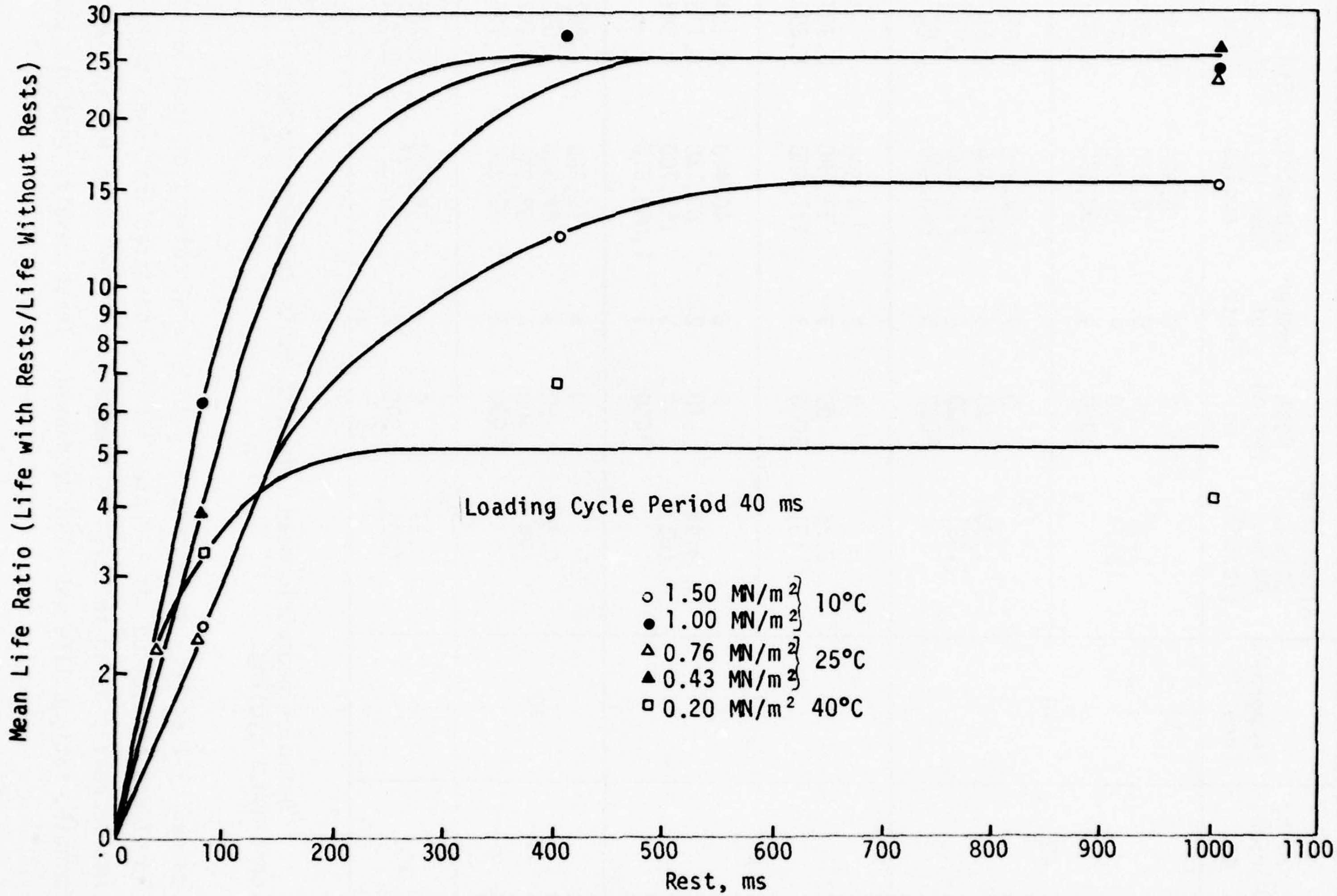


Figure 9. Effect of Increasing Rest Periods on Fatigue Life (after Raithby and Sterling, Reference 8)

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

Van Dijk et al. have also demonstrated the beneficial effect of rest periods. When they added a rest period to the loading pulse (Figure 10 [Reference 17]), the $S\text{-}N_f$ curve was shifted to the right; i.e., fatigue life was increased. The interesting feature of this 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. This waveform closely simulates the stress pulse caused by a wheel moving across a pavement. The authors also found evidence that seems to indicate the existence of some maximum rest period above which longer rest periods do not increase fatigue life (Reference 17).

2. Load Duration. Deacon studied the effect of load duration by varying the duration while holding the loading frequency constant; thus the rest period was also varied. Figure 11 (Reference 4) illustrates that load duration had a significant effect on fatigue life in that increased load duration produced shorter fatigue life. However, the length of the rest period was decreasing as the load duration increased (Reference 4).

3. Frequency of Loading. To determine the effect of loading frequency, Pell and Taylor 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 (Reference 19). They discovered that increasing the loading frequency increased the fatigue life and that the most significant change occurred at frequencies below 200 cycles per minute. Figure 12 (Reference 19) shows the relationship between loading frequency and cycles to failure.

For purposes of this report, loading period is defined as the length of time from the beginning of one load sequence to the beginning of another. Thus, the loading period includes load duration and rest period. Table 3 summarizes two sets of data, obtained by Raithby and Sterling, from which the effect of the loading period can be determined. One series of tests involved a loading period of 40 ms with rest periods of 0 to 1000 ms; the second involved a loading period of 400 ms with rest periods of 0 to 800 ms. The

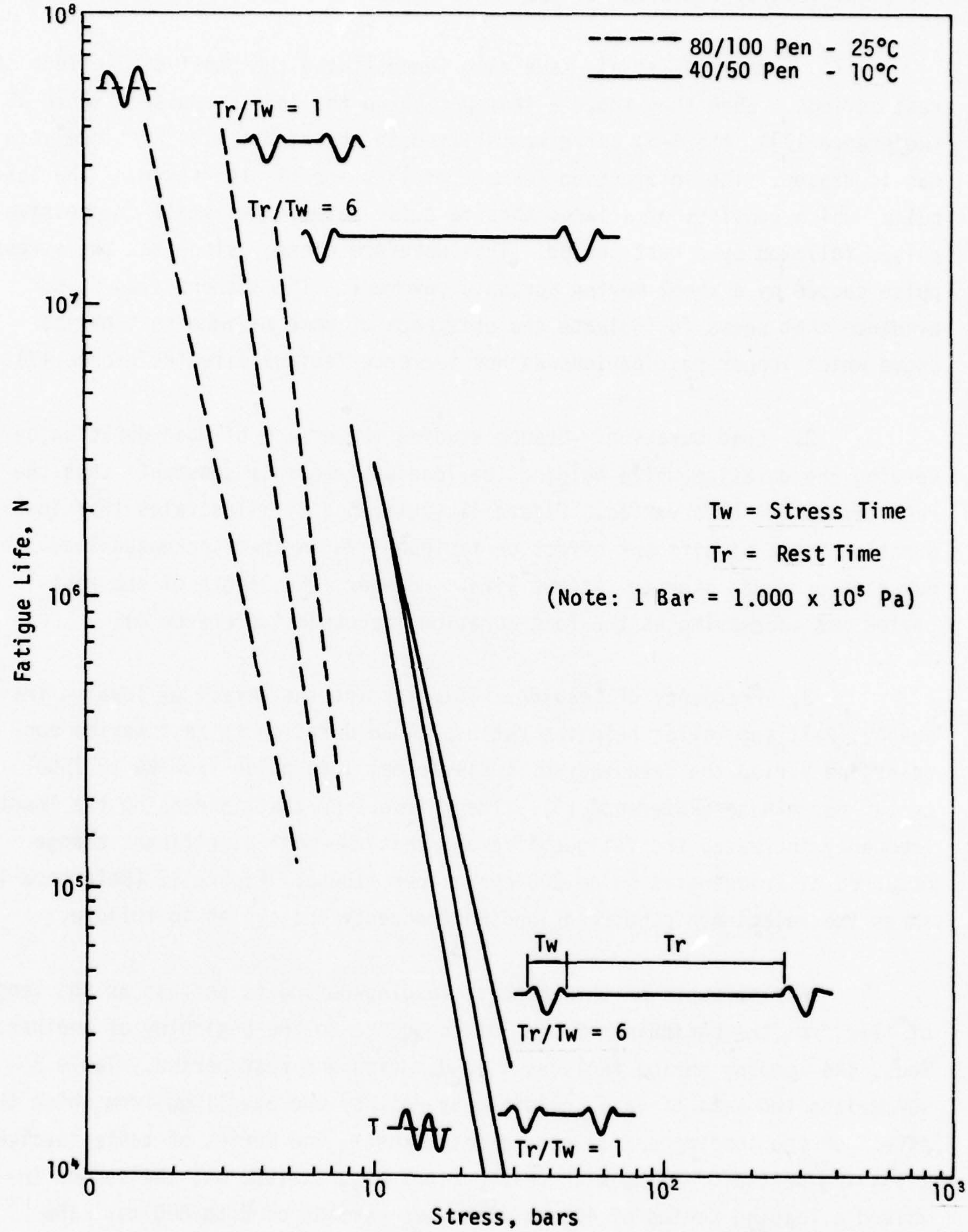


Figure 10. Effect of Rest Periods on S-N Relationships for a Cantilever Test (after Van Dijk et al., Reference 17)

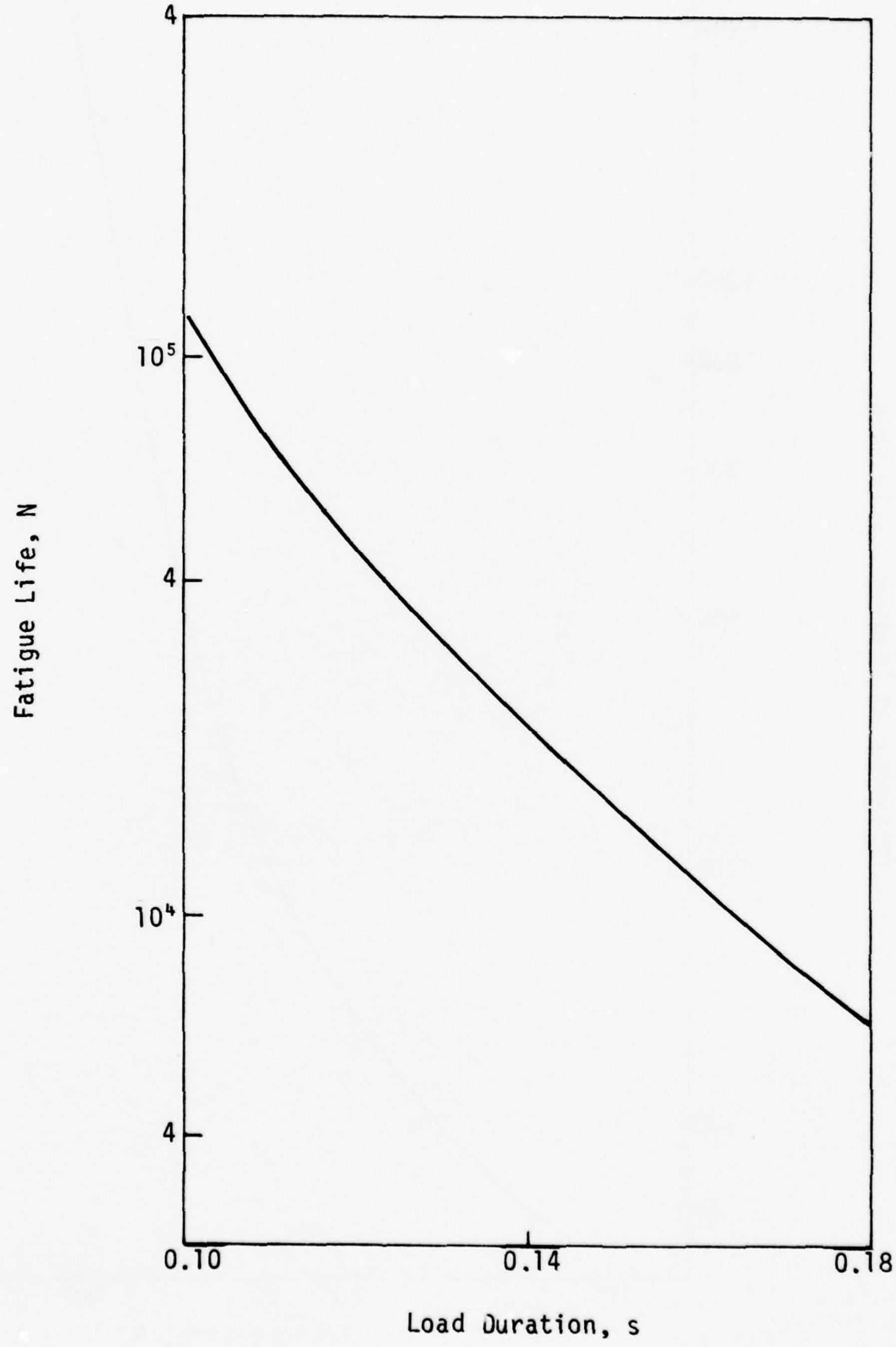


Figure 11. Effect of Load Duration on Fatigue Life for a Flexure Test (after Deacon, Reference 4)

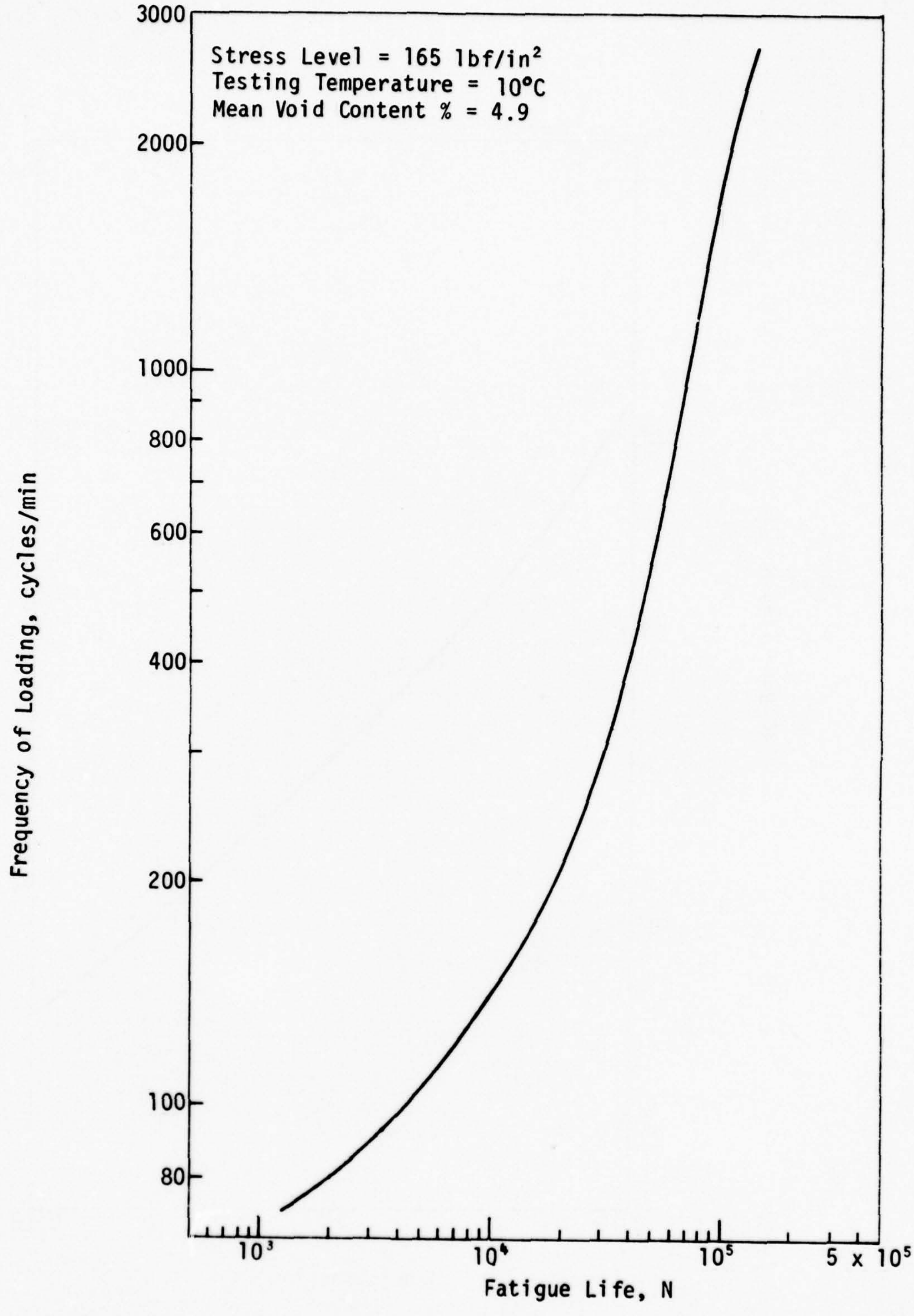


Figure 12. Effect of Loading Frequency on Fatigue Life Using Sinusoidal Loading and a Rotating Cantilever Test (after Pell and Taylor, Reference 19)

specimens subjected to the 400-ms loading period had much shorter fatigue lives, though they were tested at a lower stress level. Therefore, decreasing the loading period, which increased the frequency for a given rest period, increased fatigue life (References 7 and 8).

Creep

Creep is defined as the deformation of a material under constant stress. After studying high-temperature metal fatigue, however, Manson concluded that because failure of a material is the result of the combined effects of both alternating strain and creep, the time of exposure in relation to stress, as well as the number of cycles, must enter into the analysis (Reference 20). For example, Lai and Anderson performed a series of cyclic creep tests on AC under uniaxial compression. Specimens deformed to various degrees depending on the duration of the load, which ranged from 10 to 1000 seconds. While these are long loading periods compared to those used in most fatigue studies, creep deformation did occur in these tests (Reference 21).

Deacon, in designing a cyclic flexural fatigue-testing apparatus, provided a stress reversal to force the specimen back to its original undeflected position (Figure 13 [Reference 4]). This process eliminated creep or permanent deformation even though the load duration was only 0.1 second (Reference 4). Raithby and Sterling also recognized the possibility of creep during testing, and their test procedure prevents the occurrence of permanent deformations (Reference 8).

Majidzadeh et al. performed fatigue and creep tests on sand asphalt specimens. Load amplitude versus fatigue life and creep time to failure are plotted in Figure 14 (Reference 22), which shows a close relationship between creep and fatigue. Guirguis and Majidzadeh point out that progressive internal damage can occur in both fatigue and creep fracture testing, causing fracture of the specimen (Reference 23).

To combine fatigue and creep damage, Manson suggests that at failure the percentage of creep-rupture damage plus the percentage of fatigue damage

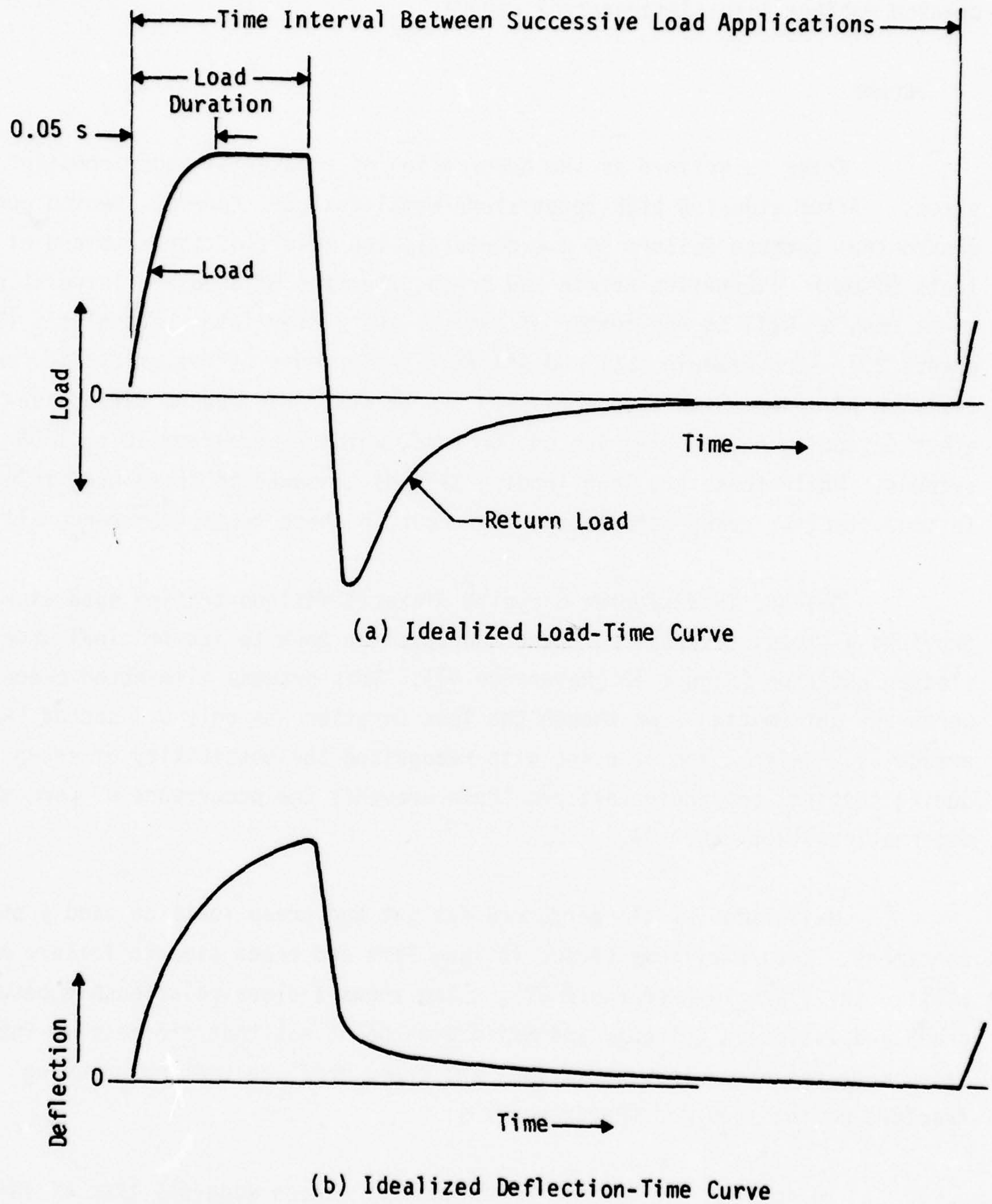


Figure 13. Load Versus Time and Deflection Versus Time Relationships for Constant-Stress Flexure Apparatus (after Deacon, Reference 4)

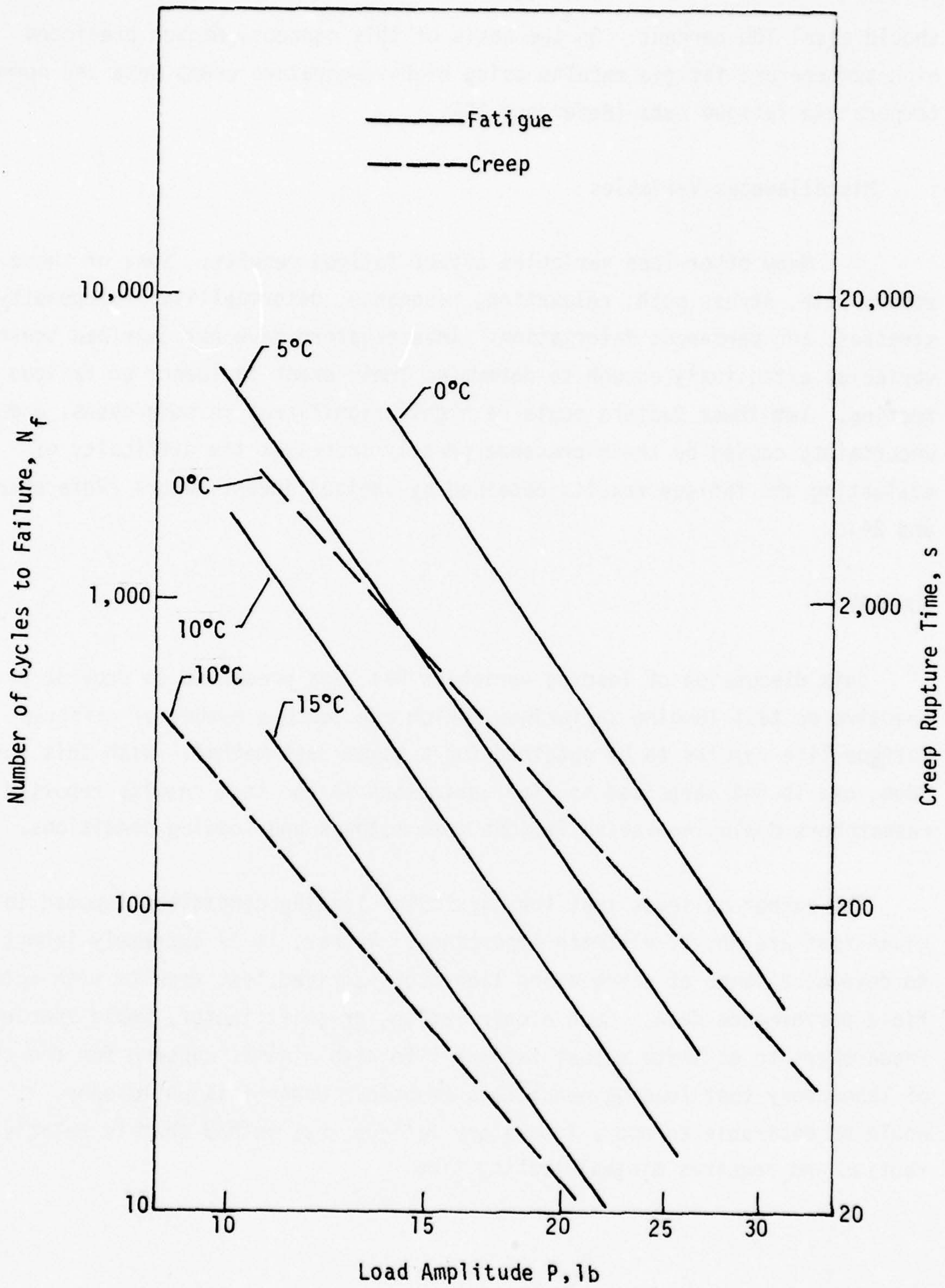


Figure 14. Comparison of Creep and Fatigue for a Flexure Test (after Majidzadeh et al., Reference 22)

should equal 100 percent. On the basis of this concept, Manson predicted high-temperature fatigue results using high-temperature creep data and normal temperature fatigue data (Reference 20).

