Repeated-Load Indirect Tensile Fatigue Characteristics of Asphalt Mixtures

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The determination of the fatigue characteristics of pavement materials is necessary for the design and evaluation of highway and airport pavements. This paper summarizes the findings of a study in which the controlled-stress, repeated-load indirect tensile test was used to investigate the fatigue characteristics of asphalt mixtures. The logarithmic relationships between fatigue life and both applied stress and initial mixture strain were evaluated and found to be linear. In addition, linear relationships were found between n_1 and the logarithm of K_1 for the strain-fatigue life relationships and between n_2 and the logarithm of K_2 for the stress-fatigue life relationships. The effects on fatigue life produced by load, asphalt content, aggregate type, and testing temperature are discussed. Fatigue life could not be estimated from only applied stress or stress difference; however, equations relating fatigue life to both the initial mixture strain and the stress-strength ratio were developed. From this study it was concluded that the repeated-load indirect tensile test is suitable for evaluating the fatigue characteristics of asphalt mixtures.

A knowledge of the fatigue behavior of asphalt materials is important in the design and evaluation of highway and airport pavements. Many of the design procedures currently used are empirical and deterministic in nature. However, in view of the developments in pavement system design and the recognition that fatigue cracking is a basic distress mode, the effects of repeated loads, or fatigue, should be considered in design. A necessary step is the determination of the fatigue characteristics of pavement materials.

Many test methods have been used to study the fatigue behavior of asphalt materials. These test methods generally have produced excellent results that have contributed to the knowledge of the fatigue behavior of asphalt materials. Nevertheless, these tests are costly and in most cases difficult to conduct. Thus, it is highly desirable to use a test method that is economical to apply and easily implemented, and an operating agency rather than a research agency should conduct the test.

Previous work (1, 2, 3, 4) suggests that the repeated-load indirect tensile test represents such a test. Thus, a laboratory study using the repeated-load indirect tensile test was conducted to investigate the fatigue behavior of asphalt materials and to demonstrate the use of the test.

EXPERIMENTAL PROGRAM

The primary objectives of the experimental phase of the study were to

1. Use the repeated-load indirect tensile test to study the fatigue characteristics of asphalt mixtures,
2. Determine the effect of selected factors on fatigue characteristics, and
3. Investigate the relationships between fatigue life and other load and mixture characteristics.

Experiment Design

The basic experiment design is given in Table 1. Factors investigated were aggregate type, asphalt content, testing temperature, and stress level. The aggregates were a crushed limestone and a rounded river gravel, which were combined to produce a gradation approximating the Texas specification for a class A, type B fine-graded base or level-up coarse or a type C coarse-graded surface course (11). These aggregates were combined with an AC-10 asphalt cement at five asphalt contents (4, 5, 6, 7, and 8 percent by total weight of the mixture). The resulting mixtures were tested at 10, 23.9, and 37.8°C (50, 75, and 100°F) at stress levels ranging between 55 and 827 kPa (8 and 120 psi).

Specimen Preparation

The materials were mixed at 135°C (275°F), and the mixtures were compacted at 121.1°C (250°F) by using the Texas gyratory shear compactor and by following the procedure specified in test method Tex-206-F, part 2 (5). After compaction, the specimens to be tested at 23.9°C (75°F) were cured for 2 days at room temperature, 23.9 ± 1.1°C (75 ± 2°F), before testing. For tests conducted at 10 and 37.8°C (50 and 100°F), specimens were cured at room temperature for 24 hours and then transferred to temperature-controlled rooms and kept

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at 10 ± 1.1°C (50 ± 2°F) or 37.8 ± 1.1°C (100 ± 2°F) for another 24 hours before testing.

Test Equipment and Procedures

The basic equipment for the repeated-load indirect tensile test included a loading system and a means of monitoring the applied loads and the horizontal and vertical deformations of the specimen. A closed-loop electrohydraulic system was used to apply the loads, and a special loading device was used to ensure that the loading platens and strips remained parallel during the test. The 12.7-mm-wide (0.5-in) fitted steel loading strips were mounted on the upper and lower platens.

Loads were monitored with a load cell and were recorded continuously. Vertical and horizontal deformations for any particular load application were measured by using linear variable displacement transformers. Permanent horizontal deformations were measured by using a cantilevered arm device that had been used in previous studies (6, 7).

A typical load pulse is shown in Figure 1, and the resulting load-deformation-time relationships are shown in Figures 1 and 2. Fatigue life was defined as the number of load applications required to completely fracture the specimen as shown in Figure 2.

ANALYSIS AND DISCUSSION

Relationships With Applied Stress

As in previous studies, a linear relationship was found to exist between the logarithm of the applied stress and the logarithm of fatigue life (Figures 3 and 4), which could be expressed as

$$N_f = K_2(1/\sigma_T)^{n_2} \quad (1)$$

where

N_f = fatigue life,
σ_T = applied tensile stress, and
n_2, K_2 = constants.

Values of K_2 varied between 11.9 Pa and 270 MPa (3.26×10^5 and 1.90×10^{13} lbf/in²) while values of n_2 varied between 2.66 and 5.19. These values of n_2 compare favorably with those reported by other investigators using other test methods (2, 8, 9, 10); however, the values of K_2 are significantly smaller, resulting in much lower fatigue lives.

In previous work Porter and Kennedy (3) analyzed the results obtained from other test methods and compared the characteristics of these tests and concluded that the results obtained from the repeated-load indirect tensile test were compatible if stress is expressed in terms of stress difference. Expressing fatigue life in terms of stress difference changes the value of K_2 but does not affect the value of n_2; thus the relationship can be expressed in the form

$$N_f = K_2'(1/\Delta\sigma)^{n_2} \quad (2)$$

where

N_f = fatigue life,
$\Delta\sigma$ = stress difference, and
K_2', n_2 = constants.

