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Test for Predicting Fatigue Life of Bituminous Concrete

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An examination of several simple test methods revealed that the indirect tensile test can be used to predict the fatigue life of bituminous concrete. This replaces the traditional, expensive, and time-consuming flexural fatigue test. The tests examined—indirect tensile, double punch, resilient modulus, flexure, resonant frequency, and pulse velocity—were selected from a literature search for use on several mixes obtained from various locations in the United States and containing a variety of asphalt cements and aggregates. The traditional flexural fatigue test was also performed on each mix, and the results were correlated with those from the simple tests. The correlations indicated that indirect tensile strength and stiffness can be used to predict the fatigue behavior of bituminous concrete. The indirect tensile method can be used for designing mixes with adequate fatigue service lives.

Failures in bituminous concrete pavements can usually be classified as (a) rutting or washboarding, a stability problem; (b) progressive cracking, a fatigue problem; or (c) fracture, a strength problem.

Fatigue is certainly one of the most common causes of failure and probably the most difficult to deal with from a design viewpoint. It is possible to establish the fatigue properties of small asphalt concrete specimens by using any of the many test methods available. However, the required equipment is expensive, and a test series takes several weeks. A materials lab, therefore, cannot routinely design mixes against fatigue, so a simple test is needed if fatigue design is to be routinely implementable.

Some of the research efforts in this area are being made by Barksdale (1) and Majidzadeh (2).

PURPOSE

The purpose of this study was to examine the literature for current fatigue tests and promising simple tests and to develop a simple test procedure capable of predicting the fatigue behavior of asphalt concrete. Several of the most promising tests were conducted, and their results were correlated with laboratory fatigue test results on asphalt concrete mixes from various locations in the United States.

SELECTION OF SIMPLE TESTS

Because tensile stresses cause fatigue failures, I selected those simple tests in which tensile failures occur. Other items considered in the selection of the tests were simplicity of sample preparation, utilization of laboratory and pavement samples, sensitivity of test method to mix properties, and capability of predicting fatigue behavior.

Of the seven test methods considered, the five selected for laboratory testing were the indirect tensile, the punch, the resilient modulus, the flexure, and the sonic. The sonic test was selected because equipment was available, no additional specimens had to be made, and there was some previous experience in which sonic measurements were correlated with fatigue (3).

LABORATORY PROCEDURE

Each of five mixes was tested in constant strain fatigue to develop relations between fatigue life and strain and stress. Similar relations were developed for these five mixes and two additional mixes in constant stress. All five simple tests were performed on each of the mixes. Correlations were made between such simple test results as strength, stiffness, and deformation at failure and constants K and n of the fatigue relation.

The simple tests yielding the best correlations with fatigue properties were judged most suitable for use in designing against fatigue failure.

Mixes

All mixes (Table 1) were of the surface type and of a maximum aggregate size less than 19.1 mm (0.75 in). The mix formula, aggregates, and asphalt from Virginia, Pennsylvania, Ohio, Utah, and California provided a variety of stabilities, aggregates, and asphalt cement types. The aggregates included granite, basalt sandstone, limestone, and gravel. The asphalt cements were AC-20, 85-100 penetration, 50-60 penetration, 120-150 penetration, and AR-40. The asphalt contents were 5.5 to 5.8 percent by design; however, the Utah mix contained 6.8 percent because of the reportedly absorptive nature of the aggregate. I anticipated that the various mixes would yield a wide range of stiffnesses and strengths.

Fatigue Tests

Flexural fatigue tests were performed at 22°C (72°F) on

Table 1. Percentages of mix design aggregates passing through sieves.

