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RELATIONSHIP OF FATIGUE TO THE TENSILE STIFFNESS OF ASPHALTIC CONCRETE

Final Report on Phase 1: Laboratory Investigation

by

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Highway Research Engineer

Virginia Highway Research Council
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ABSTRACT

The correlation between asphaltic concrete tensile stiffness and fatigue life was determined in the laboratory. Constant strain fatigue tests were utilized and indirect tensile tests were selected because of their simplicity and applicability. Four asphaltic concrete mixes of different stiffnesses were tested under constant strain fatigue and indirect tension.

Each mix was fatigue tested at several strain levels in order that a strain — fatigue life relationship could be developed. This enabled the correlation of tensile stiffness and fatigue life at any of the strain levels used in the tests. A correlation between tensile stiffness and fatigue life was plotted at a 150×10^{-6} in./in. strain level. The information gathered indicates that it may be possible to predict the fatigue susceptibility of a mixture with a simple indirect tension test.

The fatigue life of a surface mixture was reduced by artificial aging and was altered by using asphalt cements of different hardnesses.

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INTRODUCTION

For many years flexible pavement systems have been designed with the purpose of providing a satisfactory service life. The designs are usually based on empirical charts developed from the results of pavement performance surveys, and the charts are used to select the structural cross section of the pavement. In some instances, pavements have developed cracking at an early age due to fatigue distress. These occurrences of early cracking prompted investigations to determine the factors that affect fatigue of asphaltic concretes. Also a fatigue design subsystem for flexible pavement design has been developed in which a proposed pavement can be analyzed for its fatigue serviceability.(1) If the fatigue analysis predicts an early failure of the pavement due to fatigue then the structural cross section must be changed or more fatigue resistant mixes used.

Basically, in order to predict the fatigue failure of a pavement system one must know both the strain-fatigue cycles relationship and the strain that the asphaltic concrete will undergo in the roadway under a design loading. The strain of the asphaltic concrete can be computed or measured, but the strain-fatigue cycles relationship is very difficult to obtain since it is influenced by many things. For instance, the field pavement may be subjected to cyclic loading at different temperatures caused primarily by seasonal changes. Also, the load strains will not be constant because of different load magnitudes. The best estimate of the strain-fatigue relationship is obtained by testing fatigue specimens in the laboratory at various strain levels, and at a temperature representing a median field temperature.

Rather complicated and expensive equipment is required for the fatigue tests and the tests are quite lengthy; therefore, it would be difficult for typical field or district laboratories to perform these tests on mix designs. In order to provide some insight into the fatigue durability of an asphaltic mixture at the field level, a quick test for predicting fatigue failure with some degree of reliability is needed. A summary of previous investigations(2) of this problem indicates that there is a correlation between mix stiffness and fatigue life. When mix stiffness is increased, the fatigue life decreases in a controlled strain mode. This correlation indicates that a simple stiffness test might possibly be used to predict fatigue failure.

In the investigation reported here an attempt was made to correlate the indirect tensile test with fatigue failure. The indirect tensile test does not require elaborate equipment and results can be obtained quickly; therefore, the potential benefits warranted the investigation.

PURPOSE

The purpose of this investigation was to determine if a correlation could be developed between fatigue life and indirect tensile stiffness for several asphaltic mixtures. The intent of this work was to develop a correlation that might possibly be used to predict the suitability of asphaltic mixes from a fatigue standpoint.

SCOPE

Controlled strain tests were used to develop strain-fatigue relationships for four mixes possessing different stiffness values. The mixes were selected from those allowed under Virginia specifications with slight modifications. All stiffness and fatigue tests were performed in the laboratory.

PROCEDURE

Testing Techniques

Since fatigue failures are the result of cyclic tensile strains or stresses it was postulated that tensile stiffness would correlate best with fatigue. The tests that may be used to obtain the tensile characteristics of a material are:

1. Direct tensile tests
2. Indirect tensile tests
3. Bending tests

Hudson and Kennedy(3) summarize each test and list the difficulties with each one. They point out that it is difficult to apply pure tensile force to the direct tensile specimen, and the gripping procedure is rather tedious. The disadvantages of the bending test are the undefined stress distribution across the specimen and the influence of surface irregularities. The advantages of the indirect tensile test seem to outnumber the disadvantages, therefore, it was used to evaluate the tensile properties of highway materials including asphaltic concrete.

It was realized that the indirect tensile test deviates from ideal conditions for which it was intended in three respects as follows:

1. The test material is not homogeneous;

2. the theory assumes a line loading on the cylinder when in practice the load is distributed with a loading strip; and

3. stress is not proportional to strain in the test material.

Although these three conditions can not be met the test does measure tensile characteristics of an asphaltic concrete.