Miscellaneous Variables

Many other load variables affect fatigue results. Some of these are strain rate, stress path, relaxation, resonance, deformability, homogeneity of stresses, and permanent deformation. Investigators have not examined these variables extensively enough to determine their exact influence on fatigue testing. Yet these factors could be highly significant in some cases, and the uncertainty caused by their presence greatly increases the difficulty of evaluating the fatigue results obtained by various investigators (References 1 and 24).

SUMMARY

This discussion of loading variables has been presented to provide perspective on test loading variations, which can cause a number of different fatigue life results to be obtained for a given test method. With this knowledge, one is not surprised to find variations in the test results reported by researchers employing varied fatigue test methods and loading conditions.

The author believes that the particular loading conditions imposed in a given test are not of ultimate importance. Rather, it is extremely important to develop a means of correlating laboratory-derived test results with actual field performance data. Such a correlation, or shift factor, would enable researchers to estimate actual fatigue life with minimal concern for the type of laboratory test loading conditions imposed. Under this philosophy, it would be desirable to use a laboratory fatigue test method that is relatively routine and requires minimal testing time.

SECTION III
LITERATURE REVIEW AND ANALYSIS OF TEST METHODS

INTRODUCTION

Researchers have developed many test methods for characterizing the response of bituminous mixes to both load and deformation. In general, these methods may be placed in one of two categories: tests used for evaluating fatigue (fatigue tests), and tests used to measure a single strength parameter (herein called routine design tests).

In fatigue testing, a specimen is repetitively loaded, or deformed, until failure is reached. The magnitude of the applied stress, or deformation, is such that the specimen does not fail under a single application of stress; indeed, the objective is to determine the number of cycles required to produce failure at a given stress level. In routine design testing, however, the specimen is taken to failure under a single cycle of loading, or is deformed to some specified strain level. Both fatigue and routine design tests are described and reviewed in this section.

FATIGUE TESTS

For purposes of this report, fatigue tests are defined as test procedures in which samples are repetitively loaded to produce a failure that simulates the failure experienced by an in-service pavement. Many approaches have been taken to fatigue testing. Each method produces unique test results. Table 4 (Reference 3) lists the various types of fatigue tests, the names of investigators who have used them, and publication references.

Flexure Test

Because the repeated-flexure apparatus is widely accepted, many researchers have used similar data collection methods and equipment to perform tests, although control and load systems may be varied. Air or pneumatic loading or electrohydraulic loading systems can be used for testing beams. The pneumatic pressure system has been used predominantly for testing in the controlled-stress mode because it must be monitored constantly when operated

TABLE 4. SUMMARY OF FATIGUE TESTS, INVESTIGATORS, AND REFERENCES

Test Type	Investigators	References
Flexure	Deacon and Monismith	25, 26, 27
	Epps and Monismith	1
	Kallas et al.	28, 29
	Kirk	30
	Majidzadeh et al.	22
	Monismith et al.	14, 31, 32
	Santucci and Schmidt	33
Rotating Cantilever	Pell et al.	13, 19, 34
	McElvaney	5
Uniaxial	Kallas	9
	Kallas and Riley	29
	Howeedy and Herrin	35
	Raithby and Sterling	7
Repeated-Load Indirect Tensile	Moore and Kennedy	36
	Navarro and Kennedy	37
	Cowher and Kennedy	6
Cantilever	Bazin and Saunier	38
	Coffman et al.	39
	Freeme and Marais	40
	Van Dijk et al.	17
	Verstraeten	41, 42
Triaxial	Barksdale and Hicks	43
	Haas	(data unpublished)
	Morris et al.	10
	Larew and Leonards	44
	Kallas and Riley	29
Torsional	Pell	34
Diaphragm	Jimenez and Gallaway	45, 46
Rolling Wheel	Bazin and Saunier	38
	Van Dijk et al.	17
	Howeedy and Herrin	35
Simulated Subgrade	Monismith	47

(Reference 3)

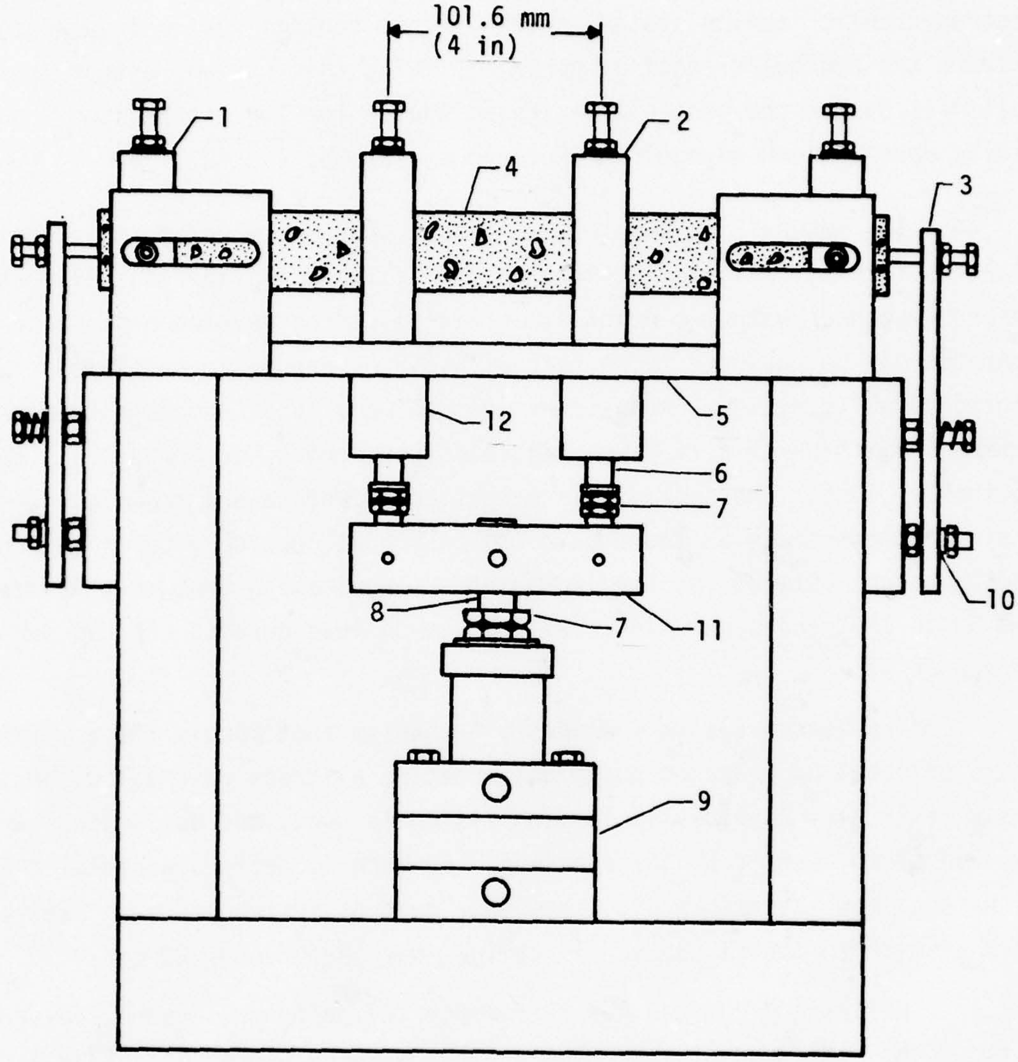
in a controlled-strain mode and because it is difficult to vary the load in order to maintain the constant deflection required for that mode. The pneumatic system can apply only a block pattern (waveform) of loading. In the electrohydraulic loading system, an electronic control system is used to activate the hydraulic loading mechanism. With this system, either the controlled-stress or the controlled-strain mode of loading can be used, and any loading waveform can be applied (References 16, 36, and 48).

In flexural fatigue testing a beam specimen mounted in a loading apparatus is used. Figure 15 (Reference 4) illustrates the controlled-stress flexure apparatus with two-point symmetrical loading developed by Deacon. The apparatus can be equipped to operate with air or pneumatic pressure or with an electrohydraulic system. Adjustments can be made to accommodate specimens of different sizes up to a 76.2-mm (3-inch)-square cross section usually 381 mm (15 inches) long. The specimen is permitted to rotate and translate by means of pinned connections at the ends. The two-point loading results in a pure bending moment between the loading points. The loading frequency varies from 30 to 100 cycles per minute with a common load duration of 0.1 second (Reference 4).

The Deacon system includes a mechanism that forces the specimen back to its original undeflected position, creating a stress reversal without strain reversal. A pneumatic loading system is used, and deflections are measured at the center of the specimen. Failure is defined as total fracture of the specimen (Reference 4). This same type of system has been used by Epps and Monismith in their research investigations (References 26 and 32).

Kallas and Puzinauskas (Reference 28) performed controlled-stress tests on the same type of apparatus as that used by Deacon, but they increased the specimen size and used an electrohydraulic loading system. A haversine waveform load pattern with a 0.1-second load duration and a 0.4-second rest period was used in these tests.

In Reference 33, Santucci and Schmidt report on the controlled-strain tests they conducted with equipment similar to Deacon's. A 0.05-second load followed by a 0.55-second rest period was used to load the specimen. Failure was defined as the number of load repetitions required to reduce the specimen to 60 percent of its initial stiffness. Kirk reports on similar controlled-strain test procedures in Reference 30.



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

Figure 15. Repeated Flexure Apparatus (after Deacon, Reference 4)

The procedures described in the preceding paragraphs are categorized as the phenomenological approach to fatigue analysis. The data obtained are analyzed by developing a relationship between an applied stress or strain level and an observed number of repetitions to failure (Reference 49). The stress-fatigue life relationship determined from the tests is correlated using a least squares regression analysis to develop a log-log plot of σ versus N_f in the following form:

$$N_f = K_2 \, (1/\sigma)^{n_2}$$

where

N_f = number of load applications to failure
K_2 = constant dependent on material characteristics
σ = initial extreme fiber bending stress
n_2 = constant (slope of regression line)

Thus, in controlled stress, equations of the above form can be used to estimate the fatigue life of an AC mix (Reference 28).

Similarly, a strain-fatigue life relationship can be developed from controlled-strain data. The log-log plots of σ versus N_f are of the following form:

$$N_f = K_1 \, (1/\varepsilon)^{n_1}$$

where

N_f = number of load repetitions to failure
K_1 = constant dependent on material characteristics
ε = initial bending strain based on center point deflection of specimen
n_1 = constant (slope of regression line) (Reference 28)

Figure 4 (in Section II) illustrates typical fatigue curves for both stress- and strain-controlled testing.

Majidzadeh et al. have studied the flexural fatigue life of AC in a controlled-stress mode using the concept of an elastic foundation (Reference 50). The beam specimens rested on a gum rubber block, and a cyclic load was applied by an electrohydraulic test machine, which generated a dynamic haversine load function at a frequency of 5 Hz. The load, applied at the rate of one to two repetitions per second, was transmitted to the test specimen through a loading head that rested on a hard rubber cushion on top of the beam. Figure 16 is a schematic illustration of the test apparatus.

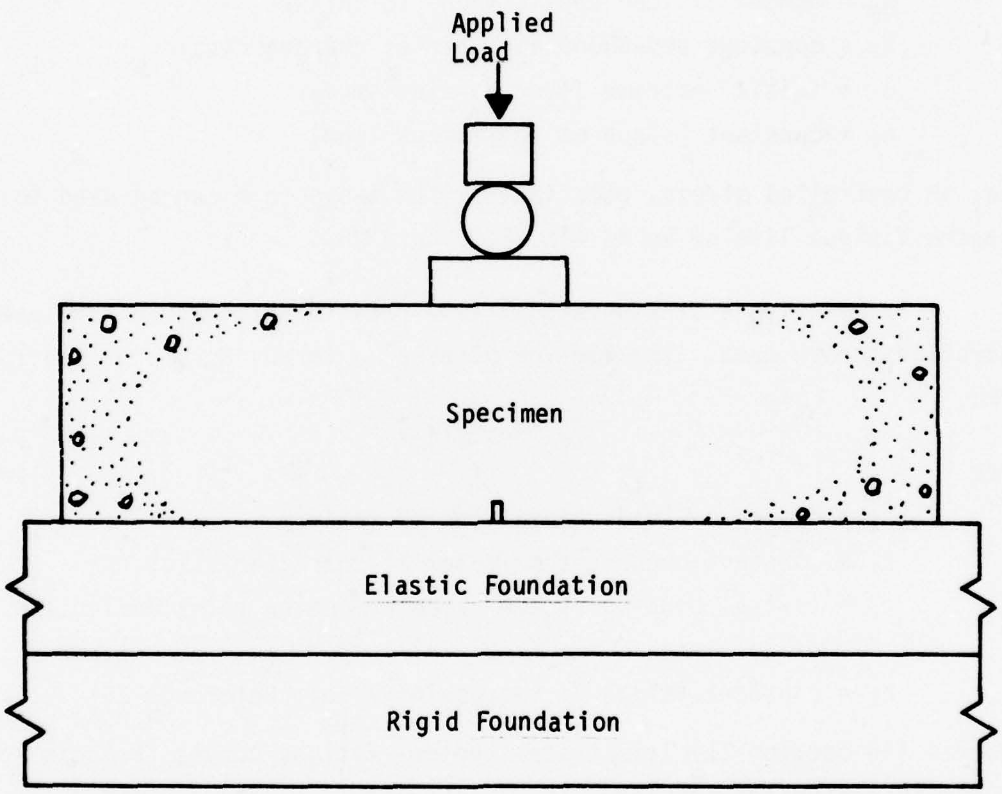


Figure 16. Flexure Apparatus

Although the test equipment used by Majidzadeh is similar to that used in other flexure tests, the data analysis is based upon continuum fracture mechanics. This mechanistic approach to the fatigue life of AC is based on a theory that describes the process of crack initiation and propagation and the specimen's ultimate failure (Reference 51). The crack propagation model, $dc/dN = AK^n$ (Paris equation), can be simply expressed as

$$N_f = \int_{c_o}^{c_f} \frac{dc}{AK^n}$$

where

N_f = number of cycles of load required to produce failure

c_f = critical crack depth

c_o = depth of starter flaw from which the crack propagates

dc = rate of crack propagation

K = stress intensity factor

A and n = material constants associated with crack growth

The rate of crack propagation is dependent on A, K, and n. The variables A and n are affected by such parameters as load frequency, external boundary conditions, temperature, dimensions of the test specimen, and statistical distribution of flaws in the material. A is most strongly affected by asphalt content and temperature; typical values would range from 0.40×10^{-6} to 3.0×10^{-6}. The constant n has a value less than 4. K, the stress-intensity factor, is a measure of the magnitude of the stress field in the vicinity of the crack as a function of load, size of crack, and geometrical and boundary conditions. The K-value is also proportional to the force that produces the crack extension. The critical value of the stress-intensity factor, K_{IC}, is a material constant that is the failure criterion for both fatigue and fracture. The parameter K_{IC}, also called fracture toughness, describes the final stages of crack propagation. Thus, failure by cracking is defined in terms of the stress-intensity factor and catastrophic failure in terms of fracture toughness (References 51 and 52).

Beam specimens are difficult to obtain from an in-service pavement because of their size. Large sections of pavement, perhaps three feet square, must be removed, transported to a laboratory, and cut to the desired size. Although nothing could be found in the literature to verify or disclaim his opinion, this author believes that the transportation of large samples from field to laboratory may alter stress conditions in the material. Thus, the sample tested in the laboratory may not truly represent the condition of the AC pavement in place. An additional disadvantage in the use of beam specimens is the length of time required to perform the test.

In summary, the flexural beam fatigue test is a versatile method of determining fatigue life. The experimentor can program variations in the mode of loading (controlled stress or strain), the type of loading (simple or compound), and the frequency of loading. Two methods of analysis (phenomenological and mechanistic) are also available. Laboratory beam samples are relatively simple to fabricate, and the testing is not extremely complicated although it is time-consuming and expensive because the beams are taken to failure. However, field specimens, because of their size, are difficult to obtain and are awkward to handle and transport from the field to the laboratory.

Rotating Bending Cantilever Test

Pell et al. have used the rotating bending cantilever type of testing apparatus (Figure 17 [Reference 34]) to determine the fatigue life of AC. The specimen is *necked down* to a circular cross section whose diameter increases symmetrically from mid-length. The specimen diameter varies from 88.9 mm (3.5 inches) at the ends to 63.5 mm (2.5 inches) at the center. A constant-stress point load is applied to the specimen through a wire connected to the head of the apparatus, and the specimen is rotated by the shaft attached to its base. A variable-speed electric motor permits the specimen to be tested over a speed range of 80 to 3000 revolutions per minute. The loading produces a sinusoidally varying bending stress of constant amplitude at any particular cross section of the specimen. The maximum stress, calculated by elastic theory, occurs just below the neck. Failure is defined as complete rupture of the specimen. A least squares regression analysis is used to correlate strain and fatigue life in an equation of the form $N_f = K\ (1/\varepsilon)^n$ (References 13, 19, 34).

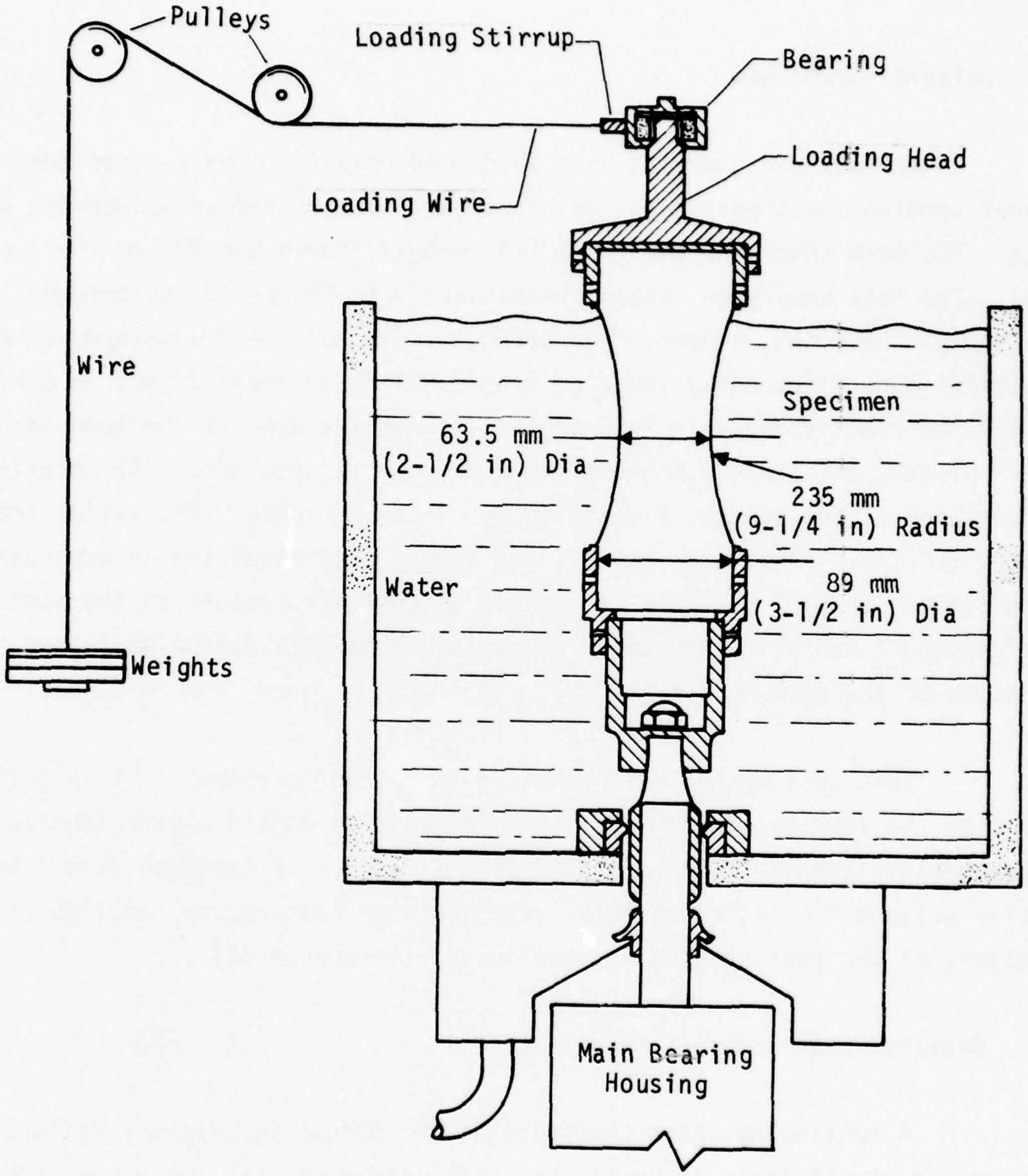


Figure 17. Rotating Cantilever Loading System (after Pell, Reference 34)

This test method is versatile in that one can apply simple or compound loads at different frequencies in the controlled-stress mode. However, the necessity of fabricating the odd-shaped specimen, which would be extremely difficult, if not impossible, to obtain from the field, is a major disadvantage.

Uniaxial Load Test

Raithby and Sterling have performed uniaxial load fatigue tests in direct tension and compression, using specimens sawn from an AC wearing surface. The test specimens are 75 mm (∿3 inches) square and 225 mm (∿9 inches) long. The test apparatus, shown schematically in Figure 18 (Reference 7), can apply sinusoidal, square, triangular, or sawtooth load waveforms or deflections over a frequency range of from 0.001 Hz to about 30 Hz. A servo-controlled electrohydraulic fatigue testing machine applies the load through steel plates, which are exposed to the ends of the specimen. The uniaxial deformation of the sample is measured by Linear Variable Differential Transducers (LVDTs). Stiffness, stress, and strain are calculated in accordance with elastic theory. Failure is defined as complete rupture of the specimen (References 7 and 8). The number of cycles to failure can be expressed by an equation of the form $N_f = K\ (1/\sigma)^n$.

This test method has presented some major problems. It is difficult to align the samples; therefore it is difficult to obtain a pure tensile force because misalignment introduces a bending stress. The specimen cannot be easily gripped for testing and the test could be hampered by handling problems. Analysis of the test results is complicated (Reference 53).