Item	Pennsylvania 85-100 Penetration (limestone)	Ohio AC-20 (gravel and natural sand)	Utah 85-100 Penetration (basalt-sandstone and limestone)	California AR-40 (granite)	Virginia No. 1 AC-20 (granite and natural sand)	Virginia No. 2 50-60 Penetration (granite and natural sand)	Virginia No. 3 120-150 Penetration (granite and natural sand)
19.10			100.0				
12.50	100.0	100.0	93.0	100.0	100.0	100.0	100.0
9.50	97.0	95.0	85.0	87.0	95.0	95.0	95.0
4.75	63.7	60.0	62.0	64.0	58.0	58.0	58.0
2.36	44.3	46.0	47.5	50.0	41.0	41.0	41.0
1.18	26.6		36.0	37.0			
0.60	18.0			26.0	19.0	19.0	19.0
0.30	12.0	12.5	22.5	19.0	11.0	11.0	11.0
0.15	7.2			11.0			
0.08	4.8	7.0	3.2		5.0	5.0	5.0
Asphalt content, % by weight	5.5	5.5	6.8	5.7	5.8	5.7	5.7
Marshall stability, kg	—	789	771	991	844	1039	964
Voids total mix, %	2.0	2.5	1.9	2.1	2.0	2.3	2.2

Note: 1 mm = 0.039 in and 1 kg = 2.2 lb.

Figure 1. Flexural fatigue test apparatus.

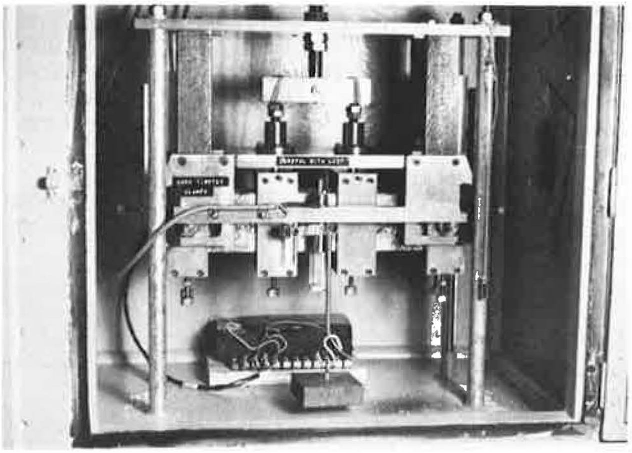
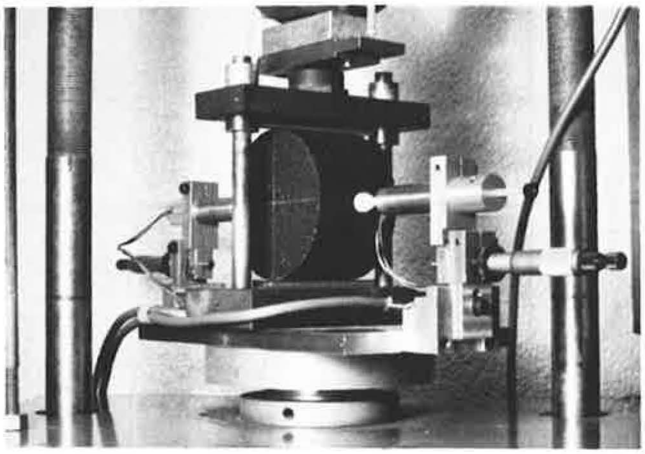


Figure 2. Indirect tensile test apparatus.



asphalt concrete beams (Figure 1) laboratory fabricated according to ASTM designation D 3202-73 and sawed to 76 by 76 by 381 mm (3 by 3 by 15 in). In the tests, the beams were simply supported and loaded at third points. A 0.1-s haversine load pulse was applied with a closed-loop electrohydraulic load system capable of applying equal repetitions of either load or deflection (strain).

The results of 10 fatigue tests at various stress and strain levels were used to develop the two fatigue relations

$$N = K_1 (1/\sigma)^{n_1} \qquad (1)$$

$$N = K_2 (1/\epsilon)^{n_2} \qquad (2)$$

where

N = number of cycles to failure,
σ = maximum tensile stress at 200 cycles,
ϵ = maximum tensile strain at 200 cycles, and
K_1, K_2, n_1, and n_2 = constants dependent on mix properties.

Failure in the constant stress tests was defined as collapse; failure in the constant strain tests was reached when the initial stiffness was reduced by one-third.

The two relations were obtained by linear regression analyses. Constant stress (load) fatigue tests were performed on seven mixes, but constant strain (deflection) tests were performed on only five mixes because of time and money limitations.