This work resulted in recommendations for future testing of asphaltic concrete in indirect tension if determinations of tensile characteristics are desired. Since results of the initial work by Hudson and Kennedy(3) and subsequent work by Hadley et al (4, 5, 6) appeared very promising it was decided to use the indirect tensile test for this investigation. Standard Marshall specimens were used in the indirect tensile tests because of the ease of fabrication and the fact that no special equipment was necessary.

The indirect tensile tests were performed with a compressive strain rate of 1 in./min. The total vertical deformation and tensile strain in the region of failure were measured. The tensile strain was measured over a one-inch gage length with a cantilever type transducer as shown in Figure 1. Also the corresponding strengths were measured so that stiffness could be computed.

Fatigue tests were performed on 2.5 in. x 3 in. x 14 in. beams simply supported and loaded at the midpoint by the fatigue device used in previous studies(7,8). The strain magnitude was selected at the beginning of each test and was monitored with a one-inch foil gage placed at the point of maximum tensile strain (Figure 2). The gage was attached with an 85-100 penetration asphalt cement so that the stiffness of the gage system would not influence the strain measurement. All fatigue tests were performed at room temperature (75°F) since this is considered close to a median annual field temperature.

Fatigue failure was defined as cracking of the beam and was monitored by gluing aluminum foil strips on the beam and detecting the cracking of one of the two strips. Each of two foil strips were glued one-half inch from each edge on the bottom (tensile surface of the beam, Figure 2) and connected in series with the timer mechanism. When either of the strips cracked, the asphalt had cracked and fatigue failure had been reached.

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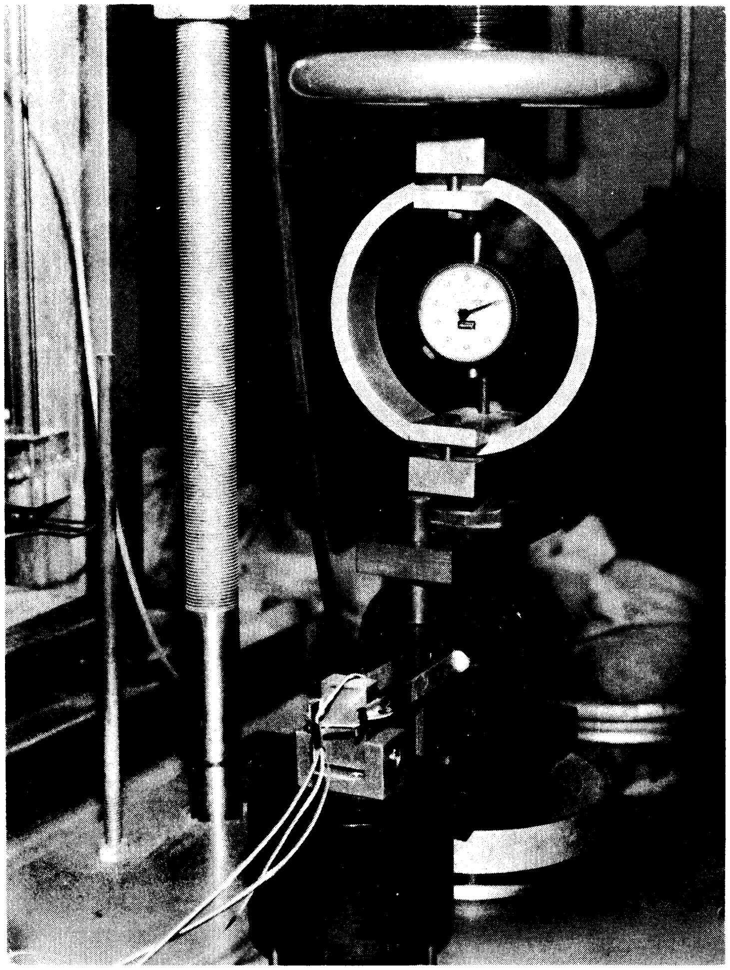

Figure 1. Tensile strain transducer.

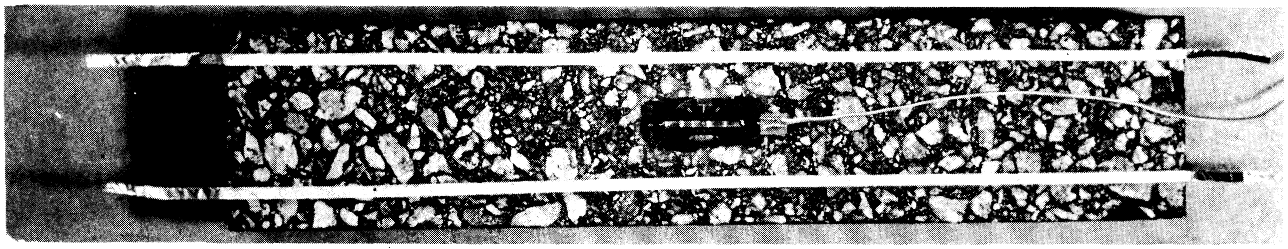

Figure 2. Fatigue specimen with strain gage and aluminum foil strips.