Values of K_2' ranged from 513 Pa to 368 CPa (1.41×10^7 to 2.53×10^{16} lbf/in²), as shown in Figures 5 and 6.

Approximate linear relationships were found to exist between n_2 and the logarithm of K_2 and between n_2 and the logarithm of K_2'. The relationships developed from a regression (by using K_2 and K_2' for stress in lbf/in²) were

$$n_2 = 0.919 + 0.312 \log K_2 \quad (r = 0.95, S_e = 0.23) \quad (3)$$

$$n_2 = 0.734 + 0.266 \log K_2' \quad (r = 0.96, S_e = 0.19) \quad (4)$$

The 95 percent confidence interval for the correlation coefficient r was between 0.85 and 0.98 for equation 3 and between 0.88 and 0.99 for equation 4. By making n_2 the independent variable, the following relationships were obtained:

$$\log K_2 = -1.867 + 2.886\, n_2 \quad (r = 0.95, S_e = 0.70) \quad (5)$$

$$\log K_2' = -1.859 + 3.485\, n_2 \quad (r = 0.96, S_e = 0.70) \quad (6)$$

Because of the above relationships, a regression analysis was conducted on the combined data from previous studies (2, 8, 9, 10). Values of K_2 for the indirect tensile test were assumed to be the values of K_2'. This analysis yields the following average relationships:

1. When n_2 is the dependent variable,

$$n_2 = 0.069 + 0.322 \log K_2 \quad (r = 0.96, S_e = 0.32) \quad (7)$$

2. When n_2 is the independent variable,

$$\log K_2 = 0.860 + 2.869\, n_2 \quad (r = 0.96, S_e = 0.97) \quad (8)$$

The 95 percent confidence interval for r was between 0.94 and 0.97. Figure 7 shows the positions of the above relationships relative to all data points. Thus, it appears that there is a relationship between K_2 and n_2, irrespective of mixture properties or test procedure.

Relationships With Initial Strain

The initial strains were estimated by dividing the applied dynamic stress by the average static modulus of elasticity (4). These estimated strain values were used to develop relationships between the logarithm of strain and the logarithm of fatigue life (Figures 8 and 9). A regression analysis was used to establish these relationships and to obtain values of the constants K_1 and n_1 for the general equation

$$N_f = K_1(1/\epsilon_{mix})^{n_1} \quad (9)$$

where

ϵ_{mix} = initial strain and
K_1, n_1 = constants.

Values of K_1 ranged from 5.65×10^{-17} to 5.01×10^{-7} and n_1 ranged from 2.66 to 5.19. These values were compared to those obtained from previous flexural and axial load tests on other mixtures (2, 8, 9, 10). Reported data indicate that K_1 generally ranges from 5.0×10^{-20} to about 5.0×10^{-5}, and n_1 ranges from about 2.5 to 6.3, depending on asphalt content, testing temperature, and testing procedure. The values of K_1 and n_1 obtained by using the repeated-load indirect tensile test compare favorably with previously reported values, and values from this study were essentially the same as those obtained for similar mixtures with the same asphalt contents and tested at the same temperature.

Thus, it appears that comparable values of K_1 and n_1

can be obtained for essentially the same mixtures, irrespective of test procedures. Because the mechanism of failure is probably strain dependent, consideration of strain at least partially accounts for the states of stress, temperature, and load pulse.

Relationship Between K_1 and n_1 Values

A linear relationship was also found to exist between n_1 and log K_1:

1. When n_1 is the dependent variable,

$$n_1 = 0.938 - 0.261 \log K_1 \quad (r = 0.98, S_e = 0.13) \qquad (10)$$

2. When log K_1 is the dependent variable,

$$\log K_1 = 3.211 - 3.719\, n_1 \quad (r = 0.98, S_e = 0.47) \qquad (11)$$

The 95 percent confidence interval for r was between 0.94 and 0.99. Recently, Pell and Cooper (10) reported an expression that was similar to equation 10:

$$n_1 = 0.5 - 0.313 \log K_1 \qquad (12)$$

Because of this similarity, an evaluation of the relationship between n_1 and log K_1 was also conducted for the combined values obtained from various other test methods and for different kinds of mixtures (2, 8, 9, 10), and the following linear relationships were obtained:

1. When n_1 is the dependent variable,

$$n_1 = 1.350 - 0.252 \log K_1 \quad (r = 0.95, S_e = 0.29) \qquad (13)$$

2. When n_1 is the independent variable,

$$\log K_1 = 3.977 - 3.609\, n_1 \quad (r = 0.95, S_e = 1.09) \qquad (14)$$

The 95 percent confidence interval for r was between 0.92 and 0.97. Figure 10 shows the positions of the above relationships relative to all data points.

The high correlation coefficients associated with these expressions show that a linear relationship exists between n_1 and log K_1, irrespective of mixture properties and test procedures.

Table 1. Factorial experiment design for repeated-load tests.

Test Temperature (°C)	Stress Level (N/cm²)	Limestone					Gravel				
		4	5	6	7	8	4	5	6	7	8
10	49.6			3					3		
	66.2			3					3		
	82.7			3					3		
23.9	5.5				5					5	
	11.0	3	5	6	8	3	3	5	7	9	3
	16.5	5	5	7	5	5	5	5	7	9	3
	22.1	3	5	7	6	3	3	6	7	9	3
	27.6	4	5	7	8	3	3	5	7	8	3
37.8	5.5			3					3		
	11.0			3					3		
	16.5			3					3		

Note: 1 N/cm² = 1.45 psi; 1° C = (1° F - 32)/1.8.