Simple Tests

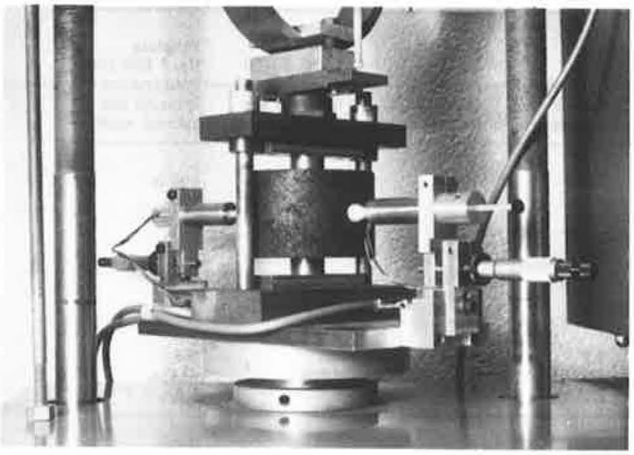
The indirect tensile test procedure reported by Anagnos and Kennedy (4) was used to test specimens 64 mm (2.5 in) thick and 102 mm (4 in) in diameter. The load was applied at a vertical deformation rate of 51 mm/min (2 in/min) (Figure 2), and the load, horizontal deformation, and vertical deformation were recorded.

The stiffness, strength, and vertical deformation were correlated with the fatigue relation constants K and n.

The punch test reported by Jimenez (5) was used to test specimens 64 mm (2.5 in) thick and 102 mm (4 in) in diameter. The specimen was centered between 25.4-mm (1-in) diameter punches compressed at 51 mm/min (2 in/min) (Figure 3). The stiffness, strength, and vertical deformation were computed and correlated with fatigue properties.

The resilient modulus test was performed on specimens 64 mm (2.5 in) thick and 102 mm (4 in) in diameter by applying a dynamic diametral load and then measuring the perpendicular diametral deformation. A 192-N (43.1-lb) load producing a 20.6-kPa (3-lbf/in^2)

Figure 3. Punch test apparatus.



tensile stress was applied for 0.1 s. Stiffness was computed by assuming a Poisson's ratio of 0.3 and then correlating it with the fatigue characteristics.

Flexure tests were performed on 76 by 76 by 190-mm (3 by 3 by 7.5-in) sawed beams. The beams were simply supported on 38-mm (1.5-in) plates and were loaded at the midpoint through a 25-mm (1-in) wide metal plate. The midspan vertical deformation and load were recorded, and elastic theory was used to compute the failure strength and stiffness.

Resonant frequency tests were performed on each fatigue beam prior to fatigue testing by ASTM method C 215-60. Only the transverse frequency measurement was used in computing the dynamic Young's modulus, which was used for correlations. (Young's modulus can be computed from the known velocity at which a sound wave travels through a material.) Pulse velocity measurements were also taken on the fatigue beams, before fatigue testing, to obtain values for use in calculating the dynamic Young's modulus.

RESULTS

Fatigue Tests

The relations developed by linear regression analyses from the fatigue tests are listed in Table 2. As expected, testing in the constant stress mode showed the stiff mixes exhibiting longer fatigue lives than the mixes with low stiffness. The slope of the linear log-log plot of the fatigue life versus stress relation was maximum for the Utah mix and minimum for the Virginia 120-150 penetration asphalt cement (Figure 4). Therefore, the stiffness of the mix may be related to the coefficient n_1 (slope) of the fatigue relation in Equation 1.

Table 2. Fatigue relations from flexural fatigue tests.