Materials and Mixtures

Four mixes (Table I) were tested in both fatigue tests and indirect tension tests. The mixes were selected to provide a wide range of stiffness values. The aggregates for each mix were recombined by individual sieve sizes in order to obtain the desired gradation. A 85-100 pen. asphalt was used in the S-3 mix rather than the 120-150 pen. asphalt normally used in order to obtain the stability necessary in fatigue tests. One of the S-5 mixes was aged in the oven to provide an indication of the effect of increased binder stiffness on fatigue life reduction. The regular binder was mixed with the aggregate using normal procedures and then the mixture was spread in a pan approximately $1\frac{1}{2}$" deep and heated in a 300°F oven for two hours. The penetration value dropped from 47 to 23 as a result of the aging process. Only three mixes were originally planned, however, due to the low scatter of results for the first mix, the number of tests was reduced by one-half for the remaining mixes to allow a fourth mix to be tested. A mix with a Virginia S-5 gradation and 120-150 pen. asphalt was selected since it was anticipated that the stiffness value would be between those for the regular S-5 and modified S-3 mixes. The S-5 mixes contained approximately 25 percent sand and 75 percent crushed granite. The S-3 mix contained 93 percent gravel and sand, and 7 percent (-#200 sieve size) granite.

The asphalt content for each mix was obtained by the Marshall design method.

TABLE I

ASPHALTIC CONCRETE MIXTURES

Mix Designation	Binder Type	Asphalt Content, %	Recovered Asphalt Penetration	Gradation, % Passing						
				Sieve 1/2	3/8	4	8	30	50	200
Virginia S-5	AP-3 85-100 pen.	5.6	47	100	90	60	45	23	15	6
Virginia S-5 Aged in Oven	AP-3 85-100 pen.	5.6	23	100	90	60	45	23	15	6
Virginia S-5	120-150 pen.	6.0	87	100	90	60	45	23	15	6
Virginia S-3	85-100 pen.	7.5	48		100	97.5	94	49	24	7

1934

RESULTS

Fatigue Tests

It has been found that the general relationship between cycles of load to failure and strain is

$$N = \left(\frac{1}{\epsilon}\right)^{n} \qquad (2)$$

in which:

N = cycles to failure

K = a constant depending on mix properties

ϵ = the magnitude of the applied strain

n = a constant

This relationship is linear between the log of applied strain, ϵ, and the log of loading cycles, N. If the constants and applied strain for a mix are known, then it is possible to predict the fatigue life of the pavement. It was necessary to develop fatigue-strain relationships for the mixes tested in order that the effect of stiffness could be determined. The Appendix contains the data for each fatigue test that was used to develop the relationships.

Figure 3 illustrates a log-log plot of the relationship for each mixture and gives the equation for each relationship. The K values range from 1.7×10^{14} to 1.4×10^{19}, and the n values from 4.3 to 6.0 for the four mixes tested. Santucci and Schmidt(9) found n values (slopes) ranging from 2.5 to 5.9 for constant strain laboratory fatigue tests, which are consistent with the values obtained in this investigation. The curve for the aged S-5 mix is located below the curve for the regular S-5 mix, indicating a lower fatigue life for the aged mix at equivalent strain levels.

Kasianchuk and Monismith(1) consider 150×10^{-6} in./in. strain magnitude as the maximum value acceptable in California. This strain level should provide more than one million loading cycles before failure. At a 150×10^{-6} in./in. strain level the S-3 mix and S-5 mix with 120-150 penetration asphalt had fatigue lives of 1,340,000 cycles and 1,400,000 cycles respectively. The regular S-5 mix with a recovered asphalt penetration of 47 had a fatigue life of 750,000 and the aged S-5 mix with a recovered asphalt penetration of 23 had a fatigue life of 50,000 cycles. These results substantiate the past field observations that mixes containing asphalts with penetration values less than 30 will experience premature failures.