Repeated-Load Indirect Tensile Test

A continuing research effort at the Center for Highway Research at the University of Texas at Austin has been concerned with the use of the repeated-load indirect tensile test for determining AC fatigue life (Reference 54). The test was developed on the basis of the theory of elasticity, through which it can be shown that applying a uniform compressive load perpendicular

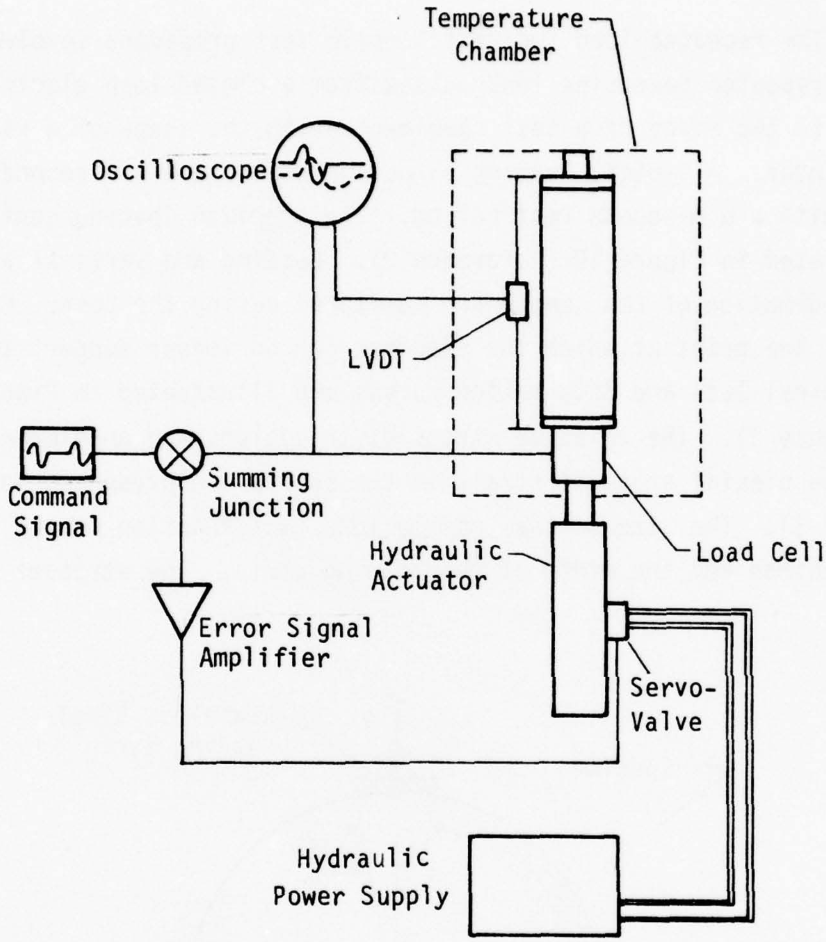


Figure 18. Uniaxial Load Test (after Raithby and Sterling, Reference 7)

to the horizontal diametral plane of a thin disk produces a uniform tensile stress over the vertical diametral plane containing the applied load (References 55, 56, and 57). After repeated loading, the specimen will fail by splitting along the vertical diameter.

The repeated-load indirect tensile test procedure involves application of repeated haversine load pulses from a closed-loop electrohydraulic apparatus to the sides of a test specimen having the shape of a right circular cylinder. A typical loading situation would be a 0.4-second load duration with a 0.6-second rest period. The specimen loading configuration is illustrated in Figure 19 (Reference 3). Loading and vertical and horizontal deformation of the sample are monitored during the test. Failure is defined as the point at which the specimen can no longer support the applied load. Typical load and deformation curves are illustrated in Figures 20 and 21 (Reference 3). The relative stress distributions and an element illustrating the biaxial state of stress in the sample are presented in Figure 22 (Reference 3). The size of the tensile zone is a function of the diameter of the specimen and the width of the loading strip. The stresses in the

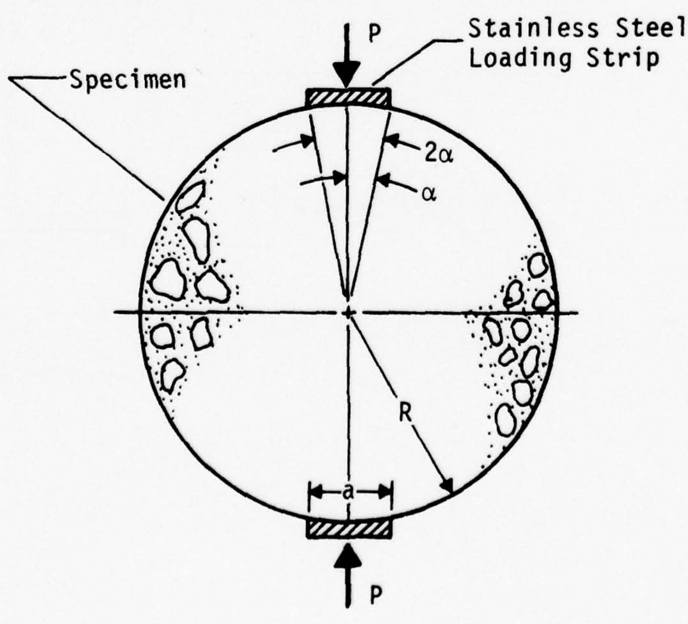


Figure 19. Indirect Tensile Test (after Porter and Kennedy, Reference 3)

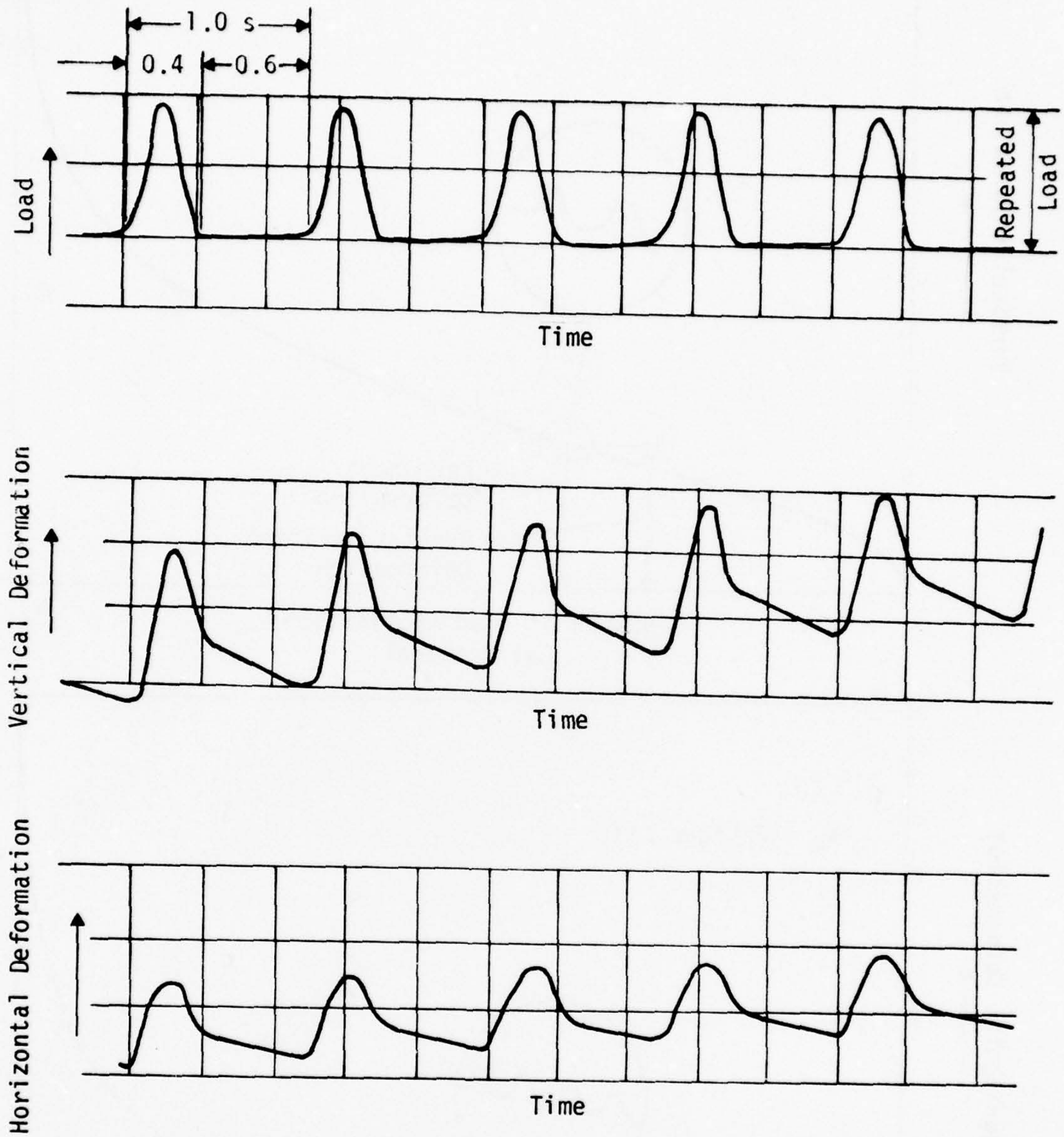


Figure 20. Load Pulse and Associated Deformation Data for Repeated-Load Indirect Tensile Test (after Porter and Kennedy, Reference 3)

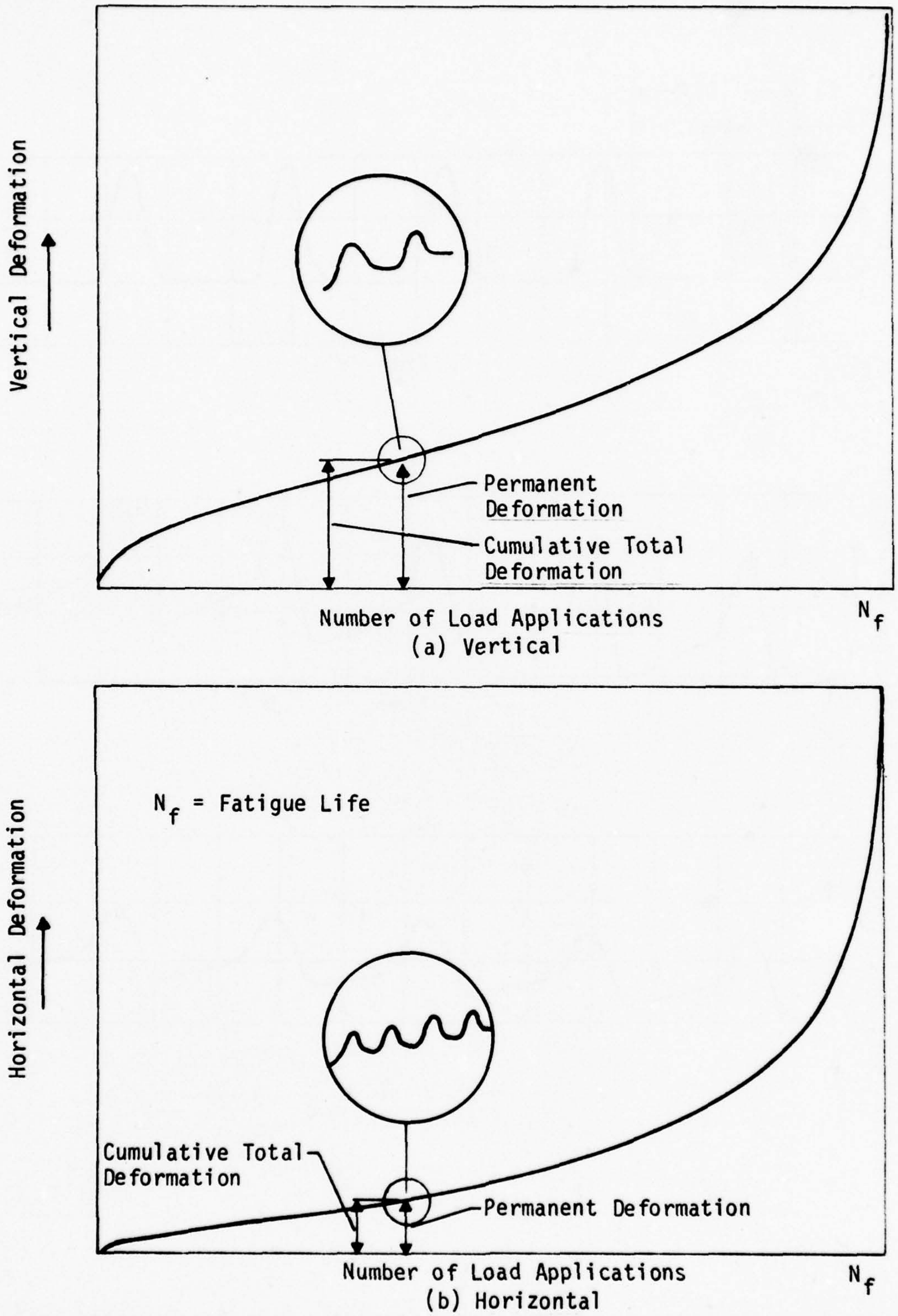


Figure 21. Relationships Between Number of Load Applications and Vertical and Horizontal Deformation for Repeated-Load Indirect Tensile Test (after Porter and Kennedy, Reference 3)

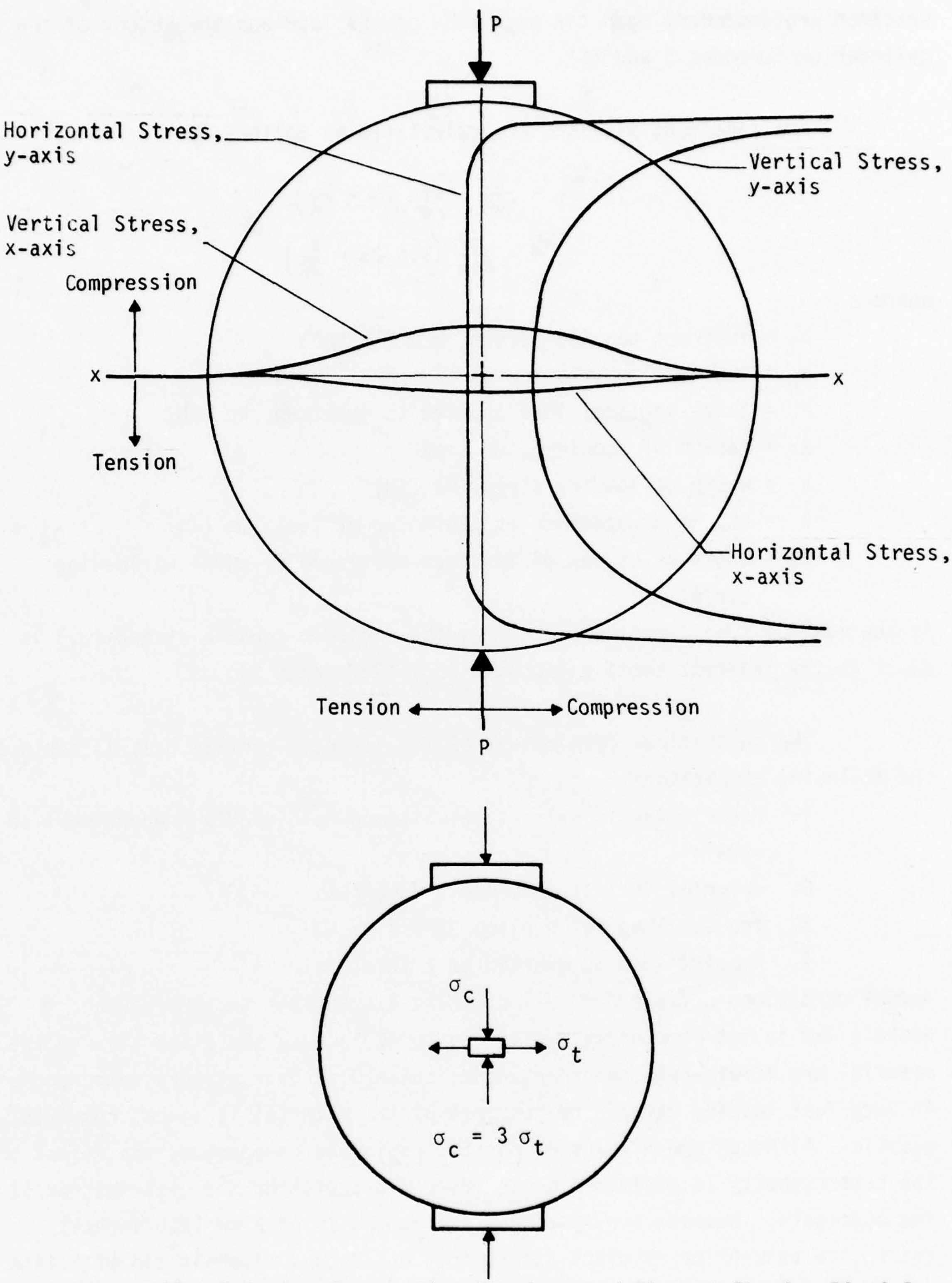


Figure 22. Relative Stress Distributions and Element Showing Biaxial State of Stress for Indirect Tensile Test (after Porter and Kennedy, Reference 3)

specimen are dependent upon the magnitude of the load and the height of the cylinder (References 3 and 58).

The resultant stresses are calculated as follows:

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

$$\sigma_c = -\frac{6P}{\pi ah}\left(\sin 2\alpha - \frac{a}{2R}\right)$$

where

σ_T = indirect tensile stress, MPa (lb/in^2)

σ_c = indirect compressive stress, MPa (lb/in^2)

P = total vertical load applied to specimen, kg (lb)

R = radius of specimen, mm (in)

a = width of loading strip, mm (in)

h = height of specimen at beginning of test, mm (in)

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

At the maximum total vertical load (P), the indirect tensile stress (σ_T) is equal to the indirect tensile strength (S_T) (Reference 3).

The theoretical development of the indirect tensile test is based on the following assumptions:

1. Hooke's law is valid (i.e., stress is directly proportional to strain).
2. Material is isotropic and homogenous.
3. The specimen is in plane stress.
4. A point load is exerted on a thin disk.

Actual conditions deviate from all of these assumptions to some degree. Hooke's law is not completely applicable to AC because the properties of the material are strain-rate dependent, particularly at high mixture temperatures. At very fast loading rates, the response of the material is almost completely elastic. Although the mixture is not isotropic and homogenous, the effect of the heterogeneity is minimized by the random orientation and distribution of the aggregate. Because the specimens are nominally 63.5 mm (2.5 inches) thick, the assumption of plane stress does not apply. Asphalt can withstand more compressive stress than tensile stress as Figure 22 shows. Thus, even though the loading is not a point load on a thin disk, the specimen fails in tension so that the point-load assumption is not grossly invalidated. However, for the conditions to which a pavement is likely to be exposed (i.e., low stress, high strain rate, and temperatures within normal range), the lack of ideal conditions does not invalidate the theoretical assumptions to the extent that the results are inapplicable for engineering analysis of a pavement (References 48, 53, and 58).

A stress-fatigue life relationship can be developed in an equation of the form $N_f = K (1/\sigma)$. Figure 23 (Reference 3) presents fatigue curves developed by several test methods. Note that the fatigue life is plotted against the stress difference. This method is used to account for the fact that the repeated-load indirect tensile test produces a biaxial state of stress in the specimen, whereas the other test procedures produce a uniaxial state of stress. Of the laboratory-produced fatigue curves shown in Figure 23, it is obvious that the approach used by Kennedy et al. provides the most conservative estimate of fatigue life for a given stress difference.

Use of the repeated-load indirect tensile test method is particularly appealing because of the type of specimen used and the relative simplicity of the test procedure. Field or laboratory Marshall-size specimens can be easily obtained or prepared and transported.

One major problem with the test method is that no tensile load is applied to the cylinder (Reference 48). In the field, a tensile force (elastic rebound) would occur after application of the compressive load; thus, the pavement would tend to return to its original undeflected position. Because this test does not apply a tensile load to the specimen, the laboratory-determined fatigue life may not be comparable to actual fatigue life in the field. The lack of a tensile load probably explains why the Kennedy et al. fatigue curve (Figure 23) is the most conservative predictor of fatigue life.

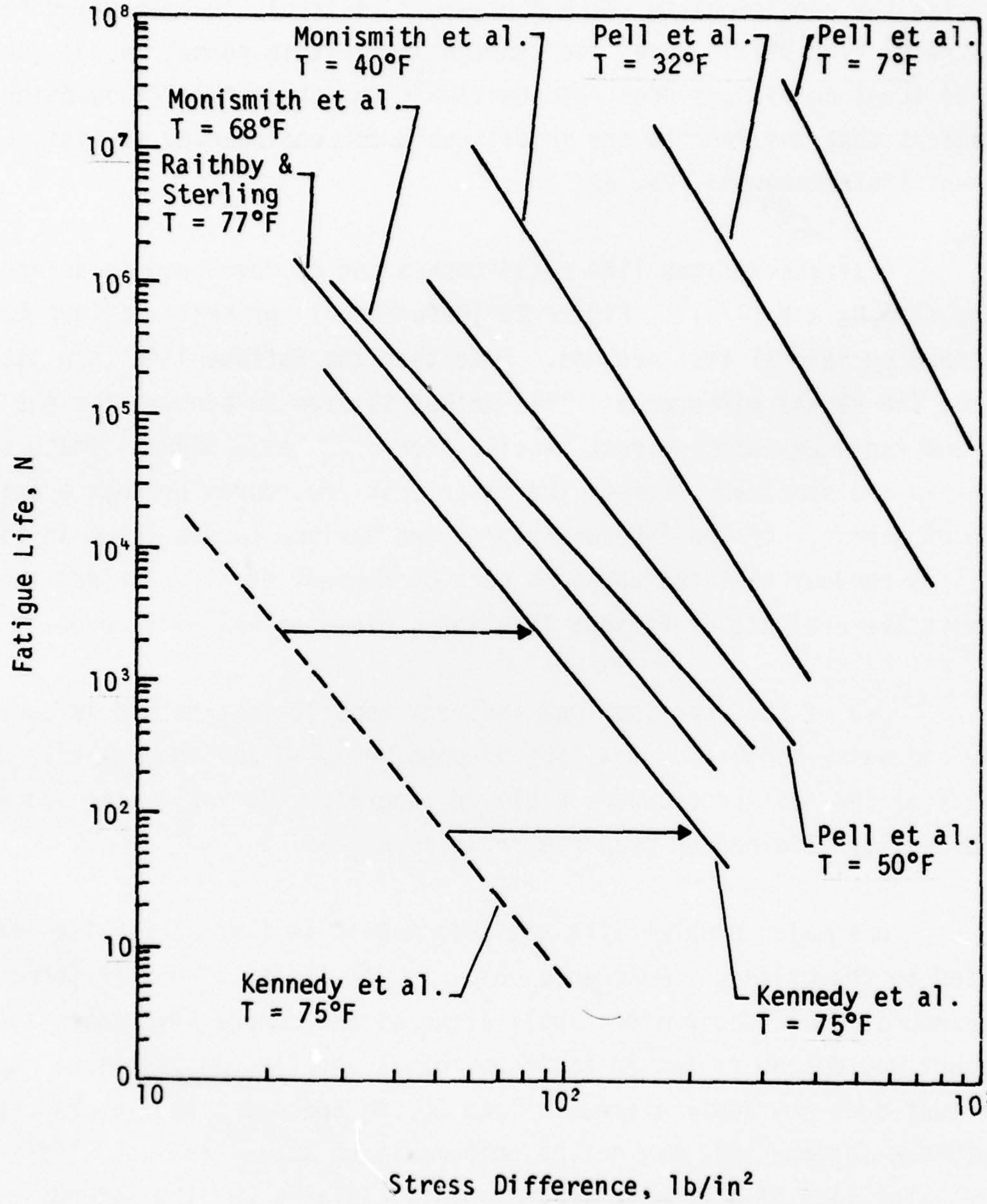


Figure 23. Typical Stress Difference-Fatigue Life Relationships for Various Test Methods (after Porter and Kennedy, Reference 3)

Cantilever Test

The cantilever test method has been used in investigations by Bazin and Saunier, Coffman et al., Freeme and Marais, Van Dijk et al., and Verstraeten. The specimen used for the cantilever test is trapezoidal in shape (Figure 24 [Reference 39]). The specimen is tested in a closed-loop electrohydraulic loading system. It is loaded through a pretensioned wire attached through the top plate as illustrated in Figure 25 (Reference 39). The loading is stress-controlled, a sinusoidal pattern creating a constant stress along the outside fibers of the specimen. Lines of conductive paint connected to a galvonometer are placed on the sloping faces of the trapezoid to detect cracks so that the failure of the samples can be monitored. Failure is defined as complete fracture of the sample. The results can be expressed by an equation of the form $N_f = K\,(1/\varepsilon)^n$ (References 17, 38, 39, and 40).