	$N = K_1(1/\sigma)^{n_1}$ (σ, kPa)		$N = K_2(1/\epsilon)^{n_2}$	
Mix	K_1	n_1	K_2	n_2
Constant Stress Fatigue Relations				
Virginia (AC-20)	8.9×10^{21}	5.9	2.8×10^{-8}	3.9
Virginia (50-60 penetration)	2.8×10^{19}	4.8	2.7×10^{-4}	2.6
Virginia (120-150 penetration)	3.0×10^{18}	4.9	8.5×10^{-2}	1.9
Pennsylvania	5.6×10^{22}	6.1	1.0×10^{-6}	3.6
Ohio	1.6×10^{22}	6.2	7.0×10^{-4}	2.5
Utah	5.1×10^{27}	7.5	9.5×10^{-9}	4.1
California	4.0×10^{27}	8.1	6.4×10^{-7}	3.8
Constant Strain Fatigue Relations				
Virginia (AC-20)	4.5×10^{16}	4.0	2.3×10^{-9}	4.4
Pennsylvania	2.6×10^{12}	2.6	3.9×10^{-4}	2.8
Ohio	1.0×10^{12}	2.5	2.3×10^{-2}	2.1
Utah	1.1×10^{21}	5.2	2.4×10^{-5}	3.1
California	8.4×10^{12}	2.9	5.2×10^{-3}	2.4

Note: $N = K_1 (0.1451)^{n_1} (1/\sigma)^{n_1}$ when σ is in pound force per square inch.

No similar observation can be made of the log fatigue life versus log strain plot for the constant strain fatigue tests (Figure 5). Four of the five mixes tested appeared to converge between 500 000 and 1 000 000 cycles, but there is apparently no relation between stiffness and slope of the fatigue relation in Equation 2.

Simple Tests

Because the stress rates used in the simple tests were not necessarily equal, the failure stresses are not directly comparable. The ranges of the average test results for the seven mixes are summarized in Table 3.

The coefficient of variation was approximately 8 percent for determining strength with the indirect tensile, punch, and flexure tests. The coefficients of variation for stiffness averaged 8 percent for the indirect tensile test, 13 percent for the punch, 8 percent for the flexure, 9 percent for the resilient modulus, 6 percent for the resonant frequency, and 5 percent for the wave velocity test.

The coefficients of variation were approximately equal for all test methods except the punch test, whose coefficient was slightly higher for the stiffness measure-

Figure 4. Constant stress tests.

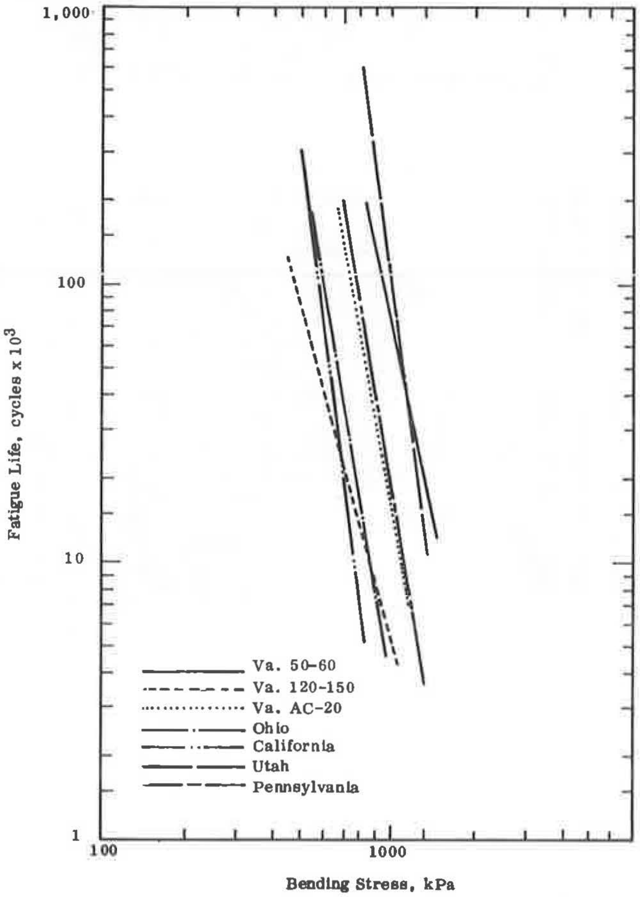
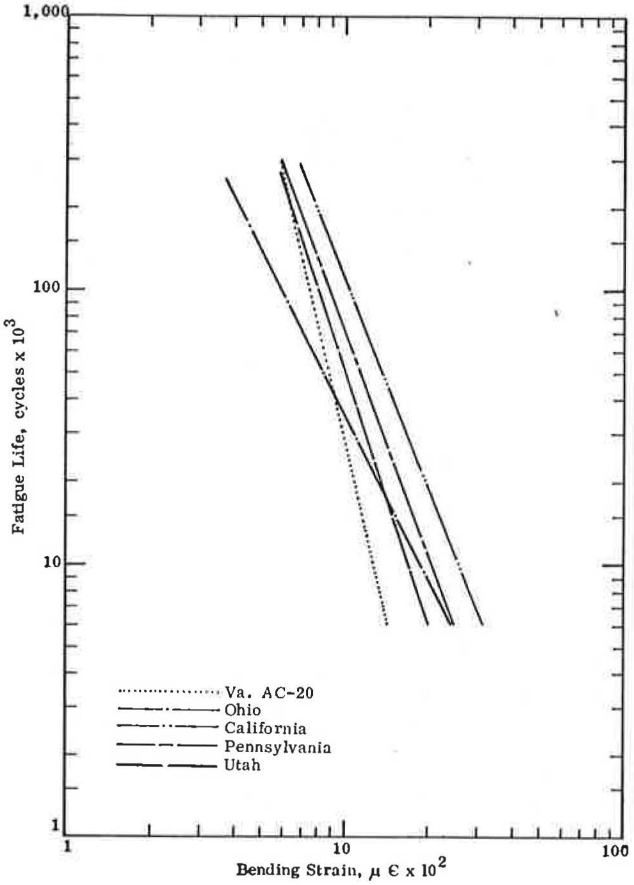


