RESULTS OF INDIRECT TENSILE TESTS RELATED TO ASPHALT FATIGUE

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The purpose of this investigation was to develop a correlation among fatigue life, magnitude of strain, and indirect tensile stiffness for 4 asphaltic concrete mixes prepared and tested in the laboratory. Constant strain fatigue tests were performed on 2.5- by 3- by 14-in. beams at several strain levels to develop a strain-fatigue life correlation for each mix. Indirect tensile tests were conducted on Marshall specimens and the stiffness measured in the region of tensile failure. Stiffness values ranged from 5,431 psi for a flexible mix to 29,070 psi for an aged stiff mix. There was a trend for the stiff mixes to yield shorter fatigue lives than did the flexible mixes if aggregates and gradation were similar. The correlation developed between stiffness and fatigue life indicates possibilities for using the indirect tensile test to design asphaltic concrete with the flexibility required to withstand repeated strain applications.

•FATIGUE was recognized as a contributor to asphalt pavement distress problems in the 1950s (1) and possibly earlier. Fatigue is complicated in asphaltic mixes by viscoelasticity, heterogeneity, anisotropy, and temperature susceptibility.

Viscoelastic analysis requires model analysis, and it is difficult to obtain a mathematical model that defines the behavior of an asphaltic mix. Temperature affects the viscosity of the asphalt, which in turn influences the behavior of the mix; therefore, field fatigue behavior may be governed by the environment.

Although the fatigue mechanism for asphaltic pavements is complex, much valuable knowledge has been gained through laboratory fatigue testing. Initial investigations were concerned with the effect of load type, mixture variables, and environmental factors. Information was gathered on the effect of asphalt content, aggregate type, void content, temperature, and type of loading. The latest efforts have been directed toward incorporating fatigue analysis into the design systems for asphalt pavements (2).

The fatigue life of a bituminous mixture may be defined by

$$N = K\,(1/\epsilon)^n$$

where

N = number of cycles to failure,
K = constant dependent on material properties,
n = constant, and
ϵ = strain magnitude.

Most design methods have been concerned with limiting the strain that may be developed in a particular bituminous layer to provide a satisfactory fatigue life.

Constant stress fatigue tests and constant strain fatigue tests have been used to define the fatigue behavior of asphaltic concrete. It is the general consensus that the constant strain tests define the behavior of thin pavement layers that contribute little to the flexural stiffness of the pavement structure and that the constant stress tests apply to

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thick bituminous layers that do contribute significantly to the stiffness of the pavement. Thin and thick layers have not been clearly defined, but a thin layer is generally considered to be less than 3 in. deep and a thick layer more than 5 in. As a result, a combination of constant stress and constant strain may be present in many pavements. For instance, a layer between 3 and 5 in. thick may behave according to both constant stress and constant strain modes. It may have ample stiffness to contribute to the load carrying ability of the pavement (constant stress mode); however, the strain is governed by the underlying layers (constant strain mode). In general, the two types of fatigue tests give opposite results. For example, under a constant stress test an increase in stiffness will result in an increased fatigue life, whereas under a constant strain test a decrease in stiffness results in an increased fatigue life (3).

The remainder of this paper will concentrate on thin asphaltic concrete layers and surface layers that behave in a constant strain mode. This mode was selected because thin surface mixes in Virginia have been observed to exhibit distress problems that hopefully may be solved through fatigue studies. The mode is used to define the fatigue behavior of thin layers and thin surface mixes, assuming that tensile strains sufficient to cause fatigue failure are developed on the top surface.