The trapezoidal specimen was chosen so that the maximum stress can be located near the middle of the sample. Field samples can be sawn from a pavement and cut into a trapezoidal shape, and laboratory specimens can be fabricated. The method allows experimentors to apply varied loading conditions by using an electrohydraulic load and control system. The major difficulties in using the cantilever test method are the problems inherent in fabricating a trapezoidal specimen and in placing the specimen in the loading apparatus.

Other Fatigue Tests

Other tests that have been used to determine AC fatigue life include triaxial, torsional, diaphragm, rolling wheel, and flexure on a simulated subgrade. The limited volume of test data available from these tests precludes any meaningful evaluation of the procedures used.

Morris et al. have used repeated-load triaxial tests to predict permanent deformation of AC pavements. The procedure consists of applying to the specimen a compressive confining stress and both tensile and compressive axial stresses (Reference 10).

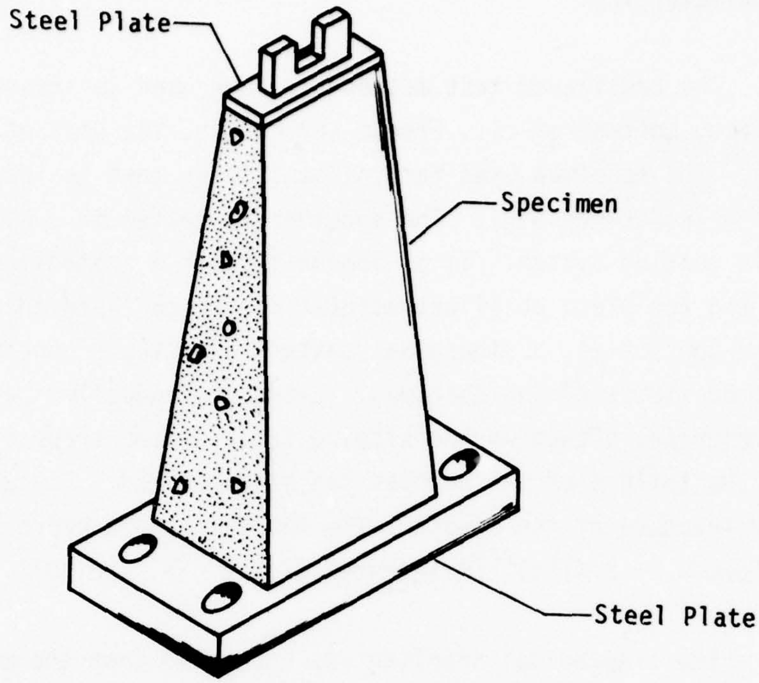


Figure 24. Trapezoidal Specimen (after Coffman et al., Reference 39)

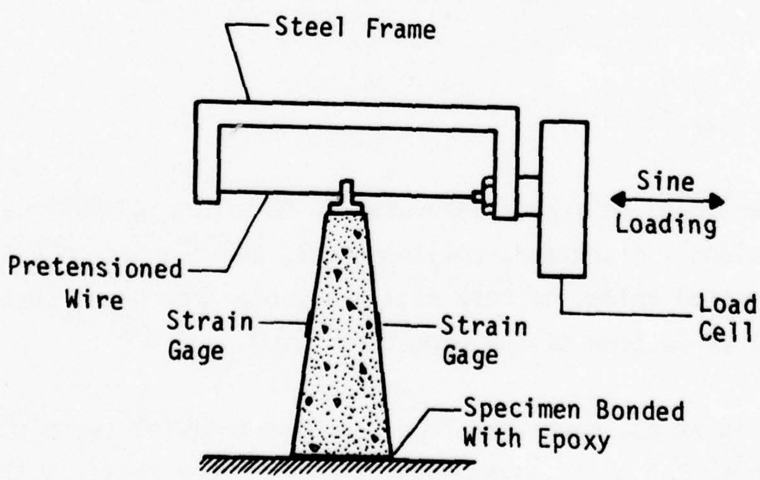


Figure 25. Trapezoidal Specimen Loading Apparatus (after Coffman et al., Reference 39)

By applying a constant-strain amplitude, Pell conducted torsional tests on solid specimens, thereby creating a pure shear biaxial state of stress (Reference 34).

Jimenez and Gallaway performed fatigue tests on AC using a device called a deflectometer. To simulate a subgrade, an 18-inch-diameter sample was mounted on top of a membrane-covered reservoir, and repeated loads were applied to the center of the specimen (References 45 and 46).

Rolling-wheel tests, in which the wheel moves back and forth, are conducted on either circular tests tracks or indoor laboratory tracks (References 17, 35, and 38).

Monismith devised a controlled-strain flexural fatigue test in which a simulated subgrade was used. The apparatus consisted of a beam specimen resting on a rubber pad placed over a bed of springs. The loading was applied to the center of the specimen (Reference 47).

Each of these test methods suffers from one or more of the following problems: difficulty of specimen fabrication, equipment cost, complexity of operation, or length of time required to complete the test (Reference 3).

ROUTINE DESIGN TESTS

A routine design test is a procedure in which the sample is subjected to a single application of stress so that its ultimate strength, or its strength at a prescribed deformation, may be determined. The results of these types of tests are examined here for their potential as indicators of fatigue properties. The intent has been to correlate a single strength property with a known fatigue parameter for the purpose of estimating the fatigue characteristics of an AC mixture. Table 5 lists the various types of routine design tests, the names of investigators who have used them, and publication references.

TABLE 5. SUMMARY OF ROUTINE DESIGN TESTS, INVESTIGATORS, AND REFERENCES

Test Type	Investigators	References
Indirect Tensile	Kennedy et al.	59
Resilient Modulus Indirect Tensile	Schmidt	55
Double Punch	Jimenez	60
Cohesiometer	Jimenez	61
Direct Tension	Epps and Monismith	27
Flexural Beam	Busby and Rader	62
Shell Nomograph	Van der Poel	63
	Heukelom	64
	Heukelom and Klomp	65
Asphalt	Pell and Cooper	66
	Anderson et al.	67
	Schmidt	68
	Van Dijk	17

Indirect Tensile Test

The indirect tensile test is a routine design test performed on a standard Marshall-size cylindrical specimen with standard testing equipment. The sample is loaded with compressive loads distributed along two opposite generators. Thaulow (Reference 69) reports that the indirect tensile strength is largely independent of the length and diameter of the specimen. Marshall-size specimens are used because they can be easily prepared and handled. Figure 26 (Reference 53) schematically illustrates the loading method. The loading produces a relatively uniform tensile stress perpendicular to and along the diametral plane containing the applied load. The sample is loaded at a constant rate to failure. The load and the vertical and horizontal deformations of the sample are monitored. The theoretical development for the test is the same as that for the repeated-load indirect tensile test.

The Center for Highway Research has used the indirect tensile test extensively (Reference 59). Maupin, at the Virginia Highway and Transportation Research Council, has also studied the indirect tensile test (Reference 48). In both studies, "acceptable" correlations between indirect tensile data and fatigue life were found.

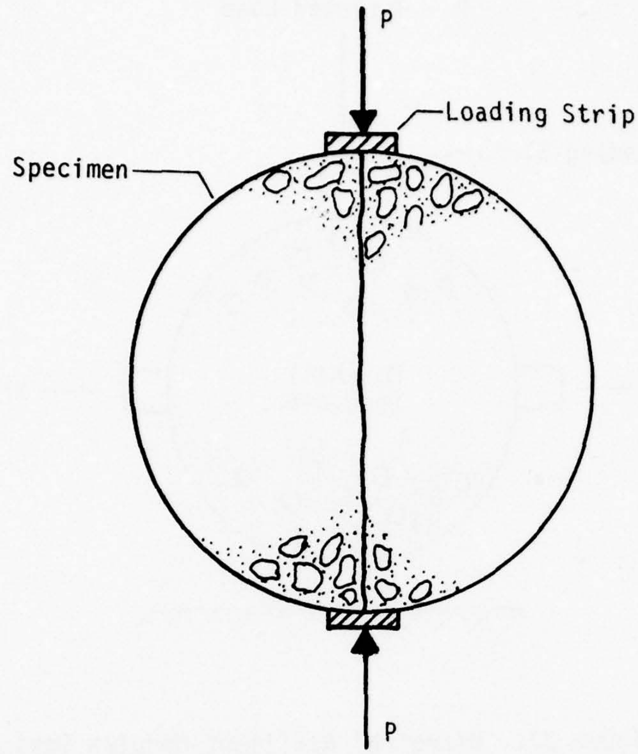


Figure 26. Indirect Tensile Test (after Hudson and Kennedy, Reference 53)

Because the test is simple, it is relatively inexpensive and can be performed by most laboratories with a low coefficient of variation. However, it is a destructive test, and many specimens (laboratory or field) must be tested to verify results. Moreover, the loading conditions do not resemble those found in the field.

Resilient-Modulus Indirect Tensile Test

The resilient-modulus indirect tensile test is identical to the repeated-load indirect tensile fatigue test, except that the resilient-modulus test procedure does not involve loading the specimen to failure. Thus, the theoretical background is the same for both tests.

Schmidt, of Chevron Research Company, has developed a diametral resilient-modulus indirect tensile test device (Figure 27). The test procedure involves applying a light pulsating load through a load cell across the vertical diameter of a Marshall specimen. Sensitive transducers, mounted on the sides of the specimen at 90-degree angles to the load cell, measure the

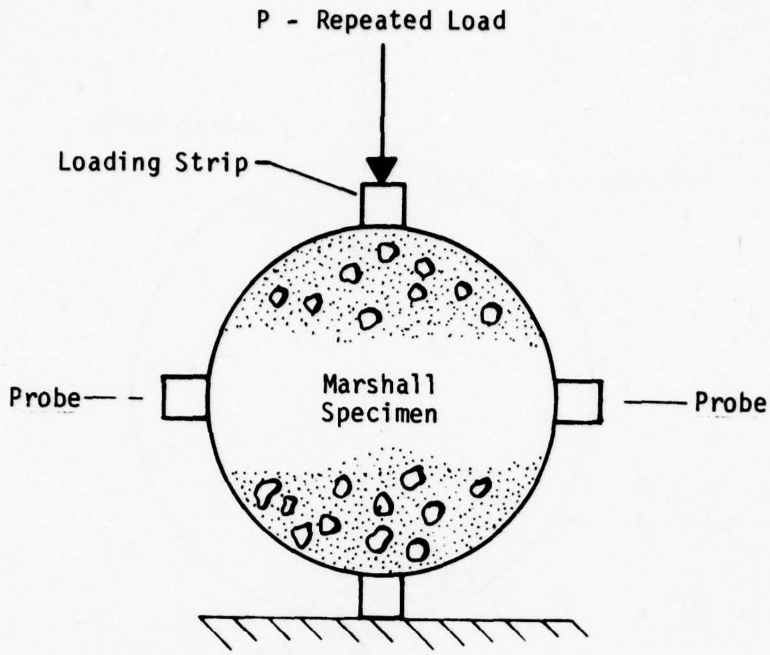


Figure 27. Diametral Resilient Modulus Device

dynamic lateral deformation of the sample. The horizontal deformation from the applied load is monitored, and the resilient modulus is calculated by assuming a value for Poisson's ratio (Reference 55). The type of transducer used in the Schmidt apparatus has an inherent disadvantage in that the transducer's spring-loaded probes must be brought into contact with the specimen. Erroneous test values can be obtained if the probes become embedded in the asphalt or do not make complete contact with the specimen (Reference 58).

In investigations performed by the Center for Highway Research, researchers have used the results of repeated-load indirect tensile tests to determine the resilient modulus and Poisson's ratio. The basic apparatus is similar to the Schmidt device except that an LVDT has been added to provide measurements of vertical deformation. Thus, the Poisson's ratio can be calculated rather than assumed.

Cheetham et al. have devised an improved method of using a test apparatus to determine resilient modulus and Poisson's ratio. The system employs a hydraulically activated and controlled loading system and noncontact probes for measuring both horizontal and vertical deformations. Poisson's ratio can be calculated; thus, a potentially large error in that calculation of resilient modulus is avoided. Because the noncontact probes do not cause the problems associated with spring-loaded probes, the resilient modulus may be predicted more accurately (Reference 58). It was found that resilient-modulus values obtained by this test method were more repeatable, with a lower coefficient of variation, than those obtained by using the Schmidt device.[1]

The resilient modulus and Poisson's ratio can be calculated from the test data by using the following equations:

$$\nu = \frac{C_1 DR + C_2}{C_3 DR + C_4}$$

$$M_R = \frac{P}{h\,x_T}(C_5 + C_6\nu)$$

where

ν = Poisson's ratio

M_R = resilient modulus

DR = deformation ratio (total vertical deformation, y_T, divided by total horizontal deformation, x_T)

P = repeated load magnitude

h = height of cylindrical specimen

X_T = total horizontal deformation

C_1, C_2, C_3, C_4, C_5, C_6 = constants dependent upon geometry (Reference 58)

Cheetham et al. (Reference 58) report that loading time is the most significant factor affecting Poisson's ratio. These investigators also found that performing the tests with 25.4-mm (1-inch)-wide loading strips was easier than with 12.7-mm (0.5-inch) strips and that there was less scatter in the resulting data. However, the 25.4-mm strips did produce somewhat lower values

Footnote

[1]Haas, R. C. G., personal communication of unpublished data to Dale S. Decker, May 1979.

of resilient modulus and Poisson's ratio. Appendix A (Reference 58) presents a stress analysis for different loading-strip widths and solutions for constants in the equations.

The resilient-modulus indirect tensile test is performed on standard Marshall-size specimens fabricated in the laboratory or cut from AC pavements. The equipment, although not standard in most laboratories, is commercially available and is relatively easy to operate. Because the test is dynamic and non-destructive, multiple loading conditions can be imposed on a single sample. (Fatigue life and resilient modulus data had not been correlated at the time this report was written.)

Double Punch Test

Jimenez (Reference 60) initially developed the double punch test to measure the stripping or debonding of asphalt from aggregate. It appears that this test can also be used in AC fatigue studies. The test is conducted by centrally loading a Marshall specimen on the top and bottom surfaces with cylindrical steel punches (Figure 28 [Reference 60]). As the punches are forced in, cones are formed in the specimen, which eventually splits along the weakest radial plane. The tensile strength can be calculated as follows:

$$\sigma_T = \frac{P}{\pi(1.2bh - a^2)}$$

where

σ_T = tensile stress, Pa (lb/in^2)
P = maximum load, N (lb)
a = radius of punch, mm (in)
b = radius of specimen, mm (in)
h = height of specimen, m (in)

The following method for calculating the modulus of elasticity was also developed:

$$E_D = \frac{KP}{d}$$

where

E_D = dynamic modulus of elasticity, Pa (lb/in^2)
P = repeated vertical load, N (lb)
d = repeated radial displacement at mid-height, mm (in)

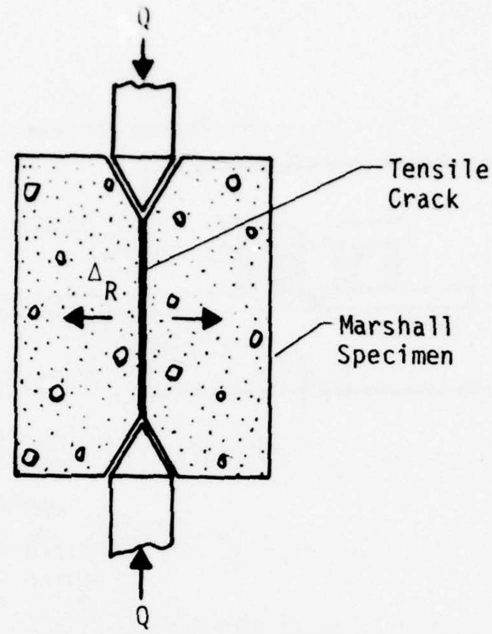


Figure 28. Failure Mechanism of Double Punch Test (after Jimenez, Reference 60)

K = coefficient from table relating specimen to height (References 48 and 60)

Nothing has been reported on the effect of mix properties on the tensile strength and modulus of elasticity determined by this test procedure.

Cohesiometer Test

The cohesiometer apparatus applies a bending moment to a specimen through a cantilever arm. The Marshall-size specimen is positioned in the test apparatus as illustrated in Figure 29 (Reference 53). An increasing load is applied through the cantilever arm until the specimen breaks. A cohesiometer value is calculated from the load at failure and the specimen dimensions (Reference 61).

The major difficulties with the cohesiometer test are the nonuniform and undefined stress distribution across the specimen and the occurrence of the maximum tensile stress at the outer surface. The latter condition amplifies the effect of surface irregularities and may result in low indicated values of tensile strength (Reference 53).

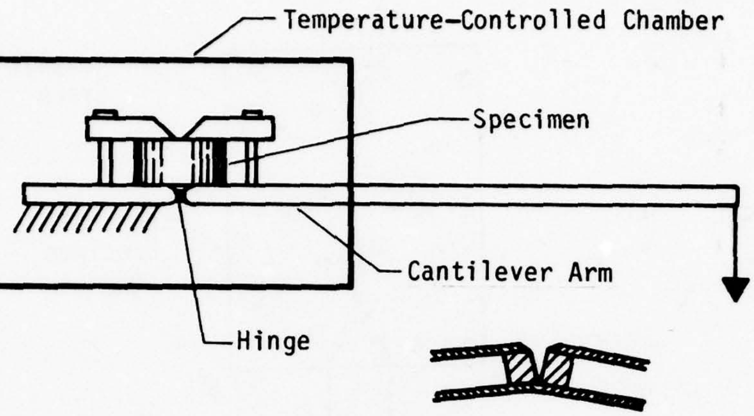


Figure 29. Cohesiometer Test (after Hudson and Kennedy, Reference 53)

Direct Tension Test

The direct tension test is performed by applying a direct axial tensile force to a specimen and measuring the load-deformation response of the material. Various sizes and shapes of specimen and methods of gripping the specimen are used. Figure 30 (References 27 and 53) illustrates two of the possible shapes. Briquet and circular cross-sectional shapes have also been used. In any case, a tensile load is applied to the specimen until failure occurs. The tensile force and the corresponding deformation of the specimens are measured, and the tensile strength and maximum elongation of the specimen are calculated (Reference 53).

Kallas performed repeated axial loading in tension, compression, and a combination of both, to determine dynamic moduli (Reference 9). The samples used were 101.6-mm (4-inch)-diameter, 203.2-mm (8-inch)-high confined specimens subjected to sinusoidal axial loading. Wire strain gages were used to measure the resultant axial strains. Several loading frequencies were used.

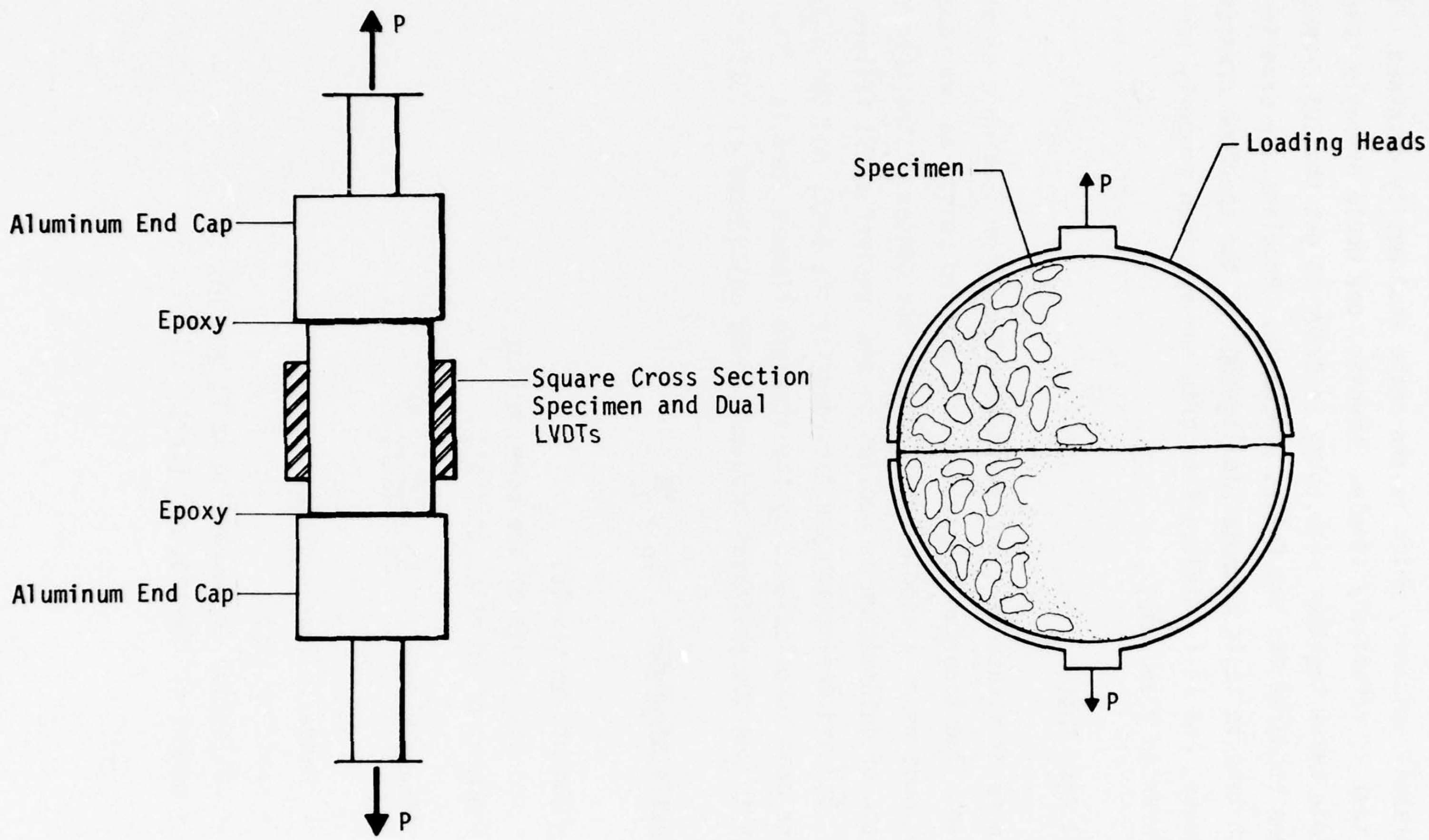


Figure 30. Two Types of Direct Tensile Tests (after Epps and Monismith, Reference 27, and Hudson and Kennedy, Reference 53)

Tensile tests can be performed on a variety of specimen types. A typical laboratory loading machine can be used to perform the direct tensile test on a Marshall specimen, which is the shape most easily obtained. In that regard, the test is relatively simple. However, one would probably have to fasten multiple cores together with epoxy in order to get the 203.2-mm-high field specimen required for the Kallas procedure. Problems are experienced in all direct tensile tests because misalignment of the specimen creates bending stresses, and it is difficult to grip the specimen properly for testing (References 9 and 53).

Flexural Beam Test

Figure 31 illustrates two standard methods for loading a simply-supported beam. The load can be applied at the third points as two equally concentrated loads or as a single-point load at the center of the specimen. A constant rate of deformation is applied to the specimen until failure occurs. The load and deflection are recorded for the test, and the modulus of rupture of the beam is calculated by the standard flexure formula. The tensile strength and the stiffness modulus can be calculated as follows:

Tensile Strength: $$S_R = \frac{Mc}{I}$$

where

M = moment, Nm (in-lb)

c = one-half depth of the beam, m (in)

I = moment of inertia, m^4 (in^4)

Stiffness Modulus: $$S_f = \frac{\Delta PL^3}{48\Delta fI}$$

where

ΔP = change in load applied, N (lb)

L = span, mm (in)

Δf = deflection corresponding to P, mm (in)

I = moment of inertia, mm^4 (in^4)

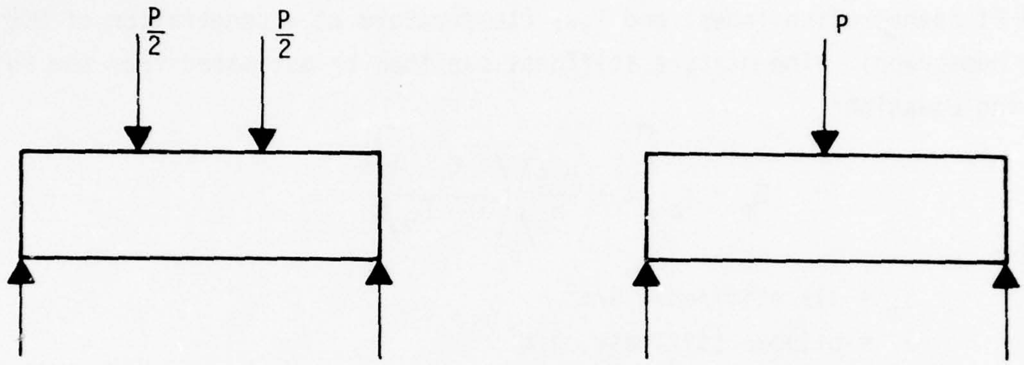


Figure 31. Loading Methods for Simply-Supported Beam

The modulus of rupture and tensile-strength formulae are based on the assumption of a linear stress-strain relationship in the material tested. This relationship is not valid for AC and causes erroneous test results.