Figure 1. Typical relationships of load and deformation versus time for repeated-load indirect tensile test.

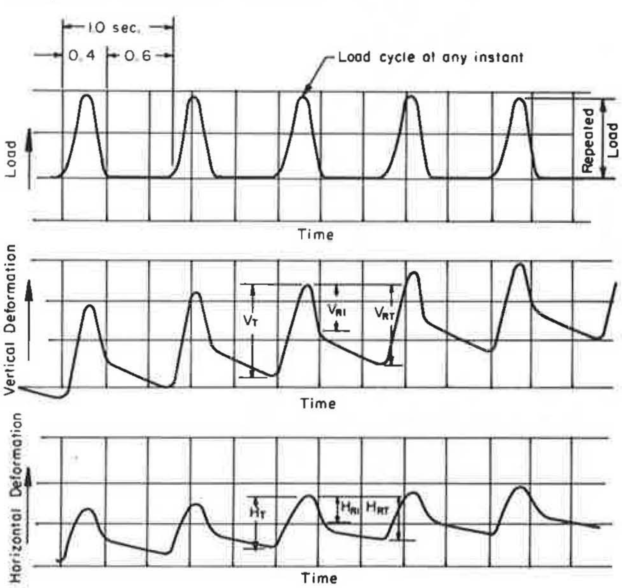


Figure 2. Relationships between number of load applications and vertical and horizontal deformation for repeated-load indirect tensile test.

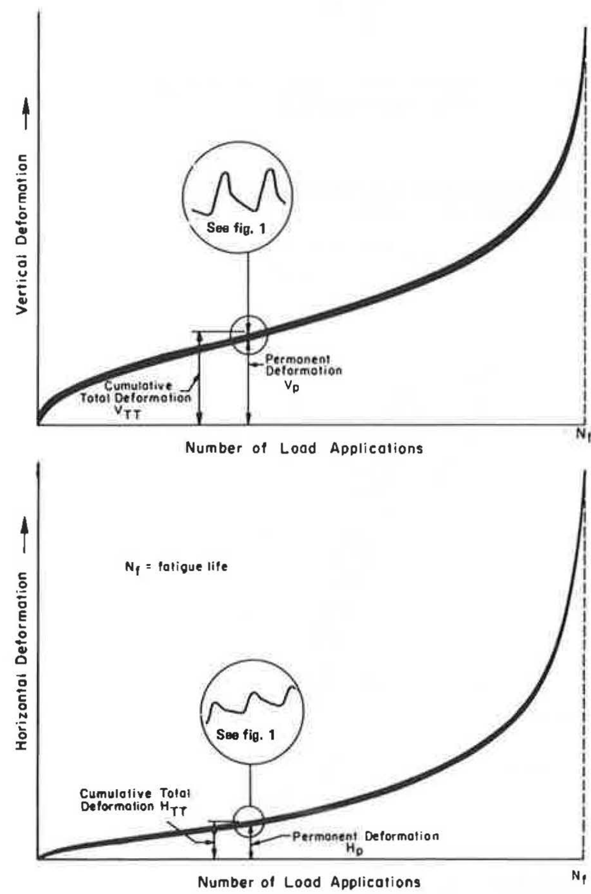
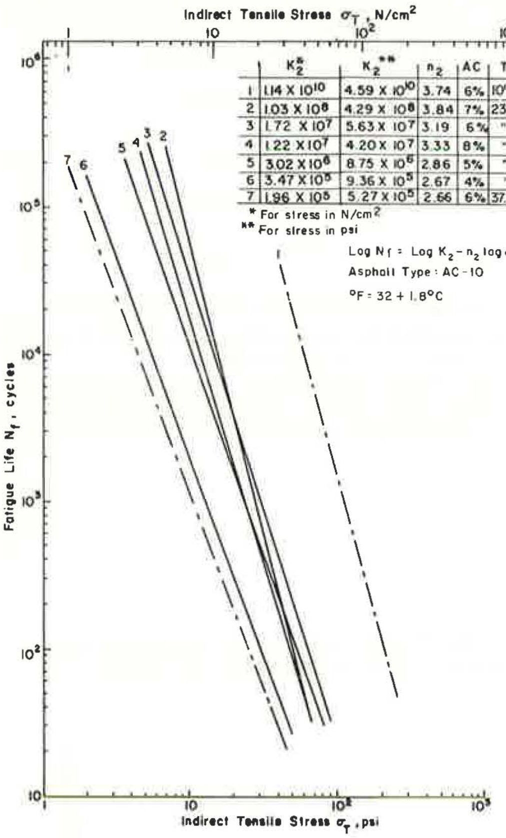
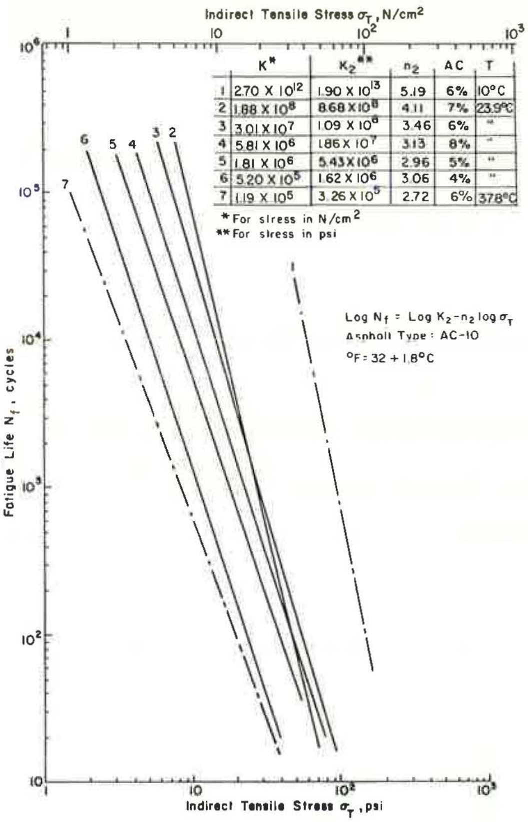


Figure 3. Relationship between fatigue life and applied tensile stress for limestone mixtures.