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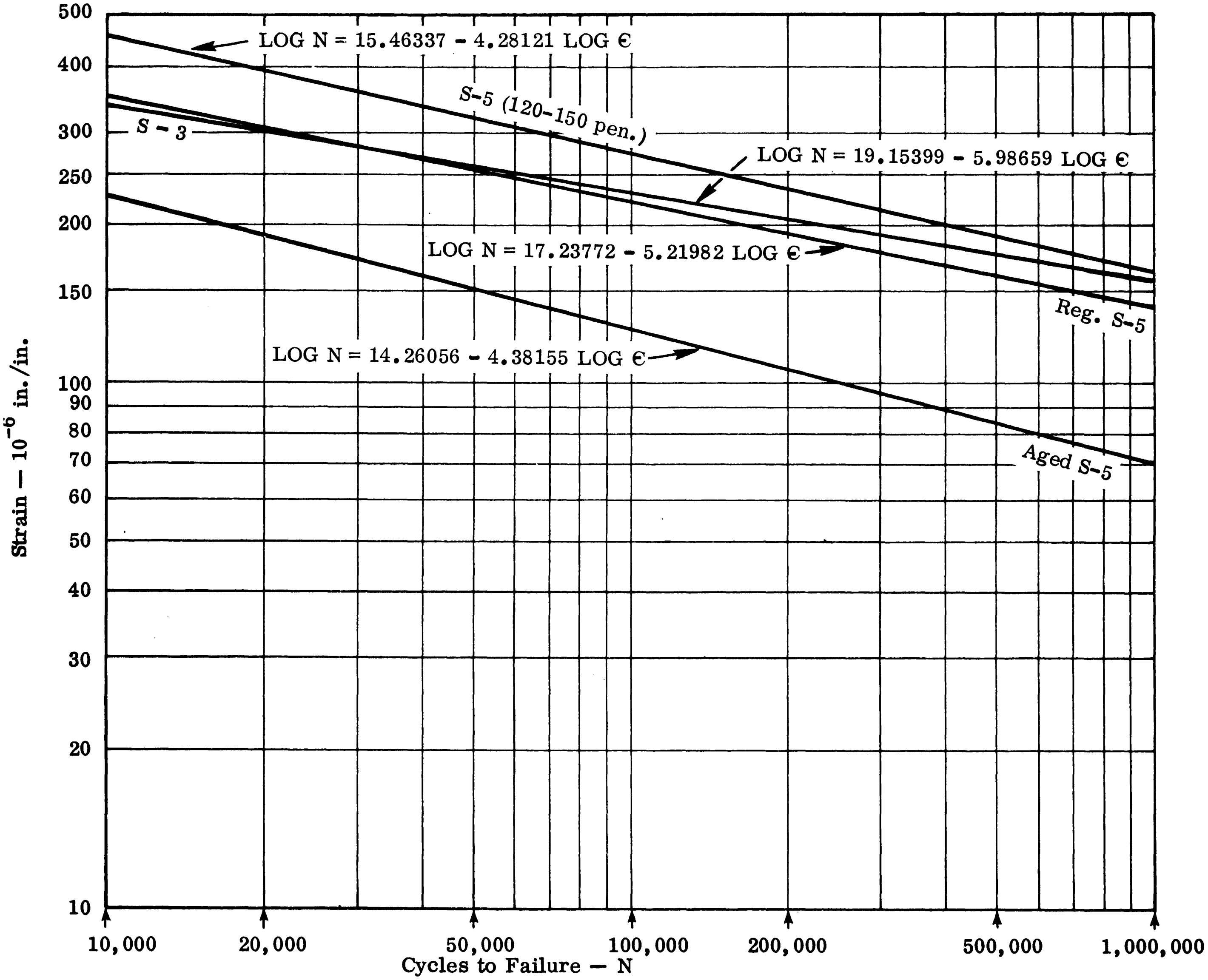

Figure 3. Constant strain fatigue tests.

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Linear regression analysis of the strain vs. fatigue cycles relationships for each mix yielded correlation coefficients around 0.9, with the exception of the S-5 mix with the 120-150 penetration asphalt cement, which had a correlation coefficient of about 0.8. This low coefficient of correlation may be caused by the lack of data since mechanical difficulties were encountered in the fatigue device and only six beams were acceptable. Additional specimens will be tested at a later date in order to verify the strain-fatigue curve for this particular mix and an addendum to this report will be published using state funds.

Indirect Tensile Tests

Eight Marshall specimens of each mix were tested in indirect tension. Average results of the tensile failure stress, vertical deformation, tensile failure strain, and the tensile stiffness at failure are listed in Table II, and results of all tests are given in the Appendix. Also included in these results is the stiffness computed at three-quarters of the failure stress.

TABLE II

TENSILE TESTS RESULTS

Mix Identification	Tensile Failure Stress, σ_{TF}, psi	Tensile Failure Strain, ϵ_{TF}, in./in. x 10^{-6}	Tensile* Failure Stiffness, S_{TF}, psi	Tensile Stiffness at* three-quarters of Failure Strength, $S_{\frac{3}{4}}$, psi	Compressive Deformation at Failure, in.
Virginia S-5	157	0.025	6,525	21,050	0.16
Aged Virginia S-5	181	0.027	7,026	29,070	0.16
Virginia S-5 (120-150 pen. binder)	92	0.030	3,130	10,700	0.13
S-3 (85-100 pen. binder)	78	0.041	1,940	5,431	0.16

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*Refer to page 9 for definitions.