Also, as mentioned earlier, asphaltic concrete stiffness, which is measured under dynamic loading, appears to be related to fatigue behavior; therefore, the stiffness of an asphaltic mix might provide some indication of its ability to sustain repetitions of strain or stress. This investigation attempted to determine whether a relation also exists between the fatigue life of a mix and its indirect tensile stiffness, i.e., a relation that may be measured by a simple laboratory test. It was thought that, if a relation could be developed among indirect tensile stiffness, strain, and fatigue life for a constant strain testing mode and if the estimated strain and desired fatigue life were known, a mix could be designed with a stiffness indicated by the relation mentioned. Although this design method would not be as thorough and exact as the fatigue design subsystem using fatigue tests, n-layered analysis, and fatigue damage summation, it would be a method of designing mixes against fatigue failure. It would be especially useful in laboratories that lack the test equipment necessary for the fatigue design subsystem.

PURPOSE AND SCOPE

The purpose of this investigation was to determine if a correlation could be developed among fatigue life, strain, and indirect tensile stiffness. It was anticipated that the correlation might be used to predict the fatigue susceptibility of asphaltic mixes.

The correlation was developed by using controlled strain fatigue tests and indirect tensile tests. The tests were performed on 4 laboratory prepared mixes selected from those allowed under Virginia specifications, with slight modifications.

PROCEDURE

Mixes

Four mixes (Table 1) were selected to provide a wide range of stiffness values, and fatigue and indirect tension tests were performed on each mix. The aggregates for each mix were recombined by sieve sizes to obtain the desired gradation. The asphalt contents were obtained by the Marshall design method. The S-5 mixes contained 25 percent sand and 75 percent crushed granite, and the S-3 mix contained 93 percent rounded gravel and sand and 7 percent granite (-No. 200 sieve size).

The S-5 mix, with an 85- to 100-penetration asphalt cement, was aged in the oven to increase its stiffness and thus provide an indication of the effect of increased asphalt stiffness on fatigue life. The artificial aging was accomplished by placing the fresh mixture approximately 1½ in. deep in a pan and heating it in a 300 F oven for 2 hours, stirring the mixture occasionally. The aging process dropped the penetration value of the recovered asphalt cement from 47 to 23 at 77 F.

A mixture with a lower stiffness was made by substituting 120- to 150-penetration asphalt. Therefore, three of the mixes had different stiffness values because of the asphalt cement characteristics. The fourth mixture, an S-3, had a low stiffness caused by aggregate characteristics and gradation.

Fatigue Tests

The constant strain fatigue tests were conducted on 2.5- by 3- by 14-in. asphaltic concrete beams made on a modified kneading compactor. Experience had been gained with the test and compaction equipment in previous studies (4, 5). The strain magnitude was monitored with a 1-in. foil strain gauge located in the center of the lower surface of the beam, which is the point of maximum tensile strain. A large strain gauge was desirable in order to negate the effect of the large aggregate particles. However, strain at a point (maximum strain) was desired, and a small strain gauge best gives this indication. It was felt that a compromise gauge length of 1 in. would serve satisfactorily. The gauge was attached with an 85- to 100-penetration asphalt cement, thereby eliminating the influence of the adhesive stiffness. The fatigue tests were performed at room temperature (75 F) because it was convenient and because 75 F was considered to be an approximate median annual field temperature for Virginia.

Fatigue failure was defined as the cracking of the tensile bending surface. The cracks were detected by gluing parallel aluminum foil strips ½ in. from each edge of the tensile surface (Fig. 1) and connecting them in series with the cutoff mechanism. When a fatigue crack formed in the asphalt, thus cracking the foil strip, the machine stopped, and the number of cycles was recorded.

Indirect Tensile Tests

Fatigue failures occur in regions where large tensile stresses and strains are present; therefore, a simple test procedure yielding tensile stiffness seemed desirable for correlation purposes. Direct tensile tests, bending tests, and indirect tensile tests may be used to obtain the tensile characteristics of a material, and Hudson and Kennedy (6) have summarized the advantages and disadvantages of each method when used on asphaltic concrete.

The gripping procedure and the application of a pure tensile force are difficult in a direct tensile test. The bending test has the disadvantage of an undefined stress distribution across the specimen and is influenced by surface irregularities. Some of the advantages of the indirect tensile test are as follows:

1. It is simple;
2. Marshall specimens may be used;
3. Surface irregularities do not seriously affect the results; and
4. The coefficient of variation of the test results is low.