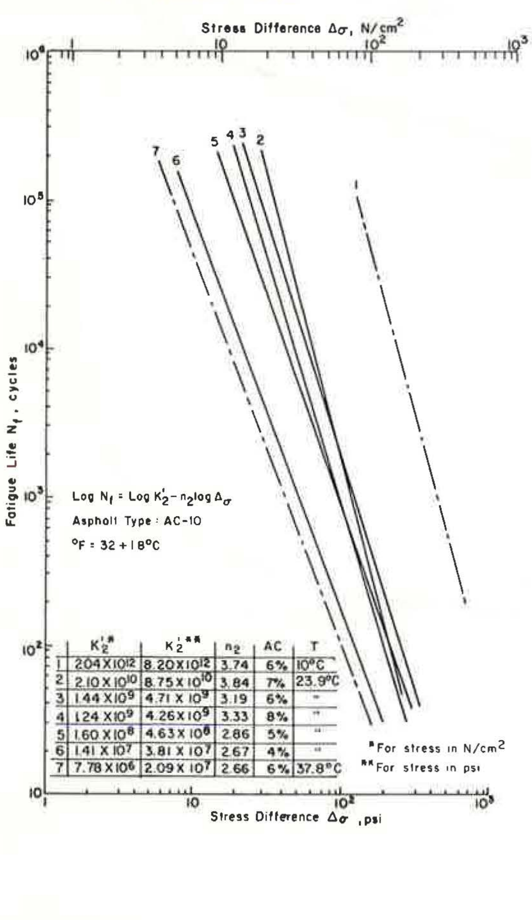
	K_2*	K_2**	n_2	AC	T
1	1.14 X 10^{10}	4.59 X 10^{10}	3.74	6%	10°C
2	1.03 X 10^{8}	4.29 X 10^{8}	3.84	7%	23.9°C
3	1.72 X 10^{7}	5.63 X 10^{7}	3.19	6%	"
4	1.22 X 10^{7}	4.20 X 10^{7}	3.33	8%	"
5	3.02 X 10^{6}	8.75 X 10^{6}	2.86	5%	"
6	3.47 X 10^{5}	9.36 X 10^{5}	2.67	4%	"
7	1.96 X 10^{5}	5.27 X 10^{5}	2.66	6%	37.8°C

Figure 4. Relationship between fatigue life and applied tensile stress for gravel mixtures.



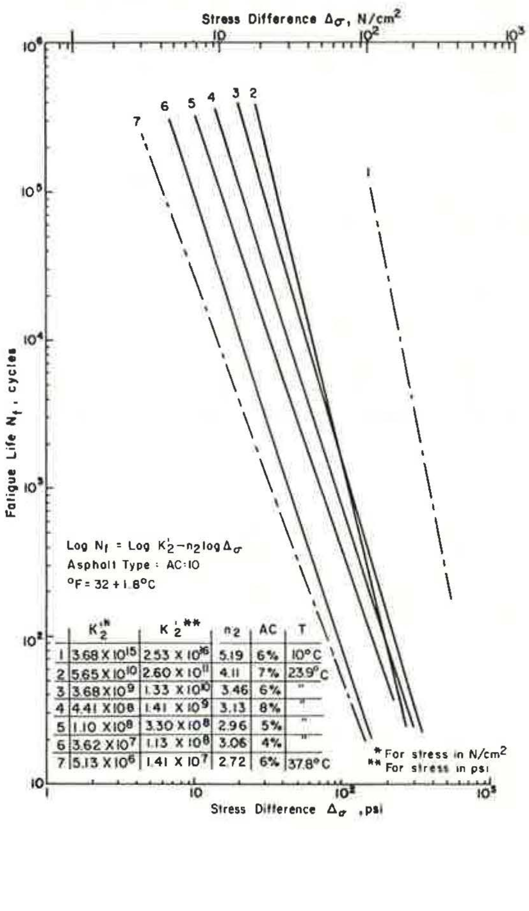
	K*	K_2**	n_2	AC	T
1	2.70 X 10^{12}	1.90 X 10^{13}	5.19	6%	10°C
2	1.88 X 10^{8}	8.68 X 10^{8}	4.11	7%	23.9°C
3	3.01 X 10^{7}	1.09 X 10^{8}	3.46	6%	"
4	5.81 X 10^{6}	1.86 X 10^{7}	3.13	8%	"
5	1.81 X 10^{6}	5.43 X 10^{6}	2.96	5%	"
6	5.20 X 10^{5}	1.62 X 10^{6}	3.06	4%	"
7	1.19 X 10^{5}	3.26 X 10^{5}	2.72	6%	37.8°C

Figure 5. Relationships between fatigue life and stress difference for limestone mixtures.



	K_2'*	K_2'**	n_2	AC	T
1	2.04 X 10^{12}	8.20 X 10^{12}	3.74	6%	10°C
2	2.10 X 10^{10}	8.75 X 10^{10}	3.84	7%	23.9°C
3	1.44 X 10^{9}	4.71 X 10^{9}	3.19	6%	"
4	1.24 X 10^{9}	4.26 X 10^{9}	3.33	8%	"
5	1.60 X 10^{8}	4.63 X 10^{8}	2.86	5%	"
6	1.41 X 10^{7}	3.81 X 10^{7}	2.67	4%	"
7	7.78 X 10^{6}	2.09 X 10^{7}	2.66	6%	37.8°C

Figure 6. Relationships between fatigue life and stress difference for gravel mixtures.