The major difficulties encountered in using the flexural beam test are those of the cohesiometer test: the nonuniform and undefined stress distribution across the specimen and the occurrence of the maximum tensile stress at the outer surface. The latter condition amplifies the effect of surface irregularities and may result in significant variations in the test values (References 48 and 53). Other problems with the flexural beam test include handling difficulties typical of beam specimens and the lack of full support for the specimen during the test.

Shell Nomograph

On the basis of more than 20 years of laboratory work, the Shell Oil Company has developed a method for estimating the modulus of an AC mixture. A nomographic solution is used to estimate the modulus of the AC, and a conversion is performed with equations to develop the modulus, or stiffness, of the asphalt mixture. The method is based upon the concept that the bitumen properties must be known so that the modulus of the mixture can be estimated.

Figure 32 (Reference 70) is the nomographic solution used to determine the bitumen stiffness, S_b. Figure 33 (Reference 64) is used to obtain the PI (penetration index) and T_{800} (temperature at a penetration of 800 for the nomograph). The mixture stiffness can then be estimated from the following equation:

$$S_m = S_b \left[1 + \left(\frac{2.5}{n}\right)\left(\frac{C_v}{1 - C_v}\right) \right]^n$$

where

S_m = mix stiffness, N/m^2

S_b = bitumen stiffness, N/m^2

$n = 0.83 \log_{10} [(4 \times 10^5)/S_b]$

$C_v = \dfrac{\text{Volume of Aggregate}}{V_{aggregate} + V_{asphalt}}$

The equation is applicable for air-void contents of about 3 percent and a C_v value in the range of 0.7 to 0.9. Corrections can be made for other air-void contents (References 63, 64, 65, and 70).

The stiffness modulus of the bituminous mix can also be obtained from the nomograph of Figure 34 (Reference 71), using the bitumen stiffness previously determined.

Asphalt Tests

Standard asphalt tests such as penetration, viscosity, ductility, and ring and ball temperature may not be applicable to the direct prediction of AC fatigue behavior. However, these routine design tests, which almost any laboratory can perform, may offer a possibility as indices to some fatigue life parameter.

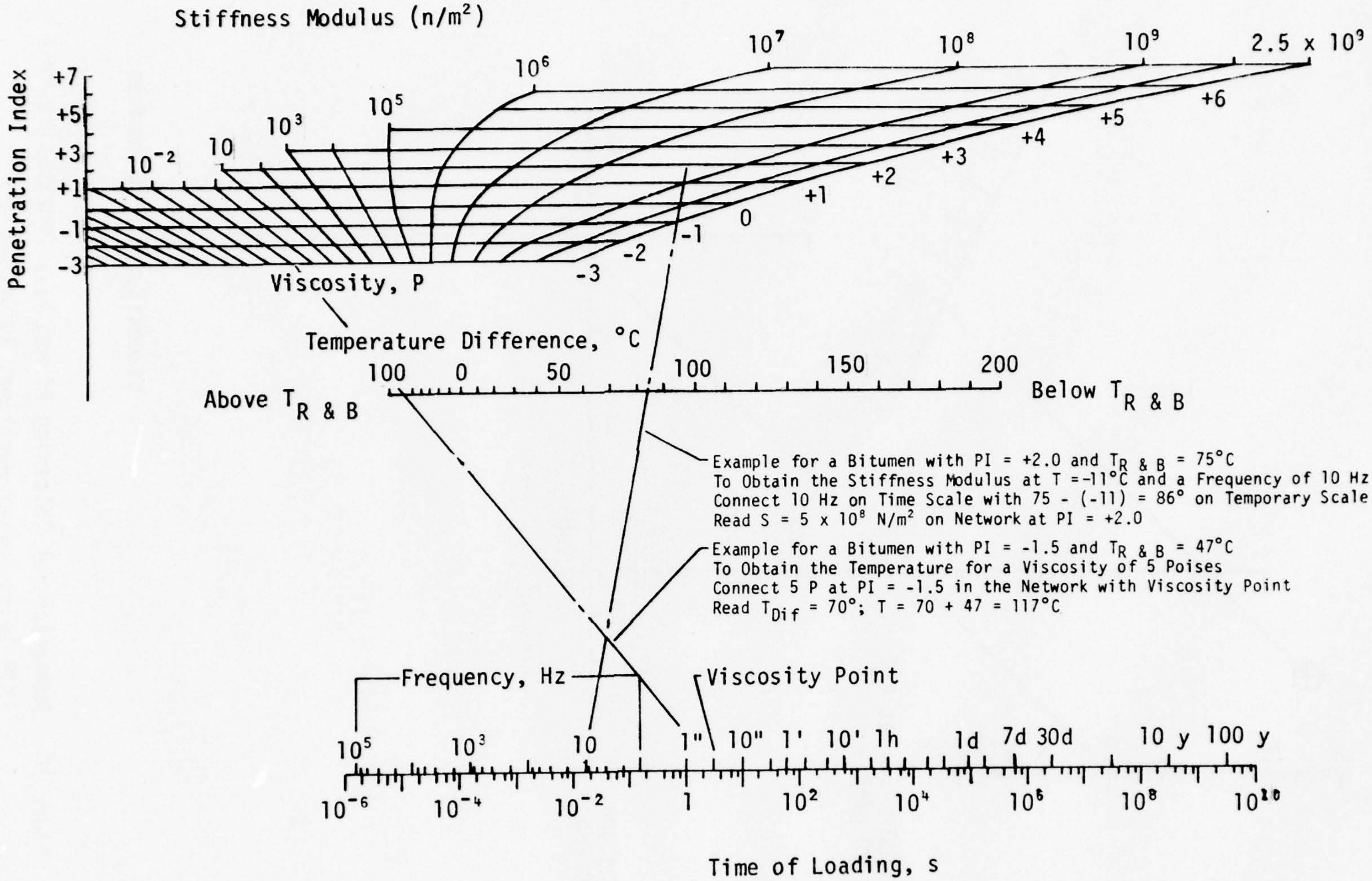


Figure 32. Shell Stiffness Nomograph (after Yoder and Witczak, Reference 70)

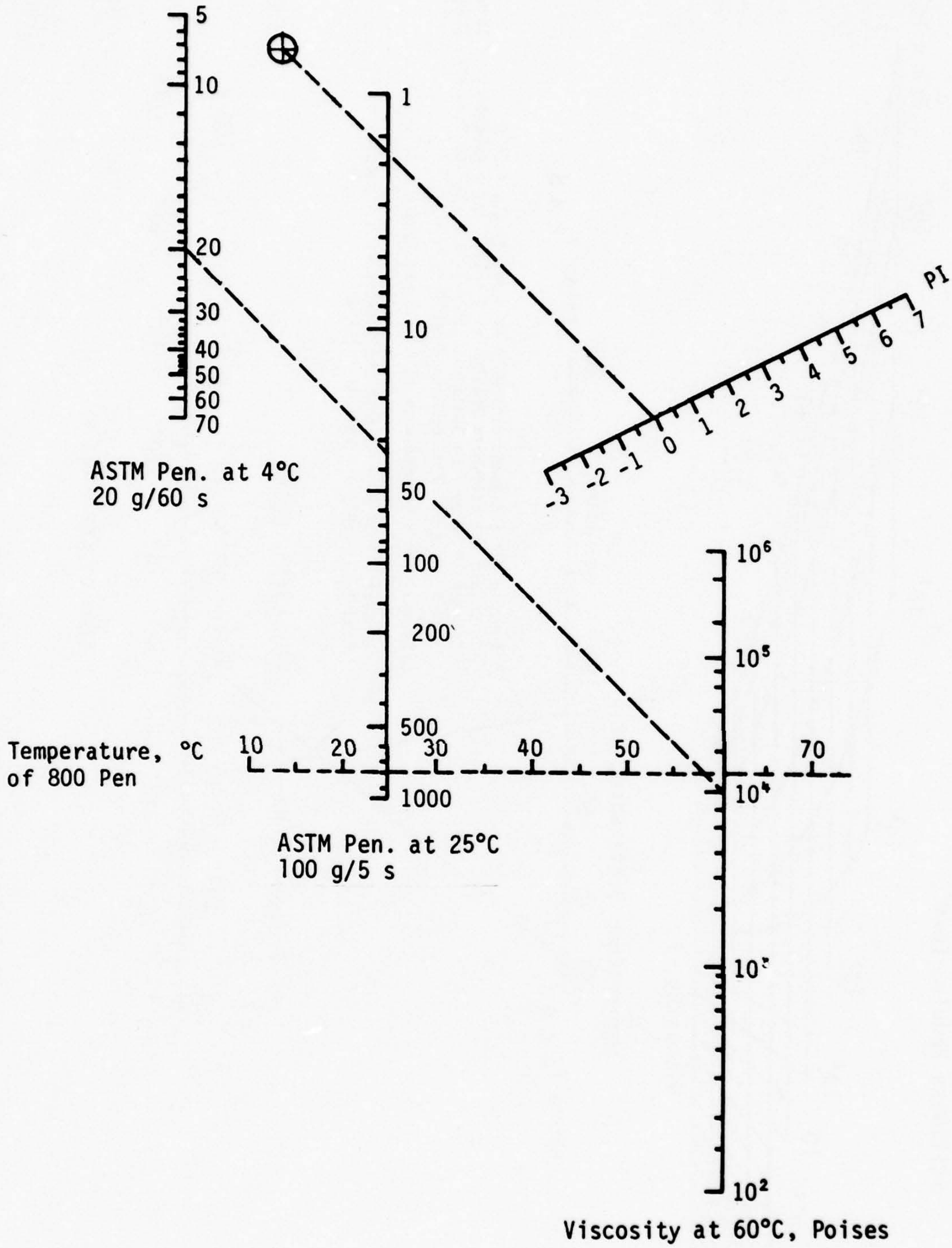
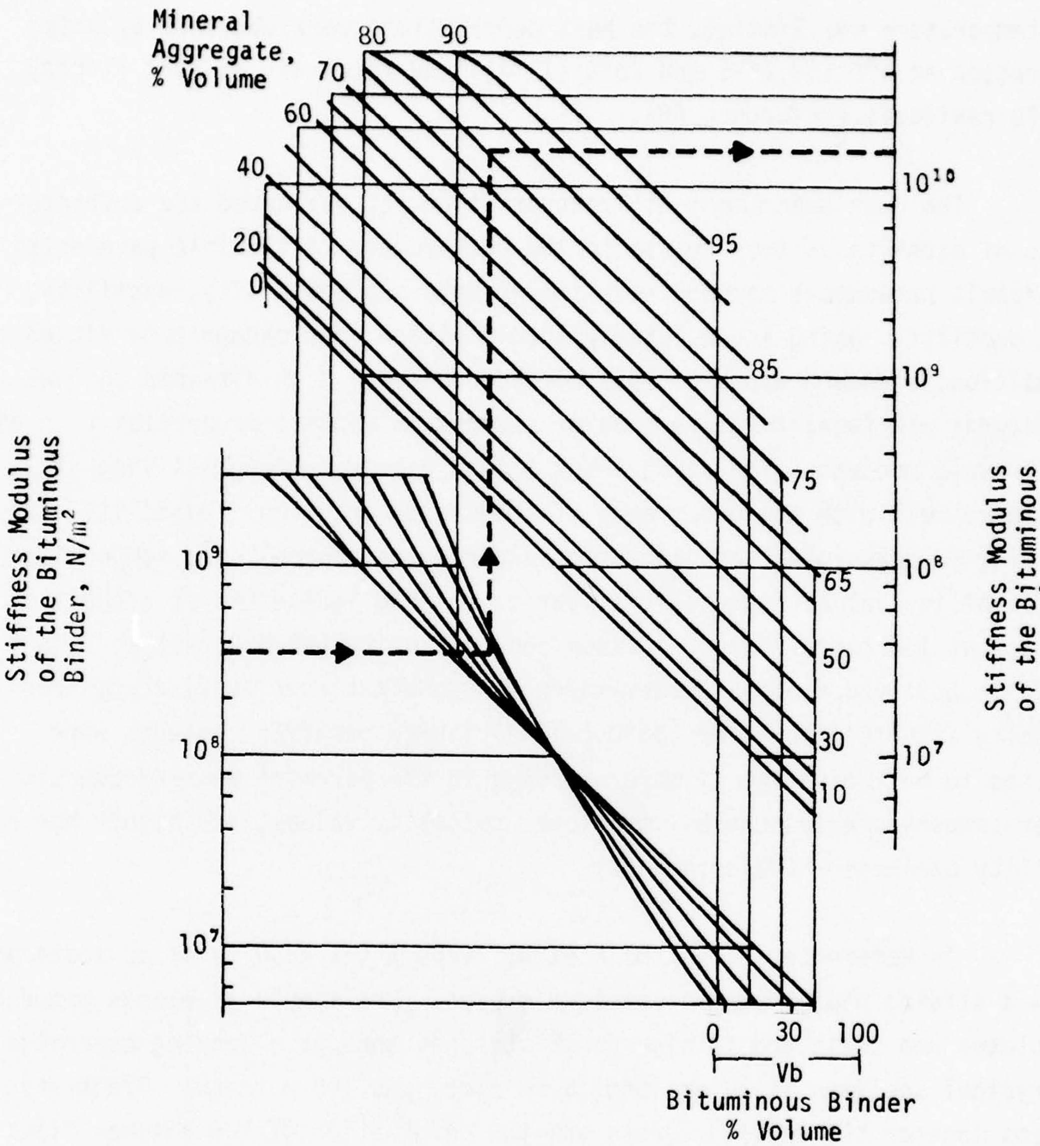


Figure 33. Nomograph for Obtaining PI and T_{800} Penetration From ASTM Tests (after Huekelom, Reference 64)



E.g.: Stiffness Modulus of the Recovered Binder 3.5×10^8 N/m²
Volume of Binder: 15%
Volume of Air: 5%
Volume of Mineral Aggregate 80%

} Stiffness Modulus of the mix 1.5×10^{10} N/m²

Figure 34. Nomograph for Predicting Stiffness Modulus of Bituminous Mixes (after Claessen et al., Reference 71)

Schmidt used standard ASTM tests on asphalt to predict low-temperature stiffness of AC mixtures. The tests used were penetration, viscosity, ductility, and rolling thin-film oven (RTFO) residual tests. When the stiffness temperature was limited, the best correlations were obtained by using penetration at 4°C (39.2°F) and 25°C (77°F), and viscosity at 60°C (140°F), on RTFO residuals (Reference 68).

The Utah Department of Transportation has evaluated the characteristics of asphalts as they relate to the performance of flexible pavements. The asphalt parameters studied were temperature susceptibility, ductility, force ductility, aging index, chemical composition, and cannon cone viscosity. In addition, standard asphalt tests were conducted. High air-void content in AC mixtures was found to cause greater changes in asphalt properties than did low air-void content. The aging index (field viscosity/original viscosity) correlated well with the occurrence of transverse cracking. Ductility, force ductility (a measurement of elongation and required force), and temperature susceptibility values reportedly appear to be good indicators of asphalt consistency at low temperatures. Cannon cone viscosity (ASTM D3205) at 25°C (77°F) is believed to be a better index of asphalt binder consistency than viscosity at 60°C (140°F) or 135°C (275°F). High paraffin contents were reported to be indicative of more cracking in the pavement wearing course, higher temperature susceptibility, lower ductility values, and higher force ductility parameters (Reference 67).

In Reference 17, Van Dijk et al. report the results of AC tests in which a sliding plate microviscometer is used. The sample is placed between two plates and subjected to sinusoidal stresses through a loading apparatus. The typical specimen is 20 mm long, 8 mm wide, and 100 μ thick. Electronic systems monitor the applied stress and the deformation of the bitumen film. A fatigue-life versus initial-strain relationship can be developed and is expressed by an equation of the form $N = k\varepsilon_0^{-p}$. The constants K and p are dependent on the particular bitumen, temperature, and frequency of loading. Although the test apparatus is relatively expensive, this procedure offers promise as a tool for predicting fatigue performance.

Pell and Cooper (Reference 66) identified a relationship between the dynamic stiffness and the mix density of a dense macadam. The maximum mix stiffness corresponds to the maximum dynamic stiffness. They also report a direct relationship between ring and ball temperature and fatigue life at a strain of 1×10^{-4}, as shown in Figure 35 (Reference 66). The research indicates that ring and ball temperature is closely related to some characteristic reference temperature for AC. Figure 36 (Reference 66) illustrates a nomographic method for the prediction of fatigue performance that was developed from Pell and Cooper's research program. Further documentation will be needed before such a relationship can be realistically identified.

With the exception of the microviscometer tests, all the asphalt tests discussed herein can be performed with the basic equipment found in a well-equipped asphalt laboratory. This advantage would be a significant aid in the analysis of fatigue life if correlations could be developed that would permit researchers to use an index parameter for fatigue life predictions.

SUMMARY OF FATIGUE AND ROUTINE DESIGN TESTS

The information presented in this section is a state-of-the-art summary that serves to provide a basis on which a fatigue prediction test method may be chosen. The objectives of the study were (1) to identify a fatigue test that could be used to define the fatigue failure curve (as shown in Figure 4) for new and existing AC surface courses; and (2) to suggest a routine design test, the data from which might be correlated with fatigue test results to provide a fatigue prediction system such as that suggested by the Shell nomograph.

Fatigue Tests

The beam fatigue test has been used more extensively than any other test method; therefore, more data are available for correlation from beam tests than from fatigue tests of other kinds. The test also provides versatility in the loading conditions that can be applied. Beam specimens, however, are difficult to obtain from the field and awkward to handle in the laboratory. Further, the beam test takes considerable time.

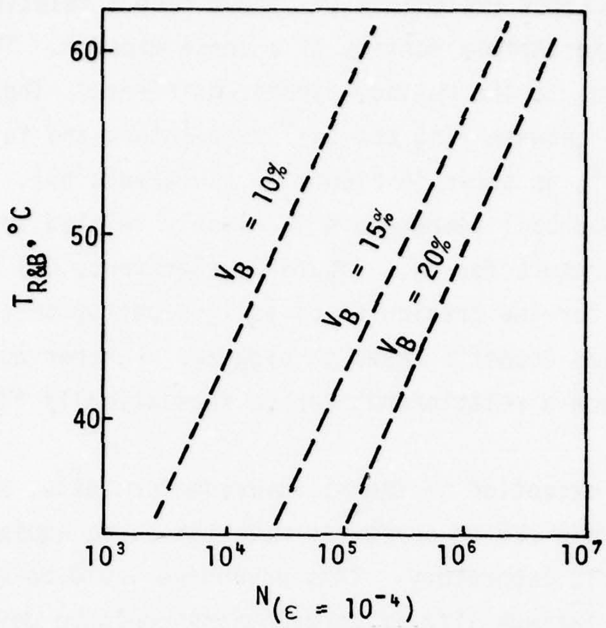


Figure 35. Ring and Ball Temperature Versus $N_{(\varepsilon = 10^{-4})}$ for Various Gradings and Binder Content (after Pell and Cooper, Reference 66)

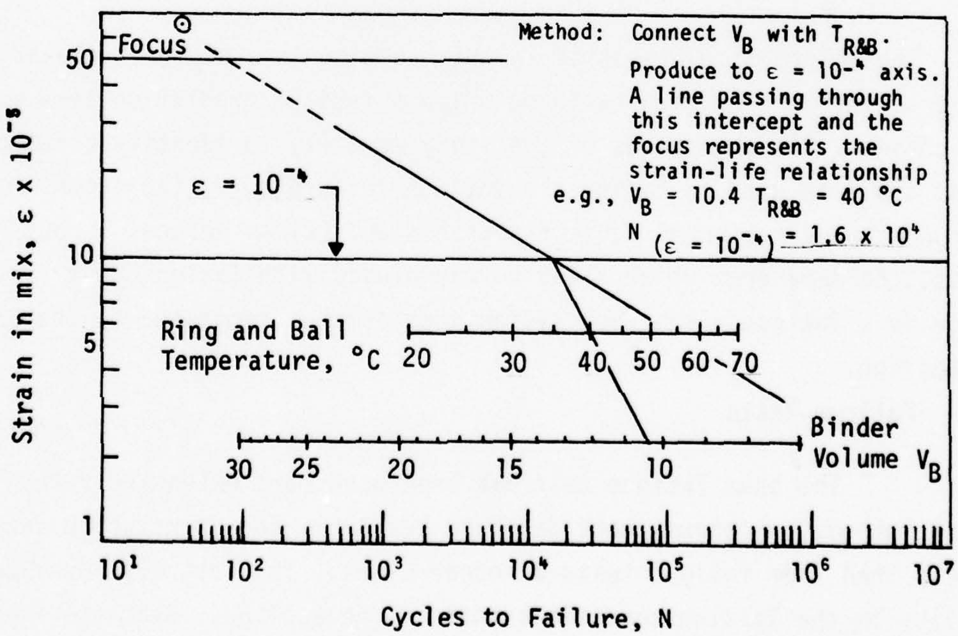


Figure 36. Nomograph for Prediction of Fatigue Performance (after Pell and Cooper, Reference 66)

The rotating bending cantilever and the trapezoidal cantilever tests were not seriously considered for use by the Air Force because of the major problems involved in obtaining field specimens and fabricating laboratory specimens. Because of difficulties associated with gripping and aligning specimens, the uniaxial-load fatigue test was excluded. The triaxial, torsional, diaphragm, rolling-wheel, and simulated subgrade tests were eliminated for combinations of the following problems: difficulty of specimen fabrication, equipment cost, complexity of operation, or length of time required to complete test.

The repeated-load indirect tensile fatigue test developed by Kennedy et al. at the Center for Highway Research is recommended for use by the U.S. Air Force. This recommendation is based on several factors, the most basic of which is that the test meets the requirement that extracted AC cores be used in the testing. A right circular cylindrical specimen is used, and the testing can be performed expeditiously, permitting a large amount of data to be generated quickly. The laboratory-measured fatigue life is not the same as field fatigue life; however, this flaw is characteristic of all types of fatigue tests. The repeated-load indirect tensile test can be conducted at a reasonable cost with samples that are easy to handle, and it holds great promise of producing reliable results.

Routine Design Tests

The direct tension test and the flexural beam test involve the same problems as those described for the uniaxial load and beam fatigue tests, respectively. The flexural beam and cohesiometer tests are unsatisfactory because of the nonuniform and undefined stress distributions across the specimen. The data bases for the double punch and sonic tests are not extensive enough to allow a judgement to be made relative to their use in the Air Force program.

In the indirect tensile test, a core-type specimen is used, and the specimen can be tested with typical laboratory loading devices. The test takes relatively little time and has a low coefficient of variation. However, the loading conditions do not resemble those found in the field, and many samples are required because each test destroys a specimen.

The resilient modulus indirect tensile test devised by Cheetham et al. is the routine design test recommended for use by the Air Force. A standard-size specimen is used for both laboratory and field work. The test theory is based upon the same principles as those of the repeated-load indirect tensile fatigue test, but in this routine design test the sample is not tested to failure and less elaborate equipment can be used. The noncontact probes provide a higher degree of repeatibility than has previously been attainable. Because the test is nondestructive, multiple testing conditions can be applied to a single specimen. The loading conditions somewhat simulate the field conditions. The test procedure is relatively simple and does not require extensive testing time. Both Poisson's ratio and the resilient modulus can be estimated from the test with a low coefficient of variation.

It is also recommended that standard asphalt tests be performed on asphalt cement with the objective of analyzing the results for their possible correlation to AC fatigue life parameters. Penetration, ductility, viscosity, softening point, gradations, and mixture proportions should be determined for each AC mixture.

SECTION IV
EFFECT OF MIXTURE AND ENVIRONMENTAL VARIABLES ON FATIGUE LIFE

INTRODUCTION

This section presents a review of materials characterization research in which some of the fatigue test methods discussed in Section III have been used.