The tensile failure stress was computed by the formula

$$\sigma_{TF} = \frac{2P}{td}$$

where

P = the compressive force

t = the thickness of the specimen

d = the diameter of the specimen.

A typical tensile stress-strain curve for the aged S-5 mix is shown in Figure 4. The initial portion of this curve is almost linear, however, due to the viscoelastic nature of asphaltic concrete the curve flattens and failure occurs in a nonlinear portion of the curve. The stiffness at three-quarters of the failure stress was used for comparison with reference to fatigue failure because the stress-strain curve is linear in this region and the results are more consistent.

The tensile failure strength ranged from 78 psi for the "flexible" mix to 181 psi for the stiff mix. The regular S-5 surface mix, which would be considered a typical Virginia mix, had a tensile failure strength of 157 psi — which compares very well with Hadley's work at this strain rate.

In general the average tensile strain at failure was less for the stiffer mixes than for the "flexible" mixes. The tensile strain at failure ranged from .025 in./in. to .041 in./in. Similarly, strain values corresponding to three-quarters failure strength ranged from .005 in./in. to .011 in./in. There appears to be no significant difference in the vertical (compressive) deformations at failure between the mixes tested.

Tensile stiffness was computed both for failure and three-quarters failure conditions by the respective formulas

$$S_{TF} = \frac{\sigma_{TF}}{\epsilon_{TF}} \quad \text{and} \quad S_{\frac{3}{4}} = \frac{\frac{3}{4}\sigma_{TF}}{\epsilon_{\frac{3}{4}}}$$

where:

S = the tensile stiffness

σ_{TF} = the tensile stress

ϵ_{TF} = the tensile strain

$\epsilon_{\frac{3}{4}}$ = the tensile strain at $\frac{3}{4}\sigma_{TF}$

The stiffness at three-quarters failure strength, $S_{\frac{3}{4}}$, is used for the stiffness comparison since it is in the region of the stress-strain relationship that is nearly linear and should be more applicable to fatigue failures than ultimate failure stiffness. As expected, the mixture that had been aged in the oven until the bitumen penetration dropped to 23 had the highest three-quarter stiffness, of 29,070 psi compared to 21,050 psi for the regular mixture. A similar mixture with a 120-150 pen. bitumen (recovered penetration = 87) had a three-quarter stiffness of 10,700 psi. The S-3 mixture had a low three-quarter stiffness of 5,430 psi, which would be expected for a fine mixture of this type. These results illustrate that stiffness at this strain rate can differ to a large extent for different types of mixes. Also the stiffness can be altered by using a bitumen with a different hardness. Although strain rates of tensile strains in pavements are much higher than those used in this test the same relative differences for stiffnesses of different mixes should exist, making this information valuable for pavement design.

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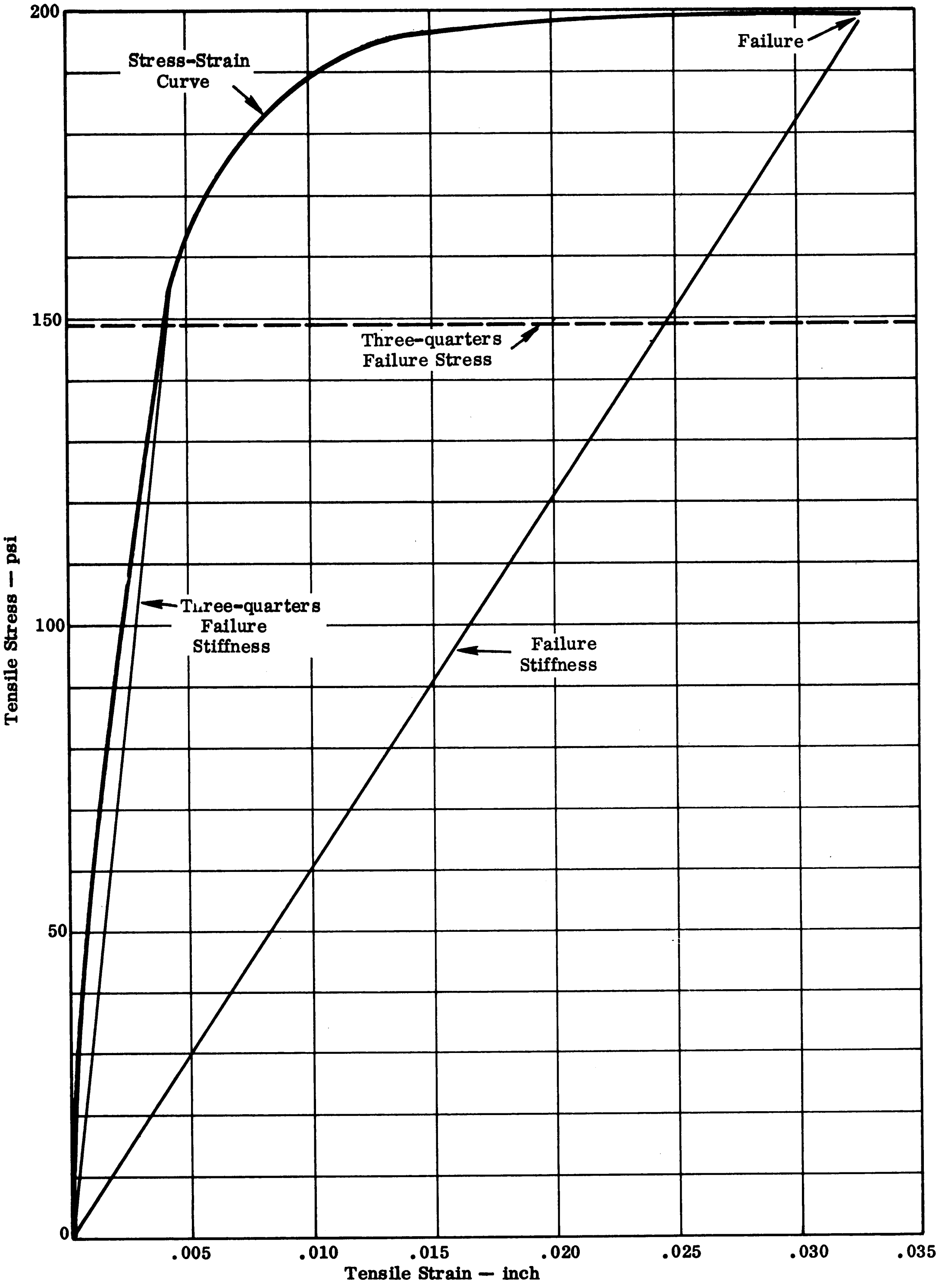