	K_2'*	K_2'**	n_2	AC	T
1	3.68 X 10^{15}	2.53 X 10^{16}	5.19	6%	10°C
2	5.65 X 10^{10}	2.60 X 10^{11}	4.11	7%	23.9°C
3	3.68 X 10^{9}	1.33 X 10^{10}	3.46	6%	"
4	4.41 X 10^{8}	1.41 X 10^{9}	3.13	8%	"
5	1.10 X 10^{8}	3.30 X 10^{8}	2.96	5%	"
6	3.62 X 10^{7}	1.13 X 10^{8}	3.06	4%	"
7	5.13 X 10^{6}	1.41 X 10^{7}	2.72	6%	37.8°C

Focal Point of Strain-Fatigue Life Relationships

Pell and Cooper obtained a focal point of intersection, i.e., a point at which all strain-fatigue life relationships intersect, which occurred at a strain of 0.000 63 and a fatigue life of 40.

In this study, different focal points occurred and were found to depend on whether equation 10 or 11 was used, i.e., whether n_1 or log K_1 was the dependent variable in the regression analysis. When equation 10 was used, the focal point occurred at a strain of 0.000 147 and fatigue life of 3926. On the other hand, the use of equation 11 resulted in a focal point at a strain of 0.000 191 and fatigue life of 1626.

Figure 7. Relationships between n_2 and K_2.

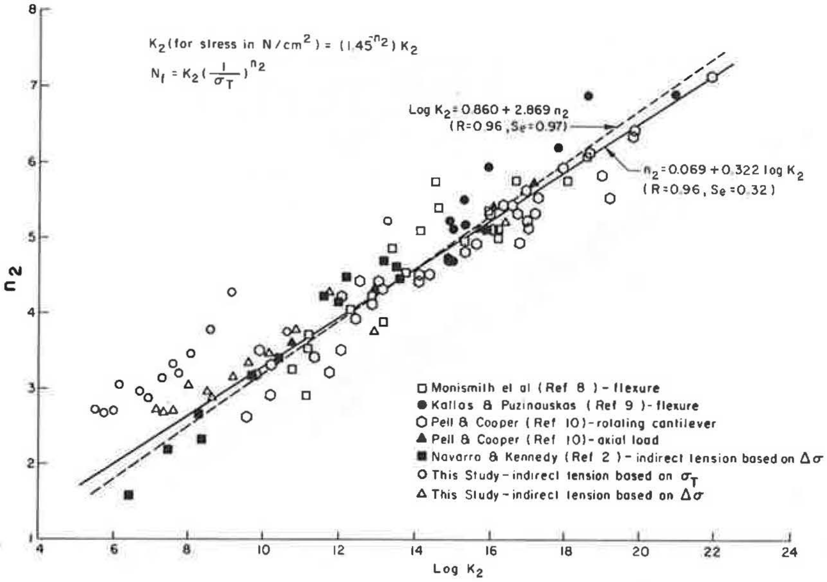


Figure 8. Relationships between fatigue life and initial strain for limestone mixtures.

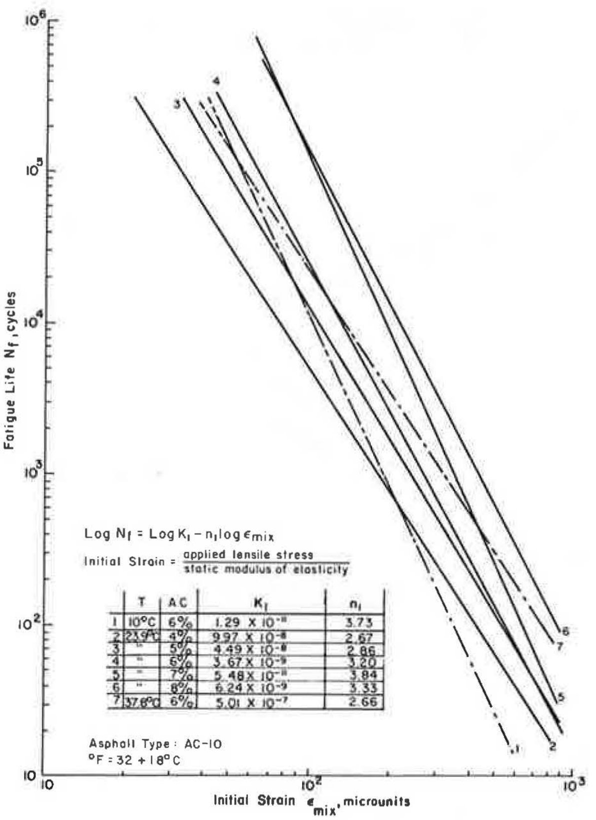
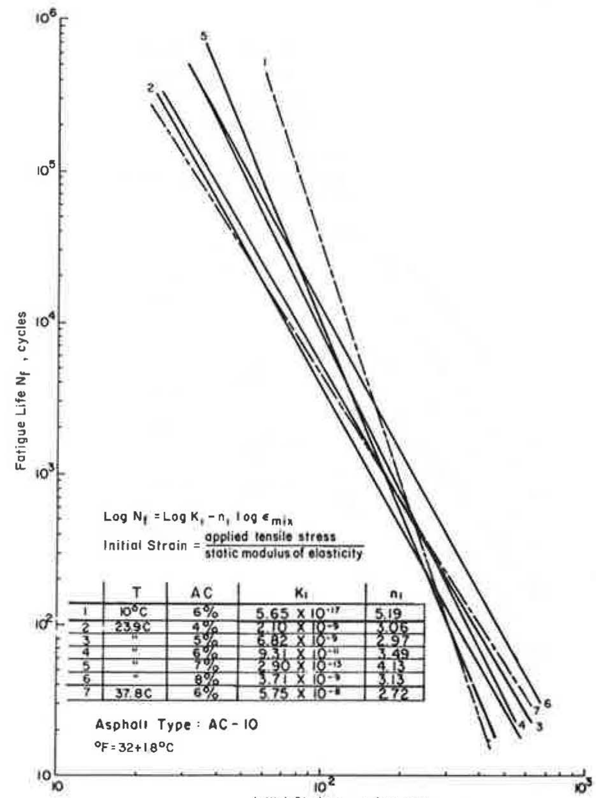