MIXTURE VARIABLES

The fatigue life of an AC mixture is highly dependent upon the mixture variables, their properties, and the relative proportions of each component of the mix. The following mixture variables are reviewed here: aggregate properties, asphalt type and grade, asphalt content, air-void content, mineral filler content, and mixture stiffness.

Aggregate Properties

AC fatigue life is influenced by aggregate angularity, surface texture, gradation, and maximum size. When angular aggregates with rough surface textures and open gradations are used in AC mixtures, the pavement may have poor compaction and therefore a shorter fatigue life. Although the rough, angular aggregates may provide a source of crack initiation and a correspondingly shorter fatigue life, they may also produce a mixture with higher stiffness than rounded, smooth-textured aggregates provide—if the material is well graded (Reference 1). (The effect of mixture stiffness on fatigue life is discussed in a subsequent section.)

On the basis of the results of controlled-stress tests on AC mixtures having gravel and crushed rock as the coarse aggregate, Pell and Taylor conclude that the type and grading of the coarse aggregate do not greatly influence the fatigue life of the mix (Reference 19). Epps and Monismith report that their controlled-stress tests indicate that aggregate type has little effect on the fatigue life of mixtures containing dense-graded aggregates of crushed granite, limestone, and river gravel (Reference 26). Bazin and Saunier report similar conclusions in Reference 38. After conducting controlled-strain tests, Kirk also concluded that aggregate type has a negligible effect on fatigue strain (Reference 30). Maupin has conducted controlled-strain tests on asphaltic mixtures containing round gravel, limestone, and slabby slate. The mixture containing the slabby slate had a significantly different fatigue life from that containing untreated limestone, which indicates that aggregate shape has an effect on fatigue behavior (Reference 72). Adedimila and Kennedy conducted tests on mixes containing limestone and gravel and report no significant difference between fatigue test results for the two types of mixes (Figure 37 [Reference 73]).

Jimenez and Gallaway report that the aggregate texture is important to a mixture's fatigue life. Their results indicate that a rough-textured aggregate can be used in a mix having a higher asphalt content than that used in a mix with smooth-textured aggregate and would have a longer fatigue life (Figure 38 [Reference 74]).

Pell, Kirk, Epps and Monismith, and Bazin and Saunier have reported on the effect of aggregate gradation on the fatigue life of asphaltic mixtures. For equivalent asphalt contents, open-graded mixtures give a shorter fatigue life than do dense-graded mixes. However, aggregate gradation has almost no effect on fatigue life that cannot be attributed to variations in asphalt content and air-void content (References 13, 26, 30, and 38). Figure 39 (Reference 26) illustrates minor fatigue life variations between fine and coarse limits of the California 12.7-mm (0.5-inch) maximum-size aggregate gradation (Reference 26). In controlled-strain tests on mixtures containing aggregates with a range of gradation, Kirk reports little change in fatigue behavior (Reference 30), while Pell indicates significant differences between mastic and sandsheet mixes (Reference 34).

No reports have related the maximum aggregate particle size to the fatigue life of the mixture. Majidzadeh maintains, however, that the particle size may significantly influence the rate of crack propagation in the mixture and may therefore affect the ultimate fatigue behavior. Further, aggregate gradation, by its expected effect on strength and stiffness, would influence the fatigue life of the mixture, while maximum particle size would affect both the workability and the economy of the mixture (Reference 50).

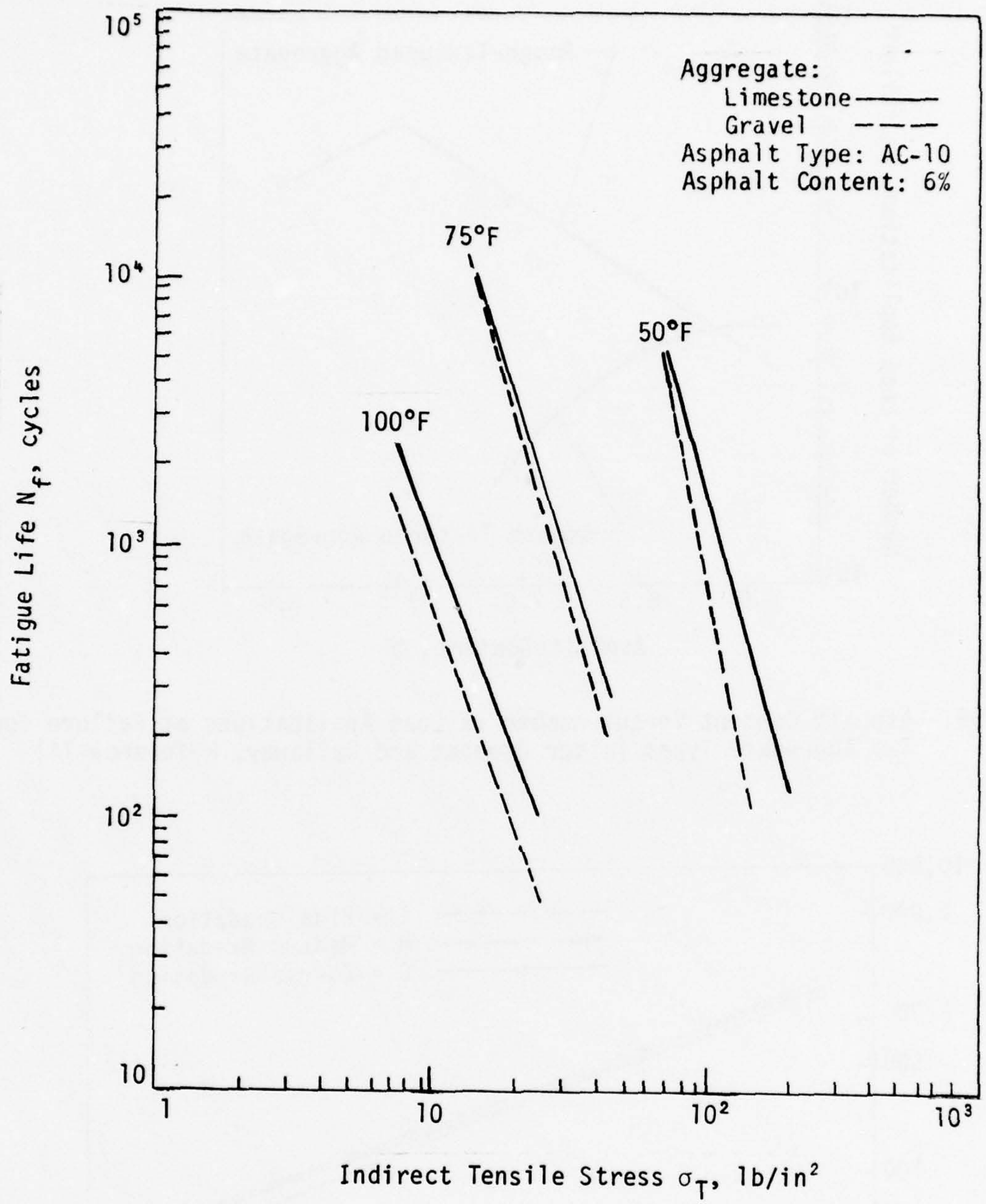


Figure 37. Effects of Aggregate Type and Testing Temperature on Fatigue Life (after Adedimila and Kennedy, Reference 73)

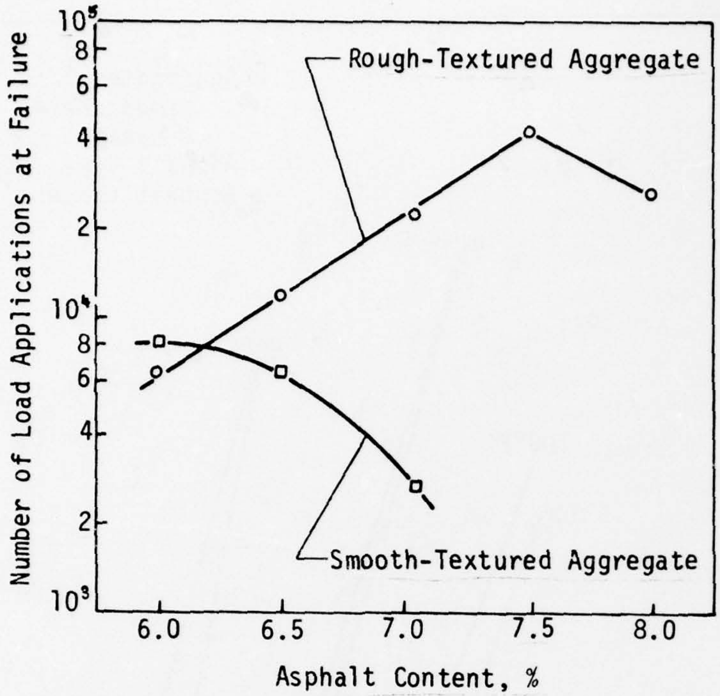


Figure 38. Asphalt Content Versus Number of Load Applications at Failure for Two Aggregate Types (after Jimenez and Gallaway, Reference 74)

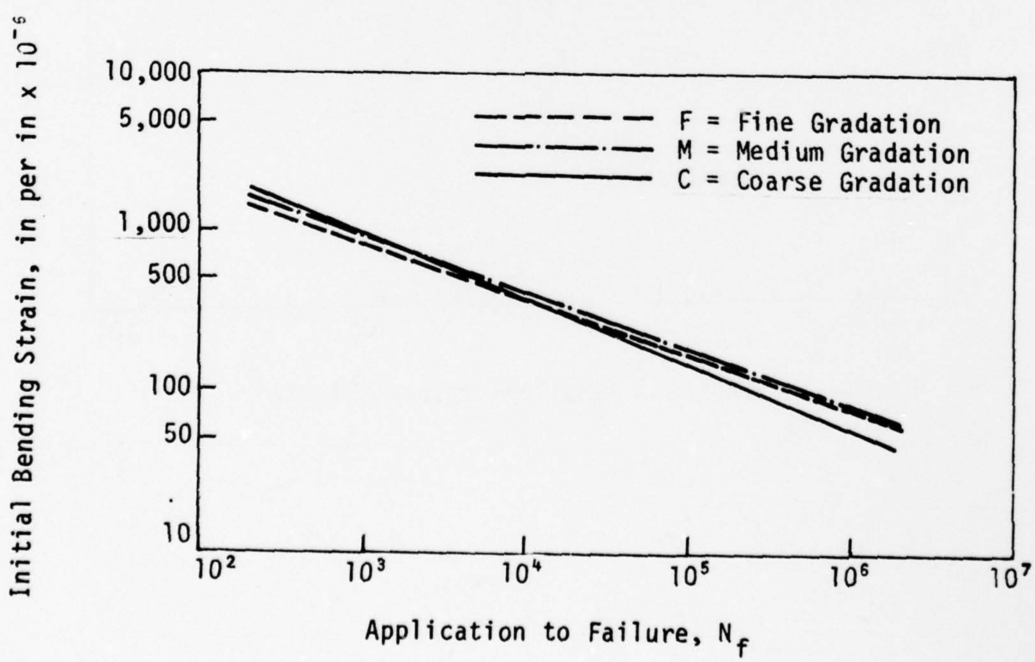


Figure 39. Effect of Aggregate Grading on Initial Mixture Bending Strain Versus N_f Plot (after Epps and Monismith, Reference 26)

Majidzadeh (Reference 50) and Salaam and Monismith (Reference 75) have reported on the effect of aggregate gradation on the fracture toughness (K_{IC}) of AC mixtures. Salaam and Monismith report that at low temperatures, finer aggregates produce increased fracture toughness. The effect of gradation is reported to be less prominent at higher temperatures. In tensile fracture testing, coarsely graded aggregates exhibited the lowest fracture toughness even though fracture toughness is indicated to be insensitive to mixture variations for other aggregate types having a finer gradation.

The fracture characteristics of the aggregate or the thickness of the asphalt film may influence the sensitivity of fracture toughness to aggregate gradation. Finely graded aggregates typically have more surface area and a thinner film layer; the result is a greater rigidity and stiffness and reduced flow properties in the binder (Reference 50).

Majidzadeh reports that no clear relationship has been established between the fatigue parameter A (in $dc/dN = AK^n$) and the aggregate properties of shape, texture, and maximum size. However, much higher values of parameter A were obtained for open-graded slag aggregate mixes than for dense-graded mixes. The higher A values indicate a shorter fatigue life (Reference 50).

Asphalt Type and Grade

The primary influence of asphalt type and grade on AC fatigue life is related to changes in mixture stiffness. It is generally recognized that an increase in asphalt hardness increases the mixture stiffness and the fatigue life of the mixture in the controlled-stress mode of loading. The opposite relationship occurs in the controlled-strain mode of loading (Reference 1).

In controlled-stress fatigue testing on mixes having identical aggregate gradings and asphalt contents, but different asphalt grades, Pell et al. report that the extent of the mixture's nonlinear behavior over the range of stress levels used dictates the slope of the strain-versus-fatigue life relationship. Thus, the position and slope of the strain-life curve are dependent upon the bitumen used. Pell reports that a regression line for a strain-life relationship will have a slope in the range of 5.3 to 5.9 for linear mix behavior conditions. He defines linear behavior as a situation in which stiffness is independent of stress level and in which the following conditions exist:

1. low void content;
2. low testing temperature (also, presumably, a high speed of loading); and
3. adequate quantities of filler and binder in the mix (Reference 19).

The regression-line slope for nonlinear mix conditions ranges from 1.6 to 3.5. For test conditions including both linear and nonlinear behavior, the slope factor may be between the previously mentioned values (Reference 19). A similar relationship between slope and asphalt type for AC mixtures has been reported by Epps and Monismith (Reference 26) and Bazin and Saunier (Reference 38).

For tests on various penetration graded asphalts, Jimenez and Gallaway report that mixtures containing soft asphalts were the most flexible but had the shortest fatigue life under controlled-stress testing (Reference 74). Heukelom and Klomp also indicate that when the asphalt hardness is increased, the mixture stiffness is increased and fatigue life is improved (Reference 65). Vallerga, Finn, and Hicks report similar conclusions on the basis of their controlled-stress tests of mixtures of unaged and artifically aged asphalts (Reference 76). Pell and Taylor, Moore and Kennedy, and Epps and Monismith also report that the stiffness of the mix increases with a decrease in binder penetration (References 19, 26, and 36).

In controlled-strain testing, according to Kirk (Reference 30), fatigue strain at one million load applications is independent of asphalt hardness for penetrations ranging from 50 to 200 (measured in tenths of a millimeter). Santucci and Schmidt, however, indicate that controlled-strain fatigue life is dependent upon asphalt hardness. This conclusion is based upon tests on asphalt mixtures from various crude sources and of various penetration grades. Their test results would predict a shorter fatigue life for a harder asphalt (Reference 33).

Majidzadeh et al. report that the mechanistic fatigue parameter, A, is dependent upon asphalt hardness, a higher A-value corresponding to a softer asphalt. The dependence was more significant when asphalts of higher penetrations were compared. As in the phenomenological testing approach, the fracture mechanics test results indicate that an increase in asphalt hardness decreases the A-value and leads to a longer fatigue life (References 77 and 78). A later, more extensive research effort by Majidzadeh indicates the same general trend, and a sensitivity analysis shows that A is sensitive to the binder grade (Reference 50). Salaam and Monismith also report that fracture toughness varies with asphalt consistency (Reference 75). (This finding will be discussed further in the following subsection.)

Asphalt Content

The response of AC mixtures in controlled-stress fatigue life tests to variations in the asphalt content has been studied by Epps and Monismith (Reference 26), Jimenez and Gallaway (Reference 74), Pell (Reference 13), and Adedimila and Kennedy (Reference 73). These writers determined a maximum asphalt content, dependent on the type and grading of the aggregate, that produced the best fatigue results. This maximum corresponds to the asphalt content required for maximum mixture stiffness (modulus) and is higher than the maximum required for mixture stability (Marshall value). Adedimila and Kennedy also report maximum asphalt content for maximum fatigue life (Figure 40 [Reference 73]). However, they report that the asphalt content giving maximum fatigue life is essentially equal to the content providing maximum stability.

In reporting on controlled-strain testing, Kirk concludes that the asphalt content is the most important factor influencing the fatigue strain of the AC mixture. The strain that causes failure after one million cycles increases with the binder content, but the increase in strain is not directly proportional to the increase in binder content (Reference 30).

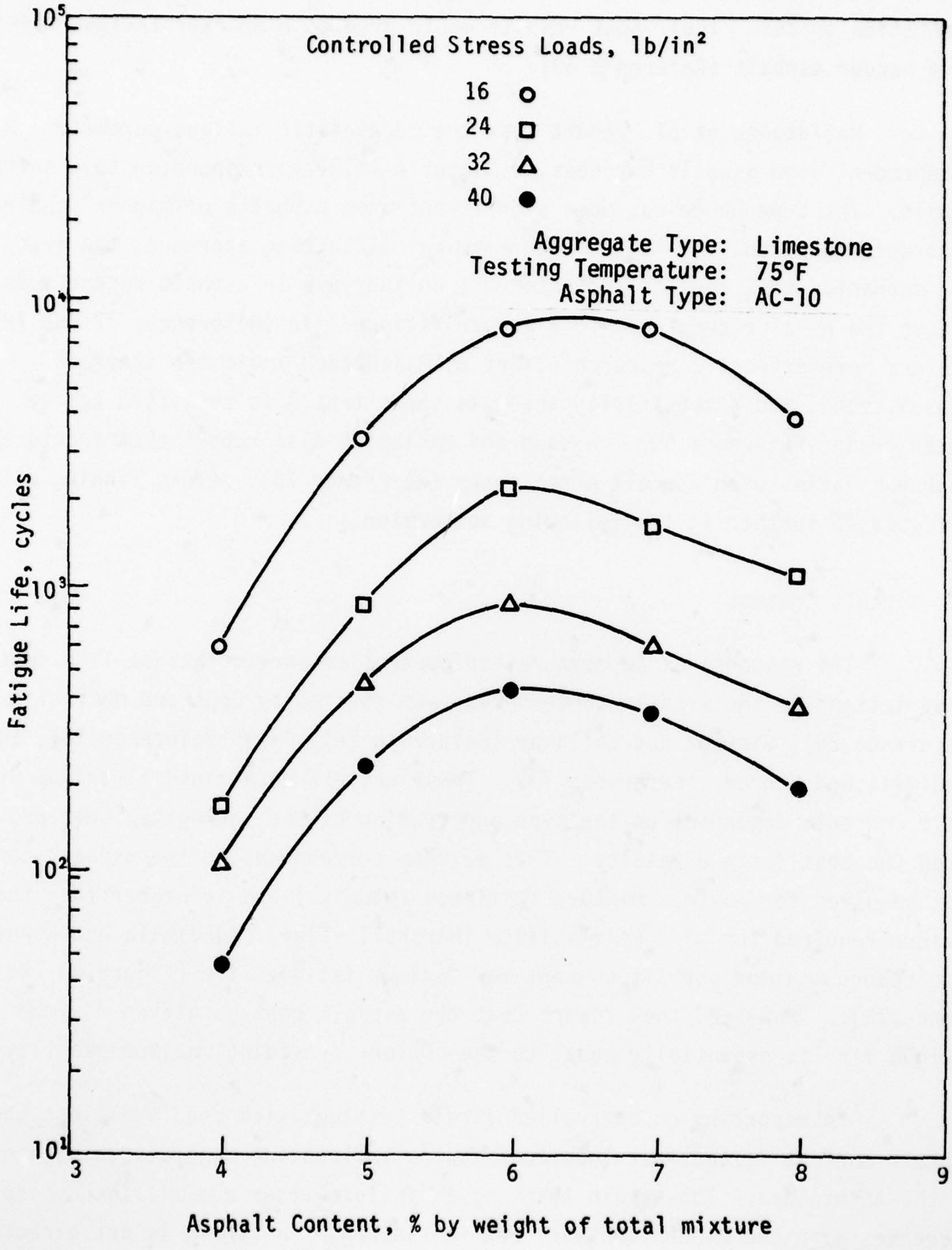


Figure 40. Effects of Asphalt Content on Fatigue Life (after Adedimila and Kennedy, Reference 73)

Fracture toughness, K_{IC}, has been reported by Salaam and Monismith to vary with asphalt content and consistency. The test temperature dictates the influence of the asphalt content on fracture toughness. An increased asphalt content at -20°F increases fracture toughness, while at 40°F an increased asphalt content decreases fracture toughness (Reference 75). This phenomenon is attributed to possible plastic flow of the asphalt mixture at 40°F (Reference 50).

On the basis of fairly extensive fracture mechanics testing, Majidzadeh et al. report that asphalt content is the most significant parameter affecting the fatigue parameter, A (Reference 50). The longest AC fatigue life is obtained at a binder content 0.5 to 1.0 percent higher than the content specified in conventional stability requirements (Reference 50).

Air-Void Content

The response of controlled-stress fatigue tests to variations in the air-void content of the mixture has been presented by Pell and Taylor (Reference 19), Epps and Monismith (Reference 26), Bazin and Saunier (Reference 38), and Adedimila and Kennedy (Reference 73). All of these investigators report reduced fatigue life and mixture stiffness when air-void content is increased. The data suggest that the structure of the voids (i.e., size, shape, and degree of interconnection) is important, as is the absolute volume of voids in the mix (Reference 26). Figure 41 (Reference 19) illustrates the effects of air-void content on fatigue life in controlled-stress loading. Adedimila and Kennedy (Reference 73) report an optimum air-void content for maximum fatigue life. Figure 42 (Reference 73) illustrates the range of test values obtained.

Test results obtained by Santucci and Schmidt indicate that a reduced air-void content gives increased fatigue life (Reference 33). Figure 43 (Reference 33) presents data for air-void content versus number of load applications to failure.

Fracture mechanics investigations by Saraf indicate that the parameter A (in $dc/dn = AK^n$) is dependent on the void content of the mixture. An increase in void content sharply increases the parameter A, which corresponds to a reduction in fatigue life (Reference 78).

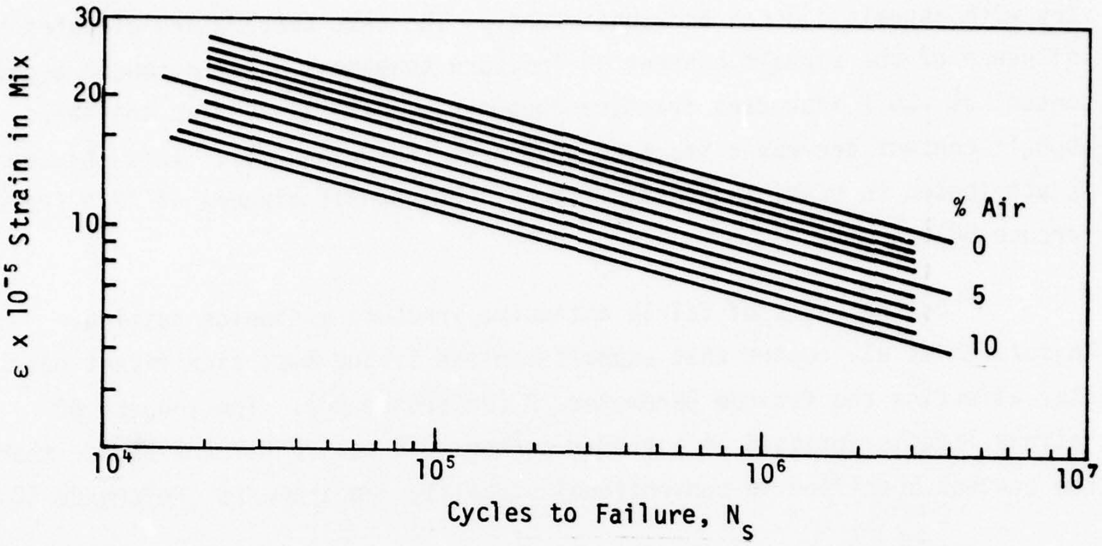


Figure 41. Effect of Void Content on Fatigue Life of Gap Graded Base Coarse Mix Containing 40/50 Penetration Bitumen (after Pell and Taylor, Reference 19)

Salaam and Monismith report that an increase in the void content of the mix decreases the fracture toughness, K_{IC}. Elevated test temperatures reduce the sensitivity of K_{IC} to the void content (Reference 75).

Mineral Filler Content

Mineral fillers may be added to AC mixtures or may occur naturally in the aggregate. Examples of fillers that are added to the mixtures are hydrated lime, fuller's earth, and portland cement; quarry screenings and limestone dust are examples of naturally occurring fillers. Most mineral filler material passes the U.S. No. 200 sieve and is included in AC mixtures to provide greater strength and stability. (Stability is a function of filler concentration and type.) The filler content is also a significant factor in the initial compaction and subsequent densification of AC mixtures (References 50 and 79).