The major disadvantages of this test are concerned with the theory. The theory assumes that the test specimen is elastic, but asphaltic concrete is viscoelastic at most environmental temperatures. Also, the theory assumes a line loading on the specimen, whereas in practice the load is distributed with a loading strip. These disadvantages are not considered serious, and the advantages seem to outweigh the disadvantages. The results of the work by Hudson and Kennedy (6) and Hadley et al. (7) indicate that the indirect tensile test can be used to predict the tensile strength of asphaltic concrete reasonably accurately.

It was decided to use the indirect tensile test on Marshall specimens (2.5 by 4 in. diameter) because no special equipment was necessary and specimen fabrication was simple. A compressive strain rate of 1 in./min was used, and compressive deformation, compressive force, and tensile strain were recorded throughout each test. The tensile strain was measured over a 1-in. gauge length in the region of maximum tensile strain with a transducer as shown in Figure 2. The tensile stress was computed, and the tensile stiffness was obtained from the stress-strain relation.

RESULTS

The indirect tension test was performed on eight Marshall specimens for each mix. A summary of the results is given in Table 2. The tensile stress σ_{TF} was computed by using the formula

$$\sigma_{TF} = 2P/\pi\, td$$

Table 1. Asphaltic concrete mixtures.

Mix	Binder	Asphalt Content (percent)	Recovered Asphalt Penetration	Gradation, Percent Passing (sieve size)						
				½	⅜	4	8	30	50	200
Virginia S-5	AP-3 85 to 100 penetration	5.6	47	100	90	60	45	23	15	6
Virginia S-5 (aged in oven)	AP-3 85 to 100 penetration	5.6	23	100	90	60	45	23	15	6
Virginia S-5	120 to 150 penetration	6.0	87	100	90	60	45	23	15	6
Virginia S-3	85 to 100 penetration	7.5	48	—	100	97.5	94	49	24	7

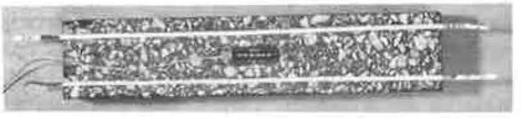


Figure 1. Fatigue specimen with strain gauge and aluminum foil strips.

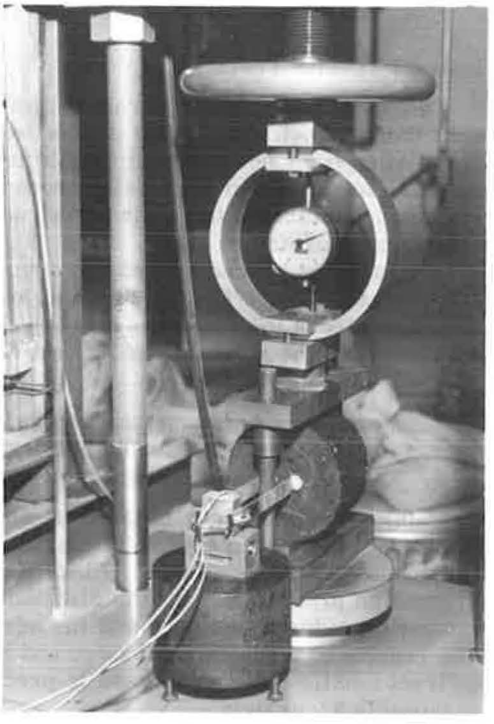


Figure 2. Tensile strain transducer.

Table 2. Tensile test results.