Figure 9. Relationship between fatigue life and initial strain for gravel mixtures.



Factors Affecting Fatigue Life

Asphalt Content

The relationships between fatigue life and asphalt content are shown in Figure 11 for the limestone and gravel mixtures tested at 23.9°C (75°F). The geometric means were used to obtain each point since fatigue life apparently has a logarithmic normal distribution.

It is evident that there was an optimum asphalt content for maximum fatigue life. For the mixtures and stress levels used in this study, stress level had a negligible effect on the optimum asphalt content; however, for the limestone mixtures the optimum appeared to decrease slightly with increased stress level.

Figure 10. Combined relationships between n_1 and K_1.

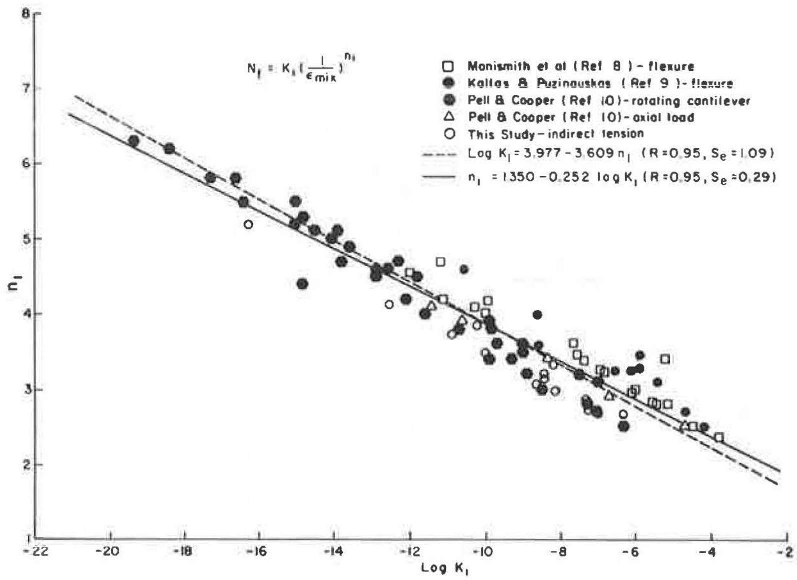


Figure 11. Effects of aggregate and asphalt content on fatigue life.

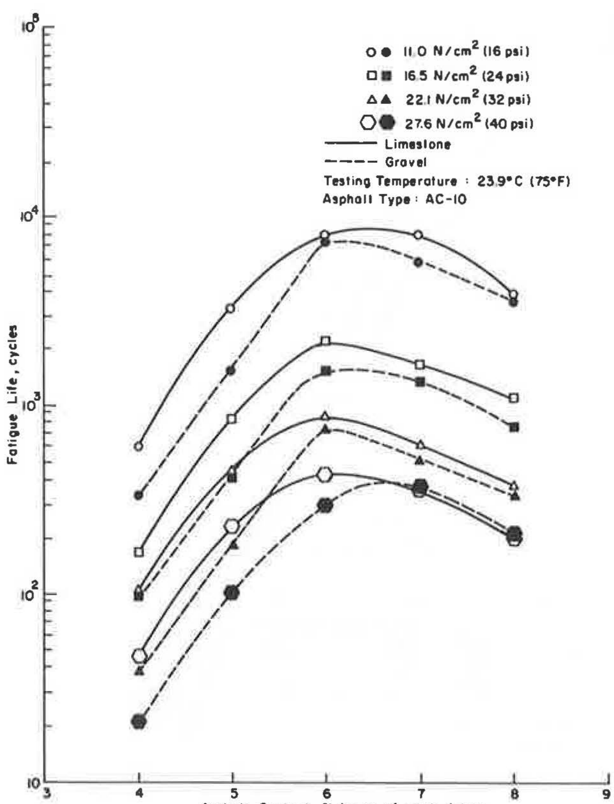
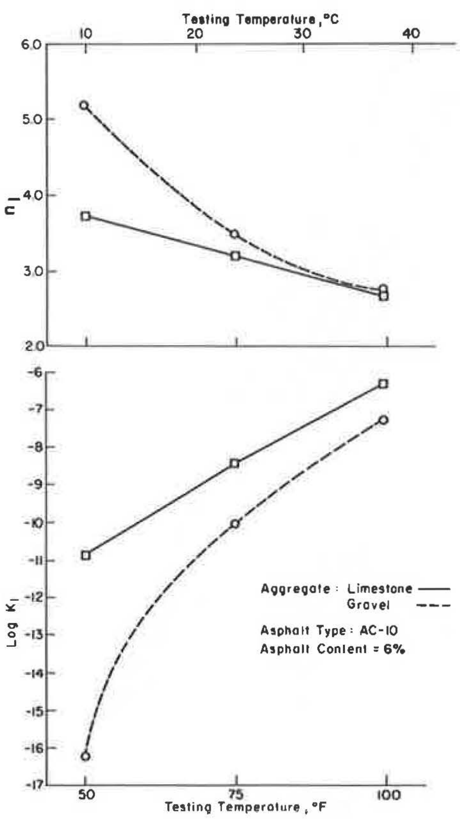


Figure 12. Effects of testing temperature on the values of K_1 and n_1.