Pell reports that improved fatigue life can be obtained by the addition of mineral filler to mixtures that normally contain no filler. He

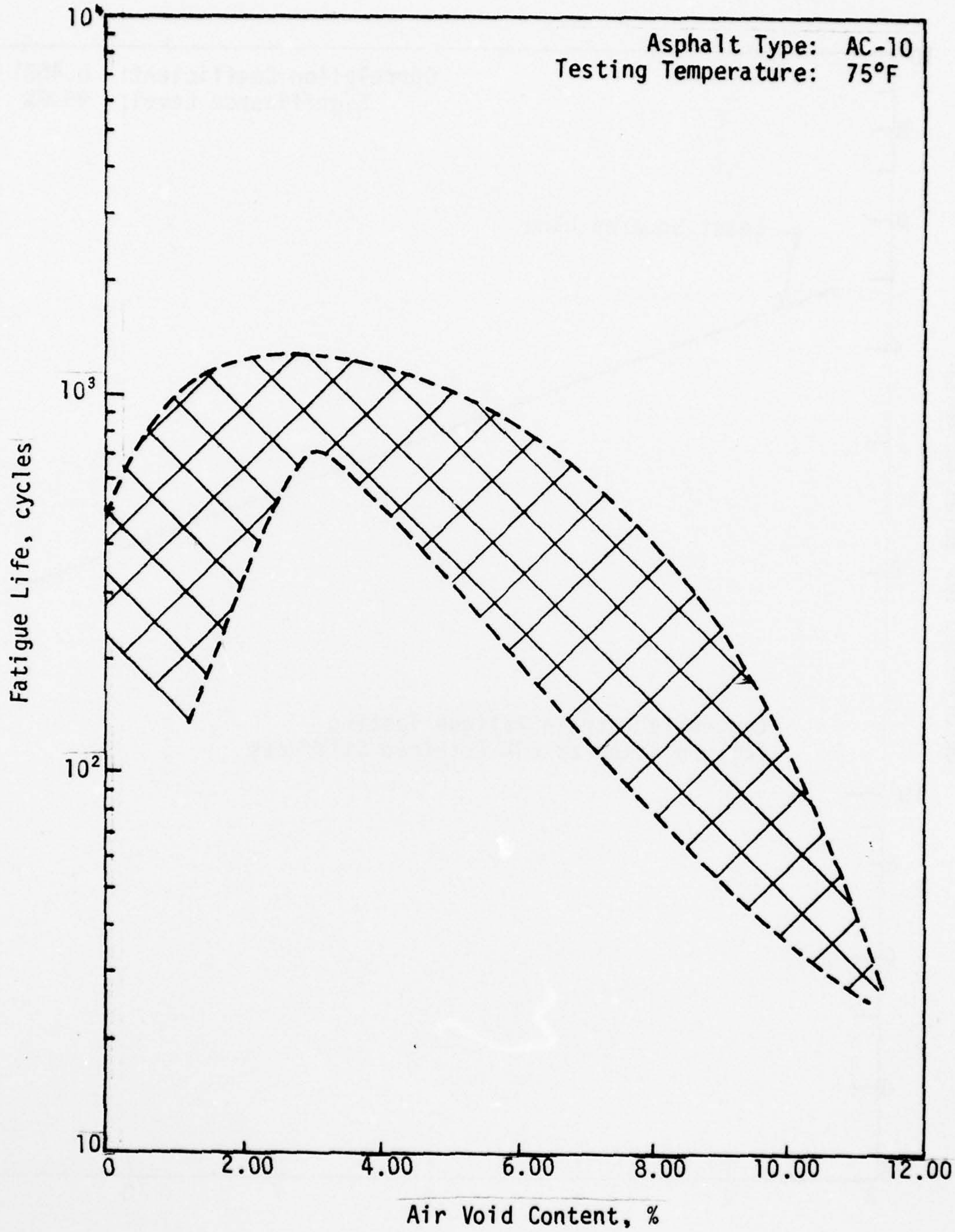


Figure 42. Relationship Between Fatigue Life and Air Void Content 32 lb/in^2 (after Adedimila and Kennedy, Reference 73)

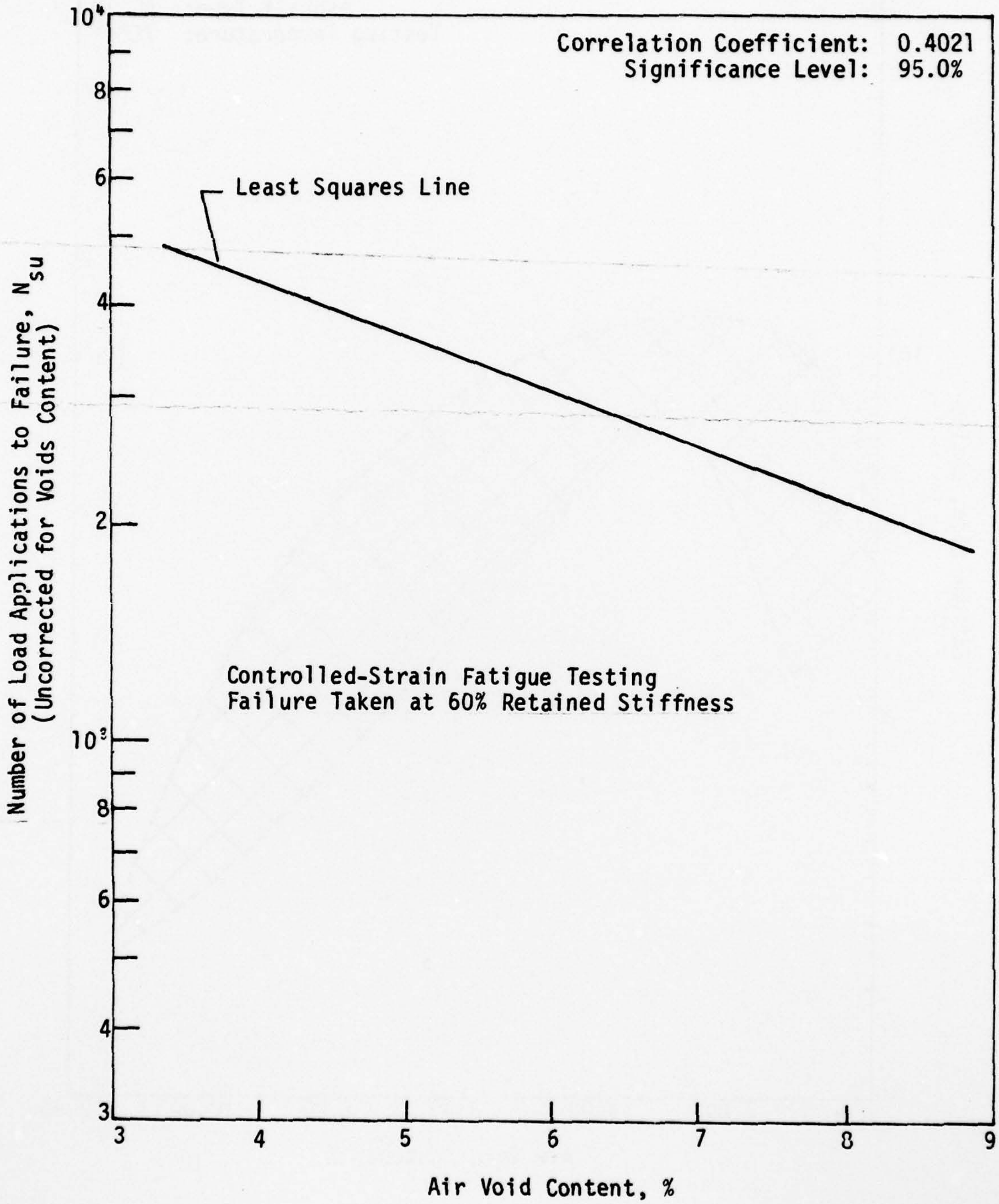


Figure 43. Effect of Void Content on Mixture Service Life (after Santucci and Schmidt, Reference 33)

attributes the improvement to a reduction in void content and an increase in stiffness. At the same time, he emphasizes that the filler must not be added in too high a proportion to the asphalt. Pell's results indicate that a 9-percent filler content is the upper limit for longer expected fatigue life (Reference 13). Similarly, Majidzadeh et al. set the upper limit at 7.5 to 8 percent (Reference 50).

Mixture Stiffness

The stiffness of an AC mixture is defined as the ratio of stress to strain as a function of time-of-loading and temperature (Reference 63). When the loading time is short or the temperature is low (or both), the stiffness approaches a constant value analogous to the modulus of elasticity. An increase in the loading time and temperature reduces the stiffness of the mixture. AC mixture stiffness is an important material characteristic from the fatigue standpoint because traffic and environmentally-induced stresses and strains in the asphalt course are dependent upon mixture stiffness (Reference 1).

In controlled-stress testing of dense-graded mixtures, Epps and Monismith found that stiffness can significantly influence the stress-fatigue life relationship. In the controlled-stress mode of loading, a longer fatigue life is generally apparent as stiffness is increased (Figure 44 [Reference 26]). The available data indicate that the initial-strain versus fatigue-life relationship is steeper as the stiffness decreases (References 19 and 26).

Santucci and Schmidt report that the initial mixture stiffness can be used to predict the fatigue life of AC beam specimens at any constant strain level under various aging and temperature conditions. For controlled-strain testing, the fatigue life is reported to decrease with increasing stiffness, a finding that contradicts controlled-stress test results. The fatigue life is also affected by the strain level as illustrated by Figure 45 (Reference 33).

Changes in mixture stiffness are the result of variations in the mixture parameters discussed in previous sections. Rough, angular aggregates,

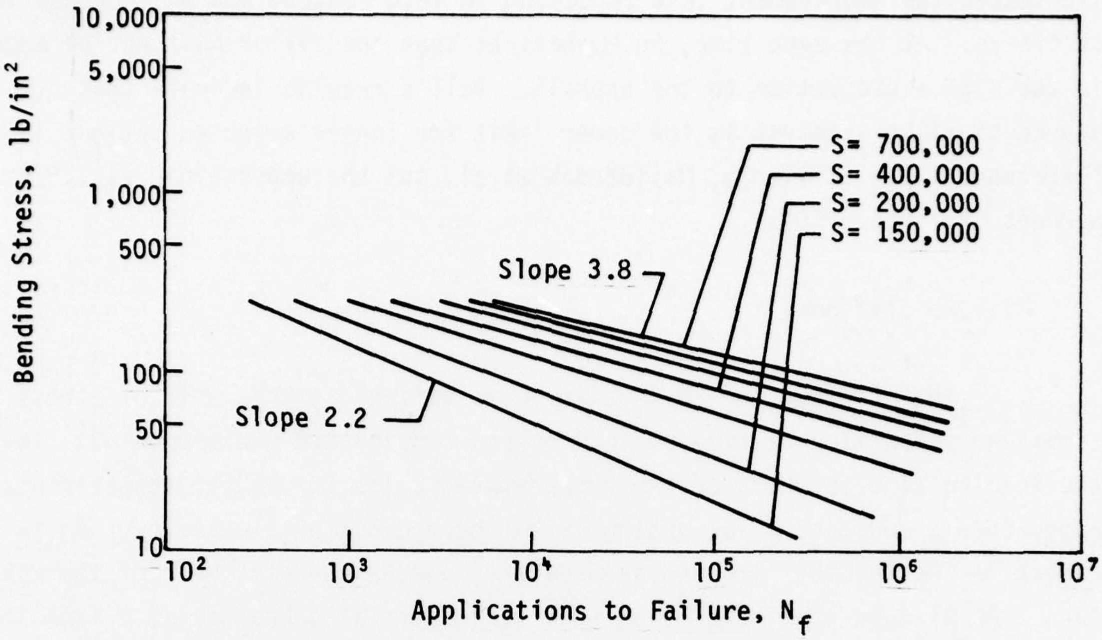


Figure 44. Bending Stress Versus Application to Failure for Mixes of Different Stiffness (after Epps and Monismith, Reference 26)

for instance, may produce a stiffer mixture than do rounded, smooth-textured aggregates; dense-graded mixtures provide a longer fatigue life than do open-graded mixes; harder asphalts increase mixture stiffness; optimum asphalt and mineral filler contents produce a maximum mixture stiffness; and a high void content reduces stiffness.

ENVIRONMENTAL VARIABLES

Variations in the environmental conditions to which a pavement is subjected greatly influence the pavement's fatigue life. Temperature and moisture fluctuations have immediate effects; long-term changes in the fatigue characteristics are caused by modifications in the material due to age (References 1 and 3).

Temperature

Saal and Pell (Reference 80), Pell and Taylor (Reference 19), Jimenez and Gallaway (Reference 74), and Adedimila and Kennedy (Reference 73)

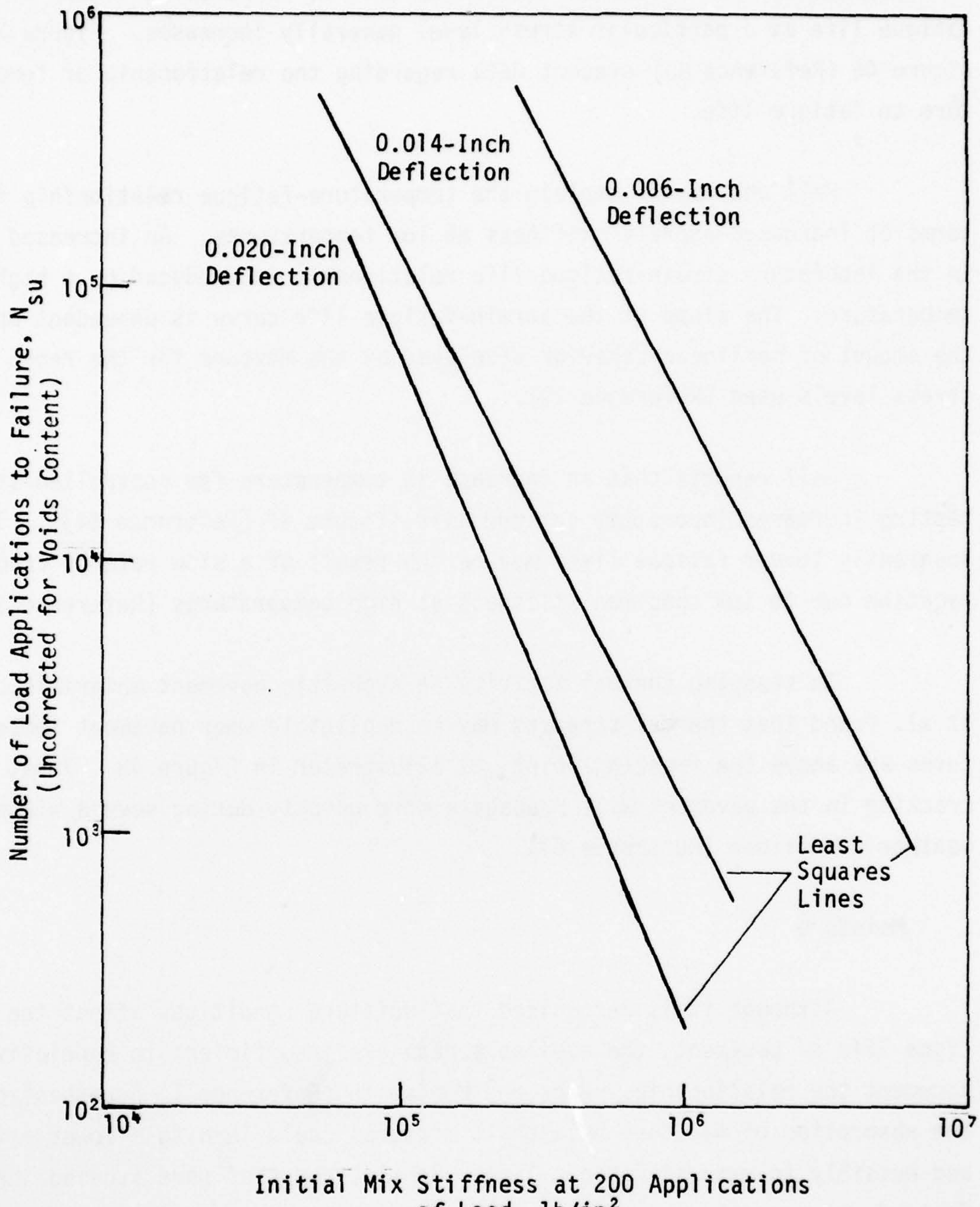


Figure 45. Prediction of Measured Service Life From Initial Mix Stiffness (after Santucci and Schmidt, Reference 33)

have presented laboratory data indicating that as temperature is decreased, fatigue life at a particular stress level generally increases. Figure 37 and Figure 46 (Reference 80) present data regarding the relationship of temperature to fatigue life.

Pell and Taylor explain the temperature-fatigue relationship in terms of increased asphalt stiffness at low temperatures. An increased slope in the laboratory strain-fatigue life relationship is produced by a higher temperature. The slope of the strain-fatigue life curve is dependent upon the amount of nonlinear behavior displayed by the mixture for the range of stress levels used (Reference 19).

Pell reports that an increase in temperature for controlled-strain testing increases laboratory fatigue life (Figure 47 [Reference 34]). These apparently longer fatigue lives may be the result of a slow rate of crack propagation due to low specimen stiffness at high temperatures (Reference 34).

In studying thermal activity in asphaltic pavement materials, Chang et al. found that thermal stresses may be negligible when pavement temperatures are above the freezing point, as illustrated in Figure 48. Thus, cracking in the pavement will propagate more quickly during severe winter weather conditions (Reference 81).

Moisture

Although it is recognized that moisture conditions affect the fatigue life of pavement, the available data are insufficient to conclusively document the relationship. Epps and Monismith (Reference 1) hypothesize that the absorption of moisture by asphalt mixtures could lead to a lower stiffness and possibly to reduced fatigue life. Schmidt and Graf have studied the effect of water on the resilient modulus of asphalt mixtures (Reference 82). Their data indicate that the resilient modulus is less for samples containing water and that the rate and amount of decrease are proportional to the concentration of the water. Upon drying, however, the moisture-deteriorated specimens return to their original resilient modulus. Since the resilient

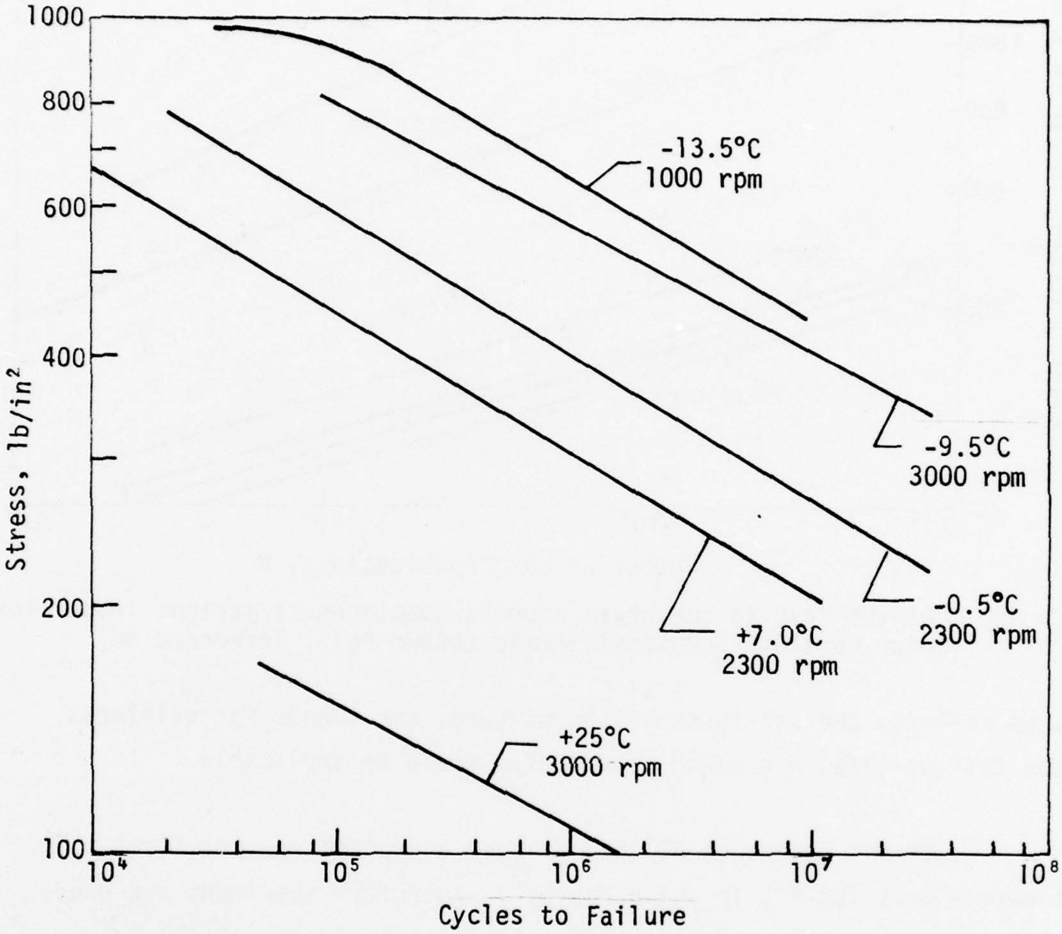


Figure 46. Fatigue Results of Sandsheet Specimens at Various Temperatures and Speeds Under Constant Bending Stress (after Saal and Pell, Reference 80)

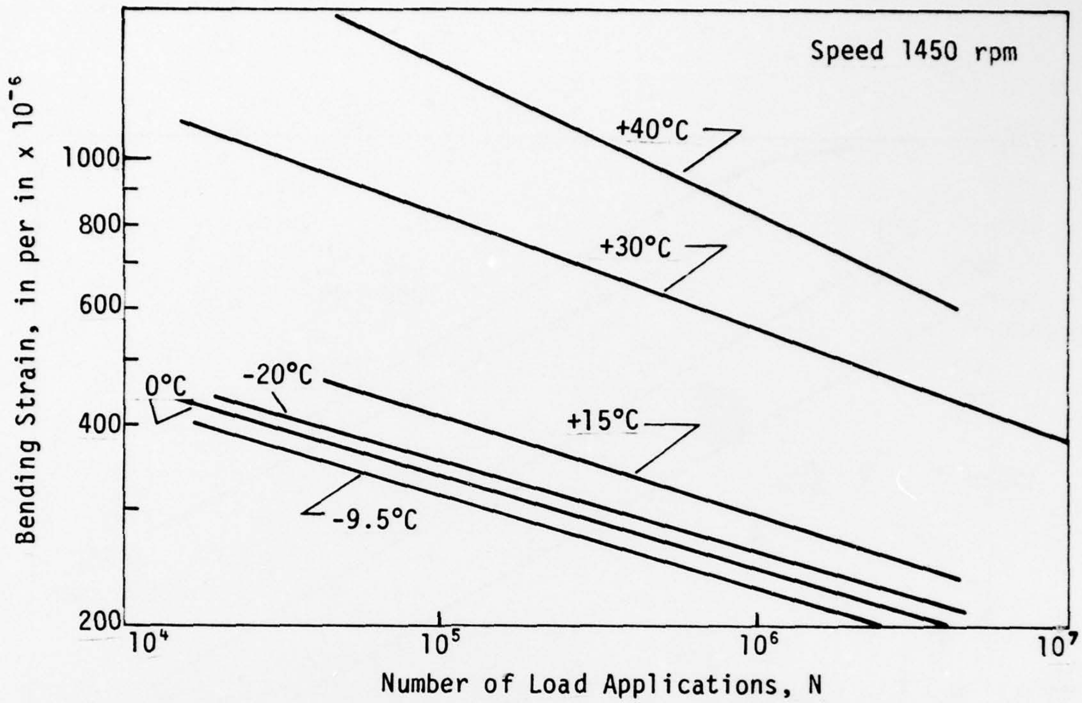


Figure 47. Fatigue Results for Sheet Asphalt Specimens at Various Temperatures Under Constant Torsional Strain (after Pell, Reference 34)

modulus reflects the stiffness of the mixture, the trends for stiffness versus fatigue life, discussed previously, would be applicable.

Lottman (Reference 83) has devised a predictive, practical moisture-damage test for AC, in which Marshall laboratory specimens are used. The test system, which is apparently workable, can consist of (1) fabricating specimens to duplicate mixture characteristics of in-place pavements; (2) exposing specimens to moisture by vacuum saturation with either freeze-plus-soak or thermal-cycle moisture conditionings; (3) mechanical testing of dry, vacuum-saturated, and moisture-conditioned specimens by indirect tension to determine tensile strength and an E-modulus; and (4) evaluating the moisture damage using the ratios between the tensile strengths of the conditioned and dry specimens and between the E-moduli of the conditioned and dry specimens. This system predicts most accurately the condition of highly and negligibly moisture-damaged pavements.