Figure 4. Stress-strain curve of typical indirect tensile test.

Correlation of Fatigue Life and Tensile Stiffness

One intent of this investigation was to determine if there was a correlation between fatigue life and tensile stiffness as determined from the indirect tensile test. As mentioned previously, other fatigue investigations have indicated that there is a correlation between asphaltic concrete stiffness and fatigue life.

It can be observed from Figure 3 that the mixtures with higher stiffness have trends toward decreased fatigue lives at strain levels used in this investigation; therefore, there appears to be a general correlation between tensile stiffness as measured by the indirect tensile test and fatigue life.

Figure 5 illustrates the type of correlation obtained between the stiffness and fatigue life at a 150 x 10^{-6} in./in. strain level for the four mixes tested. The correlation appears to be a linear relationship between tensile stiffness and fatigue life for mixes with stiffnesses ranging from 30,000 psi to 20,000 psi (aged S-5 and regular S-5 respectively). It is not clear from the data available whether the relationship is linear for stiffnesses lower than 20,000 psi, however, it may be possible that the fatigue life decreases at a faster rate at low stiffness due to the lack of general stability. It can be observed from this development if one wishes to design a bituminous pavement for one million cycles at 150 x 10^{-6} in./in. strain, then the stiffness of the asphalt should be less than approximately 18,000 psi.

It should be emphasized that the fatigue-strain relationship for the S-5 mix with 120-150 pen. asphalt is based on a reduced amount of data and that no definite conclusions should be reached until more data are obtained.