The optimum asphalt content for maximum fatigue life was generally in the range of 6 to 6.5 percent, which is slightly less than the optimum asphalt content for maximum bulk density (4).

Maximum values of n_1 and minimum values of K_1 occurred at an asphalt content of about 7 percent, which is slightly higher than the optimum asphalt content for maximum fatigue life. In addition, maximum values of K_2, K_2', and n_2 occurred at an asphalt content of approximately 7 percent.

Aggregate Type

The limestone mixtures tended to have slightly longer fatigue lives than the gravel mixtures (Figure 11). The difference decreased with decreased stress and increased asphalt content, and, in some cases, the gravel mixtures had a longer fatigue life. In nearly all cases, however, the differences in fatigue lives for limestone and gravel mixtures were very small and it was felt that both mixtures exhibited approximately the same fatigue lives. In an earlier study on the same mixtures, Moore and Kennedy (1) reported that the gravel mixtures had longer fatigue lives than the limestone mixtures; however, this effect was not a significant behavioral difference. A significant interaction effect, however, was detected between aggregate and stress: Gravel exhibited significantly longer fatigue lives at low stress levels.

Thus, it would appear that, for the conditions of this study, aggregate was not important but that, for low stress levels such as those experienced in the field, aggregate type could be a significant variable.

The gravel mixtures exhibited higher values of n_1 and lower values of K_1 than the limestone mixtures. In terms of the stress relationships, the gravel mixtures exhibited higher values of n_2, K_2, and K_2' than the limestone mixtures.

Temperature

The effect of temperature (Figures 3 and 4) was found to agree with the findings of previous studies based on stress-controlled tests. In general, fatigue life increased with decreasing temperatures for the three temperatures considered.

The effect of temperature on the regression coefficients K_1 and n_1 is shown in Figure 12. An increase in testing temperature produced an increase in K_1 but a decrease in n_1. Figure 13 shows the effect of temperature on the regression coefficients K_2, K_2', and n_2; an increase in temperature produced a decrease in both K_2 and K_2' and also in n_2.

Fatigue Life Prediction

Efforts were made to develop mathematical relationships to predict fatigue life on the basis of load variables or mixture properties so that time-consuming and costly fatigue tests would not need to be conducted.

Initial Strain

A single expression was developed for estimating fatigue life in terms of initial strain ϵ_{mix}, irrespective of asphalt content, testing temperature, and aggregate type:

$$N_f = 9.38 \times 10^{-8} (1/\epsilon_{mix})^{2.76} \tag{15}$$

Equation 15 was obtained with a coefficient of determination of 0.70 and a standard error of estimate (a

Figure 13. Effects of testing temperature on the values of K_2, K_2', and n_2.

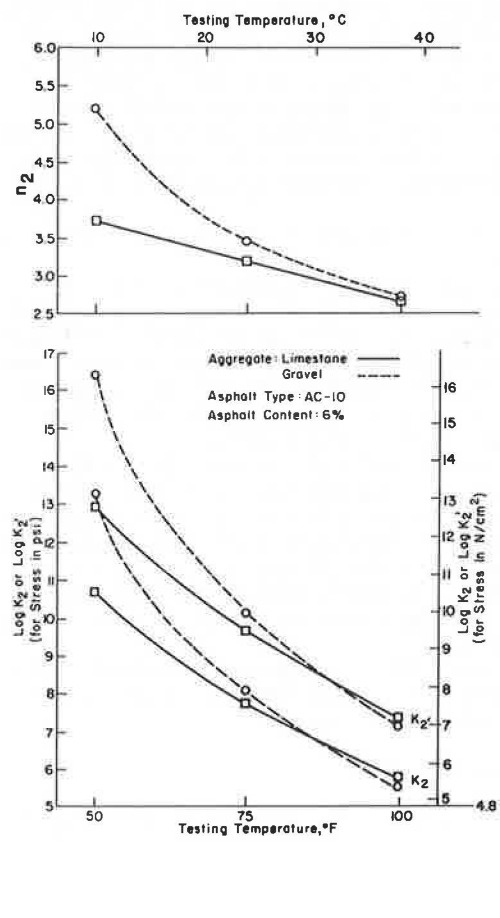
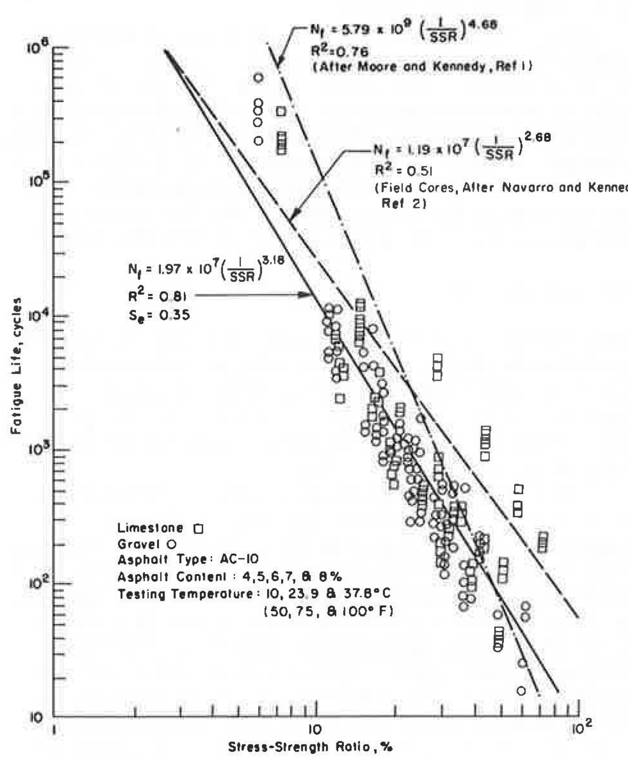


Figure 14. Relationships between fatigue life and stress-strength ratio.



measure of the variation of the logarithm of fatigue life about the regression line) of 0.44.