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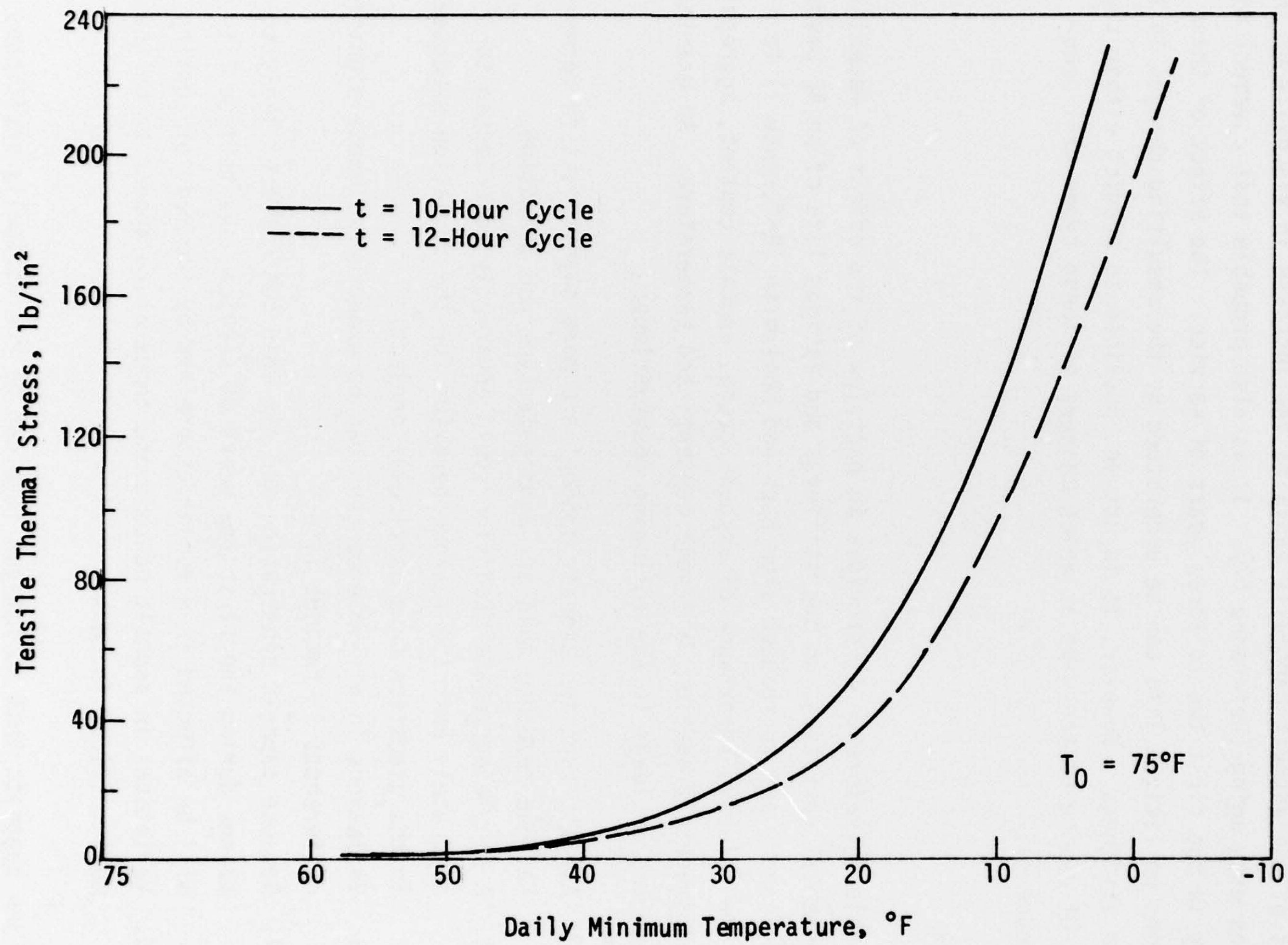

Figure 48. Maximum Thermal Stress Induced by Different Daily Minimum Temperatures

Material Changes with Age

Changes in AC material properties with age are caused by both chemical and physical variations. For example, an increase in the asphaltene content of the asphalt partially explains the increase in viscosity of the bitumens with aging (Reference 67). It is also probable that pavement will densify in the first two to three years of service. The effect of these alterations on fatigue life can be understood by the resulting changes in the mixture stiffness. However, it is not yet possible to predict either the amount of change or the time at which changes of these types will occur (Reference 1).

SUMMARY

Table 6 (Reference 1) provides an overview of the effect of material and environmental variations on the stiffness and fatigue life of an AC pavement. Tables 7 and 8 are reproduced from Epps and Monismith (Reference 1) to illustrate the relative importance of asphalt grade, asphalt content, aggregate type, aggregate gradation, air-void content, and temperature. An examination of these tables leads to the following observations:

1. Asphalt type and asphalt content are more significant in terms of fatigue response than are aggregate type and gradation.
2. A single aggregate gradation could apparently be selected to adequately describe fatigue behavior for the variation expected in the gradation on a particular project.
3. Variations in air-void content can be expected to cause significant differences in fatigue life.
4. Because asphalt penetration and air-void content are likely to change during the first few years of service, the fatigue life will be affected in a manner determined by the mode of testing.
5. Variations in asphalt content and temperature appear to be the most critical factors.

Finn suggests that AC fatigue life can be realistically envisioned as a distribution of values for a series of individual specimens (Reference 89).

TABLE 6. FACTORS AFFECTING STIFFNESS AND FATIGUE BEHAVIOR OF ASPHALT CONCRETE MIXTURES

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[c]
Air-Void Content	Decrease	Increase	Increase	Increase[c]
Temperature	Decrease	Increase[d]	Increase	Decrease

(Reference 1)

[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 finding speculative.

[c]No significant amount of data.

[d]Approaches upper limit at temperature below freezing.

Thus, fatigue test results generally have a high coefficient of variation. It is of the utmost importance, therefore, for the reader to understand that it is not now nor is it ever likely to be possible to predict exactly the fatigue life of an asphaltic concrete. Nevertheless, investigators are attempting to find a method that will enable them to make realistic estimates of fatigue life—in short, to reduce estimate error from perhaps 75 percent to 25 percent.

TABLE 7. SELECTED RESULTS FROM CONTROLLED-STRESS TESTS

Variable	Change in Variable	Change in Fatigue Life[a]	Reference
Asphalt Penetration	92-33	500,000 to 1,000,000	26
	120-60	6,000 to 250,000	74
	110-40	No significant change[b]	19
	180-40	250,000 to 1,000,000	7
	85-13	No significant change	84
Asphalt Content,[c] %	5.3-6.7	2,000 to 20,000	26
	6.0-7.5	6,000 to 40,000	74
	3.5-6.5	6,000 to 2,500,000	19
Aggregate Type	Smooth to rough surface texture	800,000 to 1,000,000	26
		8,000 to 40,000	74
		750,000 to 1,000,000	19
	Coarse to fine	450,000 to 1,000,000	26
		[d]450,000 to 1,000,000	26
		[d]150,000 to 1,000,000	34
		[d]350,000 to 1,000,000	7
Aggregate Gradation	Addition of filler, 0 to 9 percent	700,000 to 2,500,000	19
Air-Void Content, %	10-3	24,000 to 125,000 (sandsheet)	26
		250 to 15,000 (dense graded)	26
		250 to 5,000 (dense graded)	26
		30,000 to 300,000 (sandsheet)	80
	9-4.5	300,000 to 1,000,000 (sandsheet)	7
Temperature, °F	40-68	200,000 to 1,000,000 (avg. values)	85
		600,000 to 1,000,000 (avg. values)	86
	32-86	No significant change[b]	19
	14-50	No significant change	7

(Reference 1)

[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]Compari on of sheet asphalt mixtures with dense graded mixtures.

TABLE 8. SELECTED RESULTS FROM CONTROLLED-STRAIN TESTS

Variable	Change In Variable	Change in Fatigue Life[a]	Reference
Asphalt Penetration	114-47 200-50	100,000 to 9,000 No significant change	33 87
Asphalt Content		No significant data available	
Aggregate Type	Smooth to rough surface texture; rounded to angular shape	No significant change 300,000 to 1,000,000 Significant change	87, 88 85 88
Aggregate Gradation	Coarse to fine	No significant change Limited data available	87
Air-Void Content, %	9-5	2,000 to 3,500 (dense graded)	33
Temperature, °F	40-75 23-104	2,000 to 1,000,000 300,000 to 1,000,000 100 to 1,000,000	47 47 34

(Reference 1)

[a]Comparisons based on results from strain-fatigue life relationships.

SECTION V
DISCUSSION AND CONCLUSIONS

DISCUSSION

Asphaltic concrete pavements are designed to be flexible under load and to deform for a finite number of load replications. Repeated flexure ultimately leads to fatigue cracking, which is accelerated by the environmental conditions experienced by the pavement. In addition to the number of load repetitions, the pavement's fatigue life is influenced by frequency of loading, aggregate and asphalt properties (and the proportions of these in the mixture), and temperature and moisture conditions.

Many investigators have examined the effects of mixture characteristics and environmental conditions on AC fatigue life, and for about 20 years researchers around the world have attempted to develop methods of predicting the number of load repetitions a given pavement can withstand, given a particular set of circumstances. A number of approaches have been used, but only minimal success has been achieved in making such predictions. One of the major difficulties has been an inability to define realistically the shift between laboratory fatigue-test results and the actual fatigue life of a pavement. If that shift factor could be determined, it is conceivable that a reasonable estimate of fatigue life could be made on the basis of laboratory tests. The development of such a shift factor is the primary research need in the asphalt fatigue area.

Of the tests examined for the purposes of this report, the repeated-load indirect tensile test is recommended as the fatigue test procedure that should be used in U.S. Air Force investigations. In this procedure, a Marshall-type specimen is used. Thus, both laboratory and field samples would be relatively easy to obtain and transport. The test method is reasonably expeditious, so a large amount of data could be generated in a reasonable length of time.

The resilient-modulus indirect tensile test is the routine design test advocated for use by the U.S. Air Force. The procedure suggested is one developed at the University of Waterloo. A Marshall-type specimen is used for testing; thus, laboratory and field specimens are easily acquired and handled. The test is relatively quick and easy to perform. One major advantage in using this procedure is that it can provide an estimate of Poisson's ratio; thus, assumed values need not be used.

This effort also indicates that a study of the correlations between results of asphalt cement tests and AC fatigue life would be useful. Further asphalt cement tests might provide an index for such a correlation.

The author believes that an overriding emphasis should not be placed on simulating field loading and environmental conditions in the laboratory. Rather, the objective of any future effort should be to develop a shift factor that will provide a reasonable statistical correlation between a practically obtained laboratory test value and an actual field performance curve. Whether or not the laboratory test conditions simulate field conditions should be of little concern, provided the actual field fatigue life prediction is realistic.

CONCLUSIONS

1. The fatigue life of asphaltic concrete is affected by variations in the following mixture parameters: aggregate shape and gradation, asphalt grade and content, air-void content, mineral-filler content, and mixture stiffness.

2. The fatigue life is influenced by variations in the temperature and moisture conditions of a pavement, as well as by material property changes due to aging.

3. The repeated-load indirect tensile test is recommended for use by the U.S. Air Force for fatigue testing of asphaltic concrete.

4. The resilient-modulus indirect tensile test is recommended for use by the U.S. Air Force as a routine design test that can be used to estimate AC fatigue properties.

5. Tests on the asphalt cement used in AC mixtures should be performed as a possible index relating to fatigue life.

6. The primary research need in the asphalt fatigue area is the development of a shift factor that would enable investigators to predict the fatigue life of an actual pavement from laboratory test data.

7. The data should be studied for correlations between results of repeated-load indirect tensile tests and resilient-modulus indirect tensile tests. If such a correlation exists, fatigue life could be estimated from a routine design test and the need for fatigue testing would be eliminated.

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APPENDIX A

STRESS ANALYSIS FOR DIFFERENT LOADING STRIP WIDTHS[1]

ANALYSIS OF PRINCIPAL STRESSES

The equations for principal stresses in the indirect tensile test are given by Hondros [Reference 90] and assume that body forces are negligible. Figure A-1 [Reference 90] shows the notation for the polar stress components. The equations for the principal stresses are [Reference 9]:

(1) Along the vertical diameter:

(a) tangential stress

$$\sigma_{\theta y} = + \frac{2P}{\pi a h}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1-2\cos 2\alpha\, r^2/R^2 + r^4/R^4)} - \tan^{-1}\left(\frac{(1 + r^2/R^2)}{(1 - r^2/R^2)}\tan\alpha\right)\right]$$

(b) radial stress

$$\sigma_{ry} = \frac{-2P}{\pi a h}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{1-2\cos 2\alpha\, r^2/R^2 + r^4/R^4} + \tan^{-1}\left(\frac{(1 + r^2/R^2)}{(1 - r^2/R^2)}\tan\alpha\right)\right]$$

(c) shear stress $T_{r\theta} = 0$

(2) Along the horizontal diameter:

(a) tangential stress

$$\sigma_{\theta x} = \frac{-2P}{\pi a h}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1+2\cos 2\alpha\, r^2/R^2 + r^4/R^4)} + \tan^{-1}\left(\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right)\right]$$

(b) radial stress

$$\sigma_{rx} = + \frac{2P}{\pi a h}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1+2\cos 2\alpha\, r^2/R^2 + r^4/R^4)} - \tan^{-1}\left(\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right)\right]$$

(c) shear stress $T_{r\theta} = 0$

Footnote

[1] This appendix is quoted from Cheetham, A., Haas, R. C. G., and Meyer, F. R. P., *An Initial Study into the Use of Sulpher in Asphalt Pavement Recycling*, unpublished report prepared for Gulf Canada Limited by the University of Waterloo and Pavement Management Systems, Ltd., February 1979, Appendix B (Reference 58).

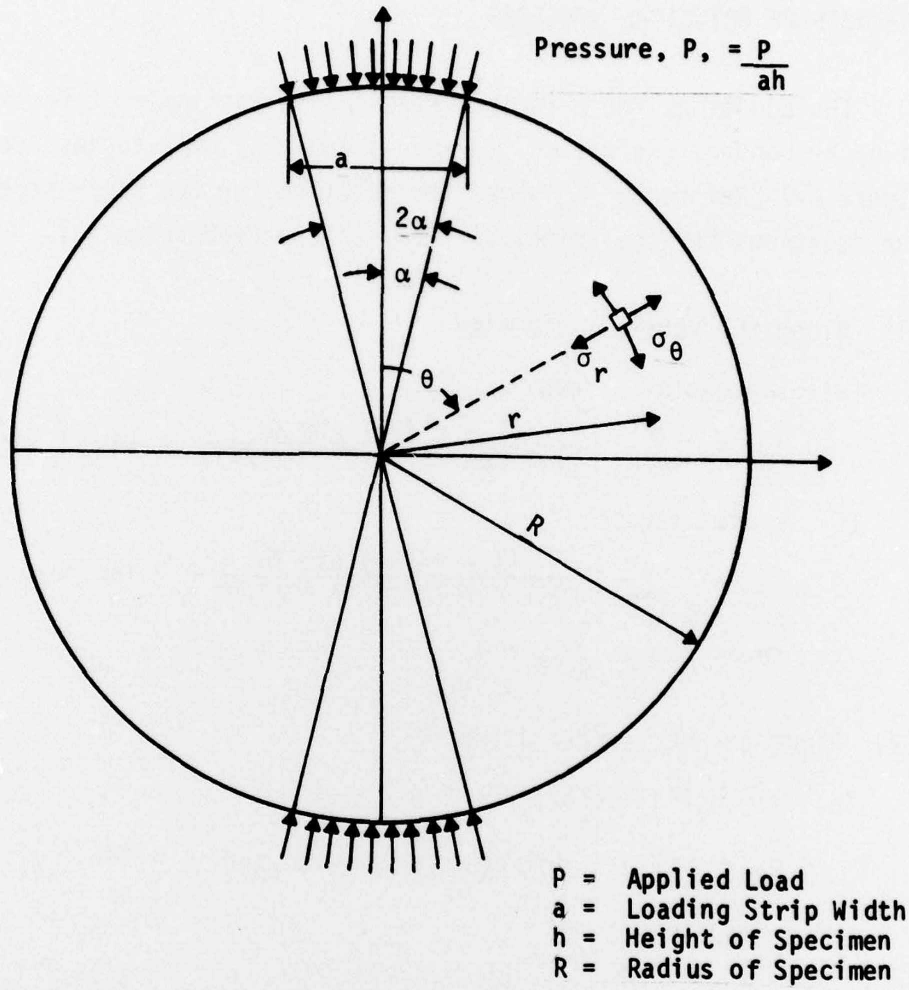


Figure A-1. Notation for Polar Stress Components in the Indirect Tensile Test (after Reference 90)

These equations produce stress distributions as were shown [in Figure 22 of Section III]. Solution of the equations for a 4-inch diameter specimen and two loading strip widths (a = half-inch and a = one-inch) are shown in Figure A-2 for a load magnitude of 100 pounds and specimen height of 2.5 inches.

In Figure A-2 the stress distributions are symmetrical about the axis perpendicular to the axis which the stress is along as shown in Figure A-1. It can be seen that the stresses along the horizontal axis are almost unchanged by the increase in strip width. The stresses along the vertical diameter are relatively unaffected at the center of the specimen but greater variation occurs nearer the loading strips where the compressive stresses are greatly decreased with the wider loading strips. The vertical tension zone is decreased from 3.2 inches to 2.8 inches with the increase in loading strip width.

Table A-1 shows the magnitude of the maximum tensile stress (which occurs at the center of the specimen) for three loading strip widths.

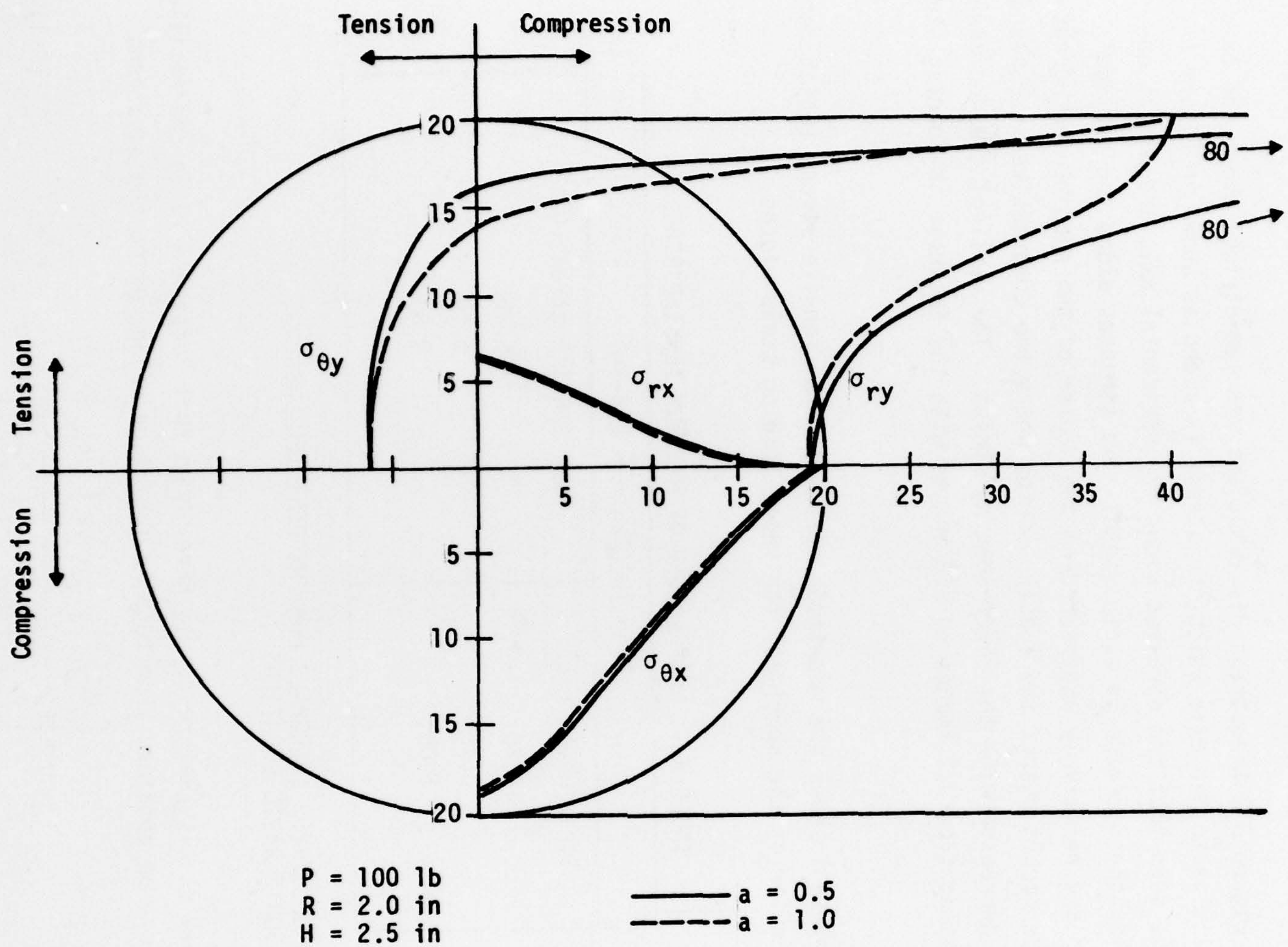
TABLE A-1. COMPARISON OF MAXIMUM TENSILE STRESSES

(P = 100 lb; h = 2.5 in)	
Strip width (in)	Max. tensile stress (lb/in^2)
0.50	6.25
0.75	6.10
1.00	5.89

SOLUTION OF STRESS INTEGRALS FOR THE RESILIENT MODULUS AND POISSON'S RATIO EQUATIONS

Hadly et al. [Reference 91] have shown that Poisson's ratio and resilient modulus can be obtained from total deformation values using the equations

$$\nu = \frac{\left[x_T \int_{-r}^{+r} \sigma_{ry} + y_T \int_{-r}^{+r} \sigma_{rx}\right]}{\left[y_T \int_{-r}^{+r} \sigma_{\theta x} + x_T \int_{-r}^{+r} \sigma_{\theta y}\right]} \qquad \text{(A-1)}$$



Note: Units along axes are stresses in lb/in^2

Figure A-2. Comparison of Principal Stress Distributions for Two Loading-Strip Widths and

$$M_R = \frac{P}{x_T}\left[\int_{-r}^{+r}\sigma_{rx}/P - \nu\int_{-r}^{+r}\sigma_{\theta x}/P\right] \quad \text{(A-2)}$$

The stress equations can be integrated for a given specimen radius and curved loading strip width. These integrations were done by computer using a numerical Romberg extrapolation technique for two loading strip widths (a - 0.5 inch and a = 1.0 inch). Table A-2 shows the computed values for the stress integrals for the two strip widths.

TABLE A-2. COMPUTED VALUES OF STRESS INTEGRALS

INTEGRAL	a = 0.5 in	a = 1.0 in
$\sigma_{\theta y}/\frac{2P}{ah}$	-0.0152	-0.0633
$\sigma_{ry}/\frac{2P}{ah}$	-0.8975	-1.3766
$\sigma_{\theta x}/\frac{2P}{ah}$	-0.2500	-0.4998
$\sigma_{rx}/\frac{2P}{ah}$	0.0674	0.1298

Equations A-1 and A-2 can be rewritten as

$$\nu = \frac{C_1\ DR + C_2}{C_3\ DR + C_4} \quad \text{(A-3)}$$

and

$$M_R = \frac{P}{hx_T}(C_5 + C_6\nu) \quad \text{(A-4)}$$

where C_i: i = 1, 2, ... 6 are constants and

DR = deformation ratio = y_T/x_T

The constants for the two loading strip widths are shown in Table A-3. (The constants can be rounded to two decimal places without causing significant errors in the calculations.)

TABLE A-3. CONSTANTS FOR USE IN ν AND M_R EQUATIONS

CONSTANT	a = 5.0 in	a = 1.0 in
C1	0.0674	0.1298
C2	-0.8975	-1.3766
C3	-0.2500	-0.4998
C4	-0.0152	-0.0633
C5	0.2696	0.2596
C6	1.0000	0.9996

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