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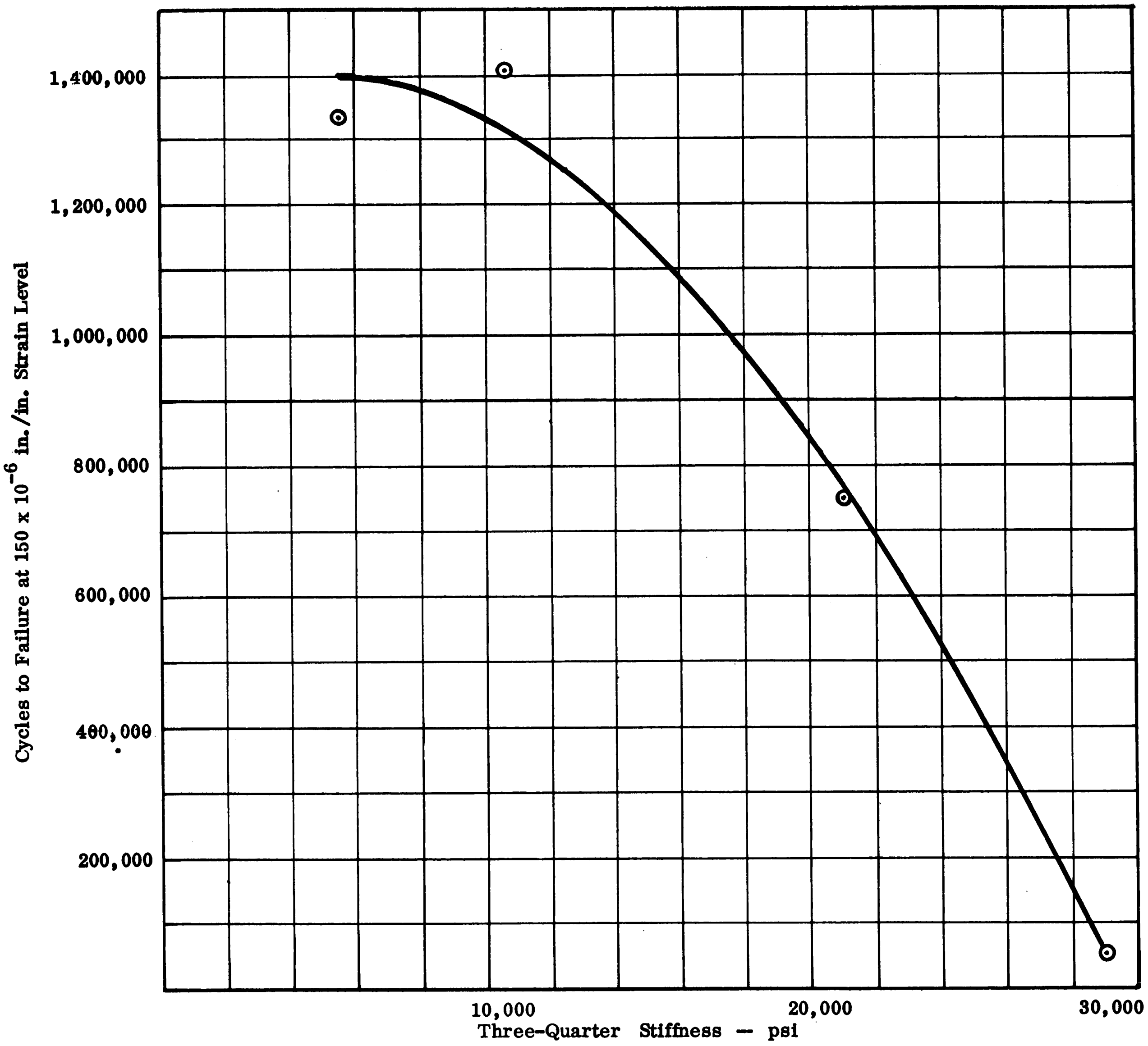

Figure 5. Stiffness-fatigue correlation.

CONCLUSIONS

1. The indirect tensile test can be used to evaluate the stiffness of an asphaltic concrete.
2. The tensile strain at failure appears to increase for mixes with lower stiffness.
3. Artificial aging of an asphaltic mixture decreases the fatigue life.
4. From the data available the mixture with the 120-150 penetration asphalt cement appeared to have a longer fatigue life than the mixture with the 85-100 penetration asphalt cement.
5. There appears to be a general correlation between tensile stiffness and fatigue life at reasonable strain levels.

RECOMMENDATIONS

The strain-fatigue relationships have been derived experimentally for a number of mixes. They indicate the magnitude of strain that may result in a shortened pavement life due to fatigue cracking.

It would be beneficial to determine if flexible pavements in general are undergoing strain cycles in sufficient magnitude and quantity to cause fatigue damage. This could be done by monitoring strains induced by traffic on actual pavements.

Also the possibility of predicting fatigue susceptibility of a mix from indirect tensile test results should be investigated further. This investigation would involve fatigue testing and indirect tensile testing of additional mixes and, ultimately, using the field strain data and fatigue -- stiffness correlation to predict the fatigue susceptibility of mixes. It is anticipated that this information will be gathered in subsequent investigations so that the indirect tensile test can be used to indicate the potential fatigue life of an asphaltic concrete.

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APPENDIX

FATIGUE RESULTS

Mix Designation	Sample No.	Voids Total Mix, %	Strain, ϵ, in./in. x 10^{-6}	Fatigue Life, Cycles
Virginia S-3	1 F-S3	17.9	280	31,931
	2 F-S3	13.1	220	351,203
	3 F-S3	17.1	270	31,590
	4 F-S3	16.8	230	151,427
	5 F-S3	16.9	205	212,887
	6 F-S3	17.1	250	57,974
	8 F-S3	17.3	230	37,525
	9 F-S3	17.2	200	193,525
	10 F-S3	17.4	150	1,029,539
	11 F-S3	17.3	240	167,306
	12 F-S3	17.5	300	15,464
	13 F-S3	17.3	190	326,276
Virginia S-5 with 120-150 pen. binder.	7 F-S5(120-150)	4.4	175	452,844
	8 F-S5(120-150)	4.4	225	172,884
	9 F-S5(120-150)	4.3	190	863,976
	10 F-S5(120-150)	4.5	300	44,069
	11 F-S5(120-150)	4.5	275	450,000
	12 F-S5(120-150)	4.6	300	39,388