In view of the inherent variability associated with fatigue behavior, equation 15 would be relatively accurate; however, errors should be expected.

Stress or Stress Difference

The values of K_2, K_2', and n_2 for each mixture and testing temperature can be used with the general stress-fatigue life or stress difference-fatigue life equations to predict fatigue life.

Further regression analyses were conducted to obtain predictive equations independent of temperature, aggregate type, and asphalt content, but these produced very low coefficients of determination. Thus, it appears that there is no universally applicable method of predicting fatigue life on the basis of applied stress or stress difference.

Stress-Strength Ratio

To account for mixture and testing differences, the relationship between fatigue life and the stress-strength ratios, which previously has been shown to be a reasonable prediction (1), was evaluated. The stress-strength ratio was defined as the ratio of the applied repeated stress to the estimated indirect tensile strength (4).

There were linear relationships between the logarithm of fatigue life and the logarithm of stress-strength ratio SSR. From regression analysis, the following prediction equation, which is independent of asphalt content, temperature, and aggregate type, was obtained:

$$N_f = 1.97 \times 10^7 (1/SSR)^{3.18} \quad (r^2 = 0.81, S_e = 0.35) \tag{16}$$

The average fatigue life predictive equation from this study was compared with those obtained from earlier studies (1, 2); Figure 14 shows that all lines fall fairly well within the data points.

Results from this study indicated that prediction of fatigue life in terms of SSR is as good as that in terms of initial strain. Like initial strain, stress-strength ratio is easy to estimate and does not involve long-term repeated-load studies. Inasmuch as estimation of tensile strength requires only the measurement of failure load and does not require deformation measurements, this relationship probably has more application in laboratories, which are not equipped to run repeated-load tests.

Air Void Content

Many studies have indicated that fatigue life of asphalt mixtures increases with decreasing air void content. However, using the indirect tensile test method in a controlled-stress test, Moore and Kennedy (1) reported that air void content was not directly related to laboratory tensile fatigue life.

In this study, the optimum air void content for maximum fatigue life was about 3 percent. However, the compactive effort as well as the gradation was held constant so that changes in air void content were dependent on the changes in asphalt content, and thus the apparent relationship with air void content was judged to be due to the effect of asphalt content since the approximate optimum asphalt content for maximum fatigue life was about 6 percent, which corresponds to an optimum air void content of about 3 percent (4).

It is, therefore, felt that any apparent relationship between fatigue life and air void content is probably due to the fact that both air void content and fatigue life are related to other factors.

Density

Density and air void content are mixture properties that are inversely related to each other. Many researchers have correlated fatigue life with air void content rather than with density. Nevertheless, because it is much easier to estimate density than air void, an attempt was made to correlate fatigue life with density.

In this study, an approximately linear relationship was found to exist between bulk density and the logarithm of fatigue life for each stress level for tests conducted at 23.9°C (75°F). However, no general ralationship was found to exist that was independent of stress.

CONCLUSIONS

Within the limits of load, mixture, and temperature variables considered in this study, the following conclusions were made.

1. The repeated-load indirect tensile test is suitable for the study of fatigue characteristics of asphalt mixtures. This is important in view of its simplicity and the ease of conducting it.
2. A linear relationship exists between the logarithm of fatigue life and (a) the logarithm of tensile stress (equation 1), (b) the logarithm of stress difference (equation 2), and (c) the logarithm of initial strain, defined as the applied repeated tensile stress divided by the average static modulus of elasticity (equation 9).
3. For the constants K_1, n_1, K_2, n_2, and K_2' of equations 1, 2, and 9, K_1 ranged between 5.65×10^{-17}, and n_1 ranged between 2.66 and 5.19. For stress, K_2 ranged between 11.9 Pa and 276 MPa (3.26×10^5 and 1.90×10^{13} lbf/in^2), K_2' ranged between 513 Pa and 368 MPa (1.41×10^4 to 2.53×10^{16} lbf/in^2), and n_2 ranged between 2.66 and 5.19. The relationships between n_1 and the logarithm of K_1 and between n_2 and the logarithm of K_2 (or K_2') were linear.
4. The optimum asphalt content for maximum fatigue life was slightly less than the optimum for density. The optimum for fatigue life decreased slightly with increasing stress level for the limestone mixtures; however, stress level did not affect the optimum asphalt content.
5. The effect of aggregate type on fatigue life was not important, but, for low stress levels such as those experienced in the field, aggregate type could be a significant variable.
6. Fatigue life increased with decreasing testing temperature.
7. Although the methods of estimating fatigue life on the basis of applied stress or stress difference were not universally applicable, the fatigue life could be estimated on the basis of its relationship with initial strain ϵ_{mix} and stress-strength ratio, which is the ratio of the applied repeated tensile stress to the indirect tensile strength from equations 15 and 16 respectively.
8. Based on the results of this study and previous studies, it was concluded that there is no general relationship between laboratory fatigue life and air void content. Although a relationship may exist for a given mixture, other mixture and construction variables are probably more important, and the effect of air void content on fatigue life will depend on the process by which the air void content is varied.
9. There was a linear relationship between the logarithm of fatigue life and bulk density, but the relationship was dependent on stress.

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