Mix	Tensile Failure Stress (psi)	Tensile Failure Strain (in./in.)	Tensile Failure Stiffness (psi)	Tensile Stiffness at Three-Quarters of Failure Strength (psi)	Compressive Deformation at Failure (in.)
Virginia S-5	157	0.025	6,525	21,050	0.16
Aged Virgina S-5	181	0.027	7,026	29,070	0.16
Virginia S-5 (120 to 150 penetration binder)	92	0.030	3,130	10,700	0.13
S-3 (85 to 100 penetration binder)	78	0.041	1,940	5,431	0.16

where

P = the compressive force,
t = the thickness of the specimen, and
d = the diameter of the specimen.

As expected, the tensile strength and stiffness were higher for the mixtures with stiffer asphalt cements. A typical stress-strain curve is shown in Figure 3 for a point in the region of the maximum tensile stress and tensile strain. The stress-strain curve is approximately linear until three-quarters of the failure stress is reached; then, as it approaches total failure, the strain increases at a faster rate than does the stress. It was felt that a stiffness value obtained from the linear portion of the stress-strain relation would be more meaningful than the failure stiffness; therefore, a stiffness value was computed using three-quarters of the failure stress and the corresponding strain value. The stiffness computed from the stress and strain values at failure has little meaning because the failure strain is not well defined and is difficult to measure.

Strain-fatigue life data were collected for each of the four mixtures. A linear log-log relation was obtained for each mixture (Fig. 4) in the form

$$N = K\,(1/\epsilon)^n$$

which was defined previously. The K values ranged from 1.8×10^{14} to 3.1×10^{20} and the n values from 4.4 to 6.0. The n values are consistent with those found by Santucci and Schmidt (8) for constant strain fatigue tests.

It can be observed that the fatigue life of the aged S-5 mix was approximately one-tenth that of the regular S-5 mix. These results agree with past observations wherein pavements containing highly aged asphalt cements displayed excessive amounts of premature cracking.

The aged S-5 mix endured 1 million strain repetitions when the strain level was maintained below 70×10^{-6} in./in. The remaining mixes survived 1 million strain repetitions when the strain level was maintained below 140×10^{-6} in./in. Other investigators (9) have found that an asphaltic concrete tested in the laboratory will endure 1 million repetitions at 150×10^{-6} in./in., which agrees reasonably well with the results of this investigation.

The stiffness values were computed by the following formulas:

$$S_{TF} = \sigma_{TF}/\epsilon_{TF} \text{ and } S_{3/4} = {}^{3}\!/_{4}\sigma_{TF}/\epsilon_{3/4}$$

where

S_{TF} = secant tensile failure stiffness,
$S_{3/4}$ = secant stiffness at three-quarters of the tensile failure stress,
σ_{TF} = tensile stress at failure,
$\epsilon_{3/4}$ = tensile strain at three-quarters failure stress, and
ϵ_{TF} = tensile strain at failure.

The aged mixture containing the asphalt cement with a 23-penetration value had a three-quarter stiffness of 29,070 psi compared to 21,050 psi for the regular mixture containing an asphalt cement with a 47-penetration value. A similar mixture containing an 87-penetration value cement had a three-quarter stiffness of 10,700 psi. These values indicate that asphalt stiffness has a profound influence on mixture stiffness, and that mixture stiffness can be controlled by using certain asphalt cements. The S-3 mixture that contained an asphalt cement with a 48-penetration value and rounded gravel and sand had a three-quarter stiffness of 5,430 psi. This low stiffness value can be attributed to the aggregate type and gradation.

Fatigue investigations have indicated some correlation between asphaltic concrete stiffness and fatigue life (3). In constant strain fatigue tests, stiff mixes have shorter fatigue lives than do flexible mixes; in constant stress fatigue tests, the stiff mixes have the longer fatigue lives.

Figure 3. Typical indirect tensile test.