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Appendix (Continued)

FATIGUE RESULTS

Mix Designation	Sample No.	Voids Total Mix, %	Strain, ϵ, in./in. x 10^{-6}	Fatigue Life, Cycles
Regular S-5	3 F-S5	4.7	300	35,237
	4 F-S5	4.4	250	99,001
	5 F-S5	4.4	270	34,016
	6 F-S5	3.9	200	273,801
	8 F-S5	4.1	225	97,172
	9 F-S5	4.0	300	24,423
	10 F-S5	4.2	275	45,100
	14 F-S5	4.3	330	9,339
	15 F-S5	4.1	190	86,381
	16 F-S5	4.3	200	131,440
	17 F-S5	4.1	230	33,049
	18 F-S5	4.1	230	66,691
	19 F-S5	4.7	200	130,439
	20 F-S5	3.7	180	458,116
	21 F-S5	4.0	250	42,963
	22 F-S5	4.5	230	178,390
	23 F-S5	4.3	300	18,419
	24 F-S5	4.2	220	124,163
	25 F-S5	4.2	170	300,617
	26 F-S5	4.4	170	916,188
	27 F-S5	4.2	230	89,892
	28 F-S5	4.1	180	274,049
	29 F-S5	4.2	170	223,101
	30 F-S5	4.3	300	15,636
Aged S-5	3 F-AS5	5.4	150	74,551
	5 F-AS5	5.5	150	40,093
	6 F-AS5	5.6	100	197,530
	8 F-AS5	5.7	115	132,936
	9 F-AS5	5.7	90	606,254
	10 F-AS5	5.6	130	302,772
	11 F-AS5	5.4	200	9,107
	12 F-AS5	5.1	95	531,904
	13 F-AS5	5.7	170	23,596
	14 F-AS5	5.5	130	66,955
	15 F-AS5	6.2	190	33,742
	16 F-AS5	5.5	105	178,946
	17 F-AS5	5.6	90	503,418

Appendix (Continued)

TENSILE TEST RESULTS

Specimen		Air Void Content, %	Failure Stress, σ_{TF}, psi.	Failure Tensile Strain, ϵ_{TF}, in./in.	Compressive Deformation At Failure in.	Failure Stiffness, S_{TF}, psi.	Three Quarter Failure Stiffness, $S_{3/4}$, psi.
Aged S-5	3	5.8	181	0.030	0.17	6030	17,000
	4	6.2	199	0.033	0.17	6040	33,100
	5	6.3	199	0.033	0.17	6020	37,300
	6	6.1	164	0.031	0.17	5300	18,900
	8	5.5	156	0.018	0.15	8670	39,000
	9	5.1	171	0.028	0.16	6220	21,400
	10	5.7	196	0.018	0.15	10,900	36,800
Regular S-5	1	5.0	164	0.016	0.17	10,200	30,800
	2	4.6	138	0.021	0.15	6,600	17,300
	3	4.4	187	0.024	0.16	7,800	35,000
	4	4.7	152	0.029	0.14	5,220	19,000
	5	4.3	158	0.027	0.14	5,880	14,000
	6	4.2	159	0.031	0.16	5,100	19,900
	7	4.3	148	0.026	0.17	5,700	17,100
	8	5.1	153	0.027	0.16	5,700	15,300
S-5 (120-150 pen.)	1	4.6	94	0.034	0.13	2,750	7,900
	2	4.4	94	0.033	0.13	2,850	10,100
	3	4.1	94	0.032	0.13	2,950	8,900
	4	4.6	94	0.034	0.13	2,800	8,900
	5	4.5	98	0.030	0.12	3,250	13,500
	6	4.2	93	0.021	0.13	4,400	15,500
	7	4.3	88	0.028	0.12	3,140	9,500
	8	4.4	85	0.029	0.13	2,920	11,600

1948

Appendix (Continued)

TENSILE TEST RESULTS

Specimen		Air Void Content %	Failure Stress, σ_{TF}, psi.	Failure Tensile Strain, ϵ_{TF}, in./in.	Compressive Deformation At Failure in.	Failure Stiffness, S_{TF}, psi.	Three Quarter Failure Stiffness, $S_{3/4}$, psi.
S-3	1	17.5	78	0.042	0.15	1860	4500
	2	16.7	80	0.049	0.17	1630	5400
	3	16.9	82	0.042	0.17	1950	5150
	4	17.1	78	0.031	0.16	2500	5600
	5	17.5	78	0.038	0.15	2050	4900
	6	17.0	80	0.044	0.16	1820	5400
	7	17.3	76	0.038	0.16	2000	7100
	8	16.8	72	0.042	0.17	1720	5400