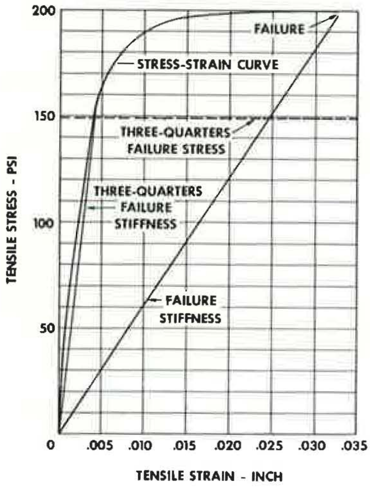


Figure 4. Constant strain fatigue tests.

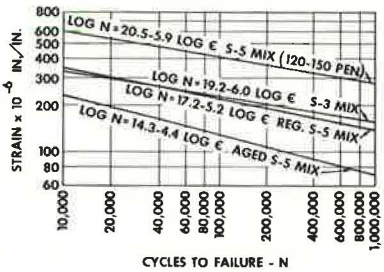


Figure 5. Fatigue versus stiffness.

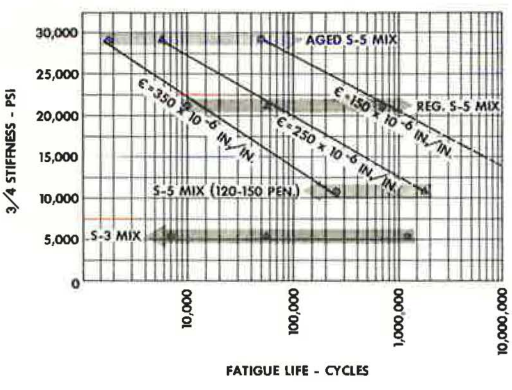
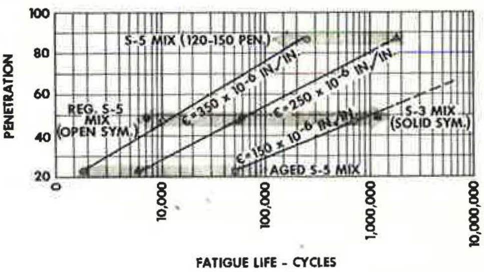


Figure 6. Fatigue versus penetration of recovered asphalt.



The fatigue lives of mixes having different stiffnesses can be compared at any strain level by using the information shown in Figure 4. Figure 5 shows a correlation developed between three-quarter indirect tensile stiffness and fatigue life at several strain levels for the 4 mixes tested. In general, fatigue life decreased as indirect tensile stiffness increased, except for the S-3 mix. Figure 6 shows the relation between fatigue life and the penetration of the recovered asphalt cement at 77 F. There is a linear semilog relation between the two for the four mixes. The available data indicate that stiffness correlates with fatigue life for mixes with different binders but similar aggregates. It is possible to design a mixture with a stiffness to endure a set number of repetitions with the aid of a correlation as shown in Figure 5. If it is desired to design a mix for 1 million cycles at 150×10^{-6} in./in., the stiffness of the mix should be kept less than about 20,000 psi.

The two methods of designing against fatigue failure in asphaltic concrete are as follows.

1. Method I—Design underlying layers so that the strain in the asphaltic concrete will be below a known damage level.
2. Method II—Design asphaltic concrete with fatigue characteristics that will withstand a known strain level.

Kasianchuk et al. (9) used a fatigue design subsystem (method I) to design a pavement against fatigue failure. The entire pavement structure was designed to limit the strain in the asphaltic concrete to 150×10^{-6} in./in., a value that presumably would ensure 1 million load repetitions.

Possibly a simpler and cheaper approach in some instances would be method II, in which the asphaltic concrete mixture would be designed such that it could withstand the required number of repetitions at the predicted strain level. The required stiffness, i.e., fatigue characteristics, can be obtained from a fatigue-stiffness correlation at the predicted strain value, and the mixture is then designed for that stiffness.

The amount of data obtained in this investigation is insufficient to permit broad conclusions; however, the results indicate that, for constant strain fatigue tests, fatigue life increases with decreased stiffness. It is felt that reliable correlations that will indicate fatigue susceptibility can be developed for asphaltic mixtures.

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