Figure 5. Constant strain tests.



ments. Therefore, test variability was not a major consideration in the evaluation.

Correlation of Simple Test and Fatigue Test Results

Simple linear correlations were performed between simple test results and selected fatigue characteristics. These correlations were performed to determine whether a simple test could be used to predict the fatigue behavior of asphalt concrete.

Constant Stress Tests

The correlation coefficients between simple test results and constant stress test results are listed in Table 4. In order to predict the fatigue relation (Equation 1), K_1 and n_1 must be known. The best correlation coefficients for n_1 were obtained from the indirect tensile stiffness (0.87) and punch stiffness (0.88). The value $\sigma_{n=1}$ is the projected stress on the fatigue curve at N = 1 cycle and allows the prediction of the K_1 value. The fatigue characteristic $\sigma_{n=1}$ yielded a 0.93 correlation coefficient with the indirect tensile stiffness. Therefore, the test results that permit the best prediction of the fatigue relation in Equation 1 are the indirect tensile strength and the stiffness. The following relations that were obtained from the correlations can be used to predict this fatigue relation in pascals.

$$n_1 = 11.6 - 0.000\,396\ E_{IT} \quad (3)$$

$$K_1 = e^{n_1 \ln(12.6\sigma_{IT} - 558)} \quad (4)$$

where E_{IT} is indirect tensile stiffness, and σ_{IT} is indirect tensile strength.

The correlations involving n_2 and log K_2 (Table 4) were inadequate for predicting the fatigue relation in Equation 2 for the constant stress fatigue test.

Constant Strain Tests

The correlation coefficients between simple test results and constant strain test results are listed in Table 5.

One must determine n_2 and K_2 before finding the fatigue relation in Equation 2. The best correlations involving n_2 were the transverse frequency modulus (0.84) and the indirect tensile strength (0.81). The best correlations from which K_2 could be determined were those of the resilient modulus (0.95), the transverse frequency modulus (0.85), and the indirect tensile strength (0.85). For efficiency, I preferred to use the same simple test for both constant stress and constant strain fatigue

Table 3. Simple test average value ranges for seven mixes.

Parameter	Indirect Tensile	Punch	Flexure	Resilient Modulus	Resonant Frequency	Wave Velocity Moduli
Strength, MPa	0.489 to 1.10	0.510 to 0.937	2.31 to 4.97	–	–	–
Failure, stiffness, MPa	75 to 126	101 to 220	33.8 to 57.9	634 to 2210	6340 to 8540	24 800 to 30 900
Failure, vertical deformation, mm	3.78 to 5.33	4.85 to 7.90	3.71 to 4.90	–	–	–

Note: 1 MPa = 145 lbf/in² and 1 mm = 0.039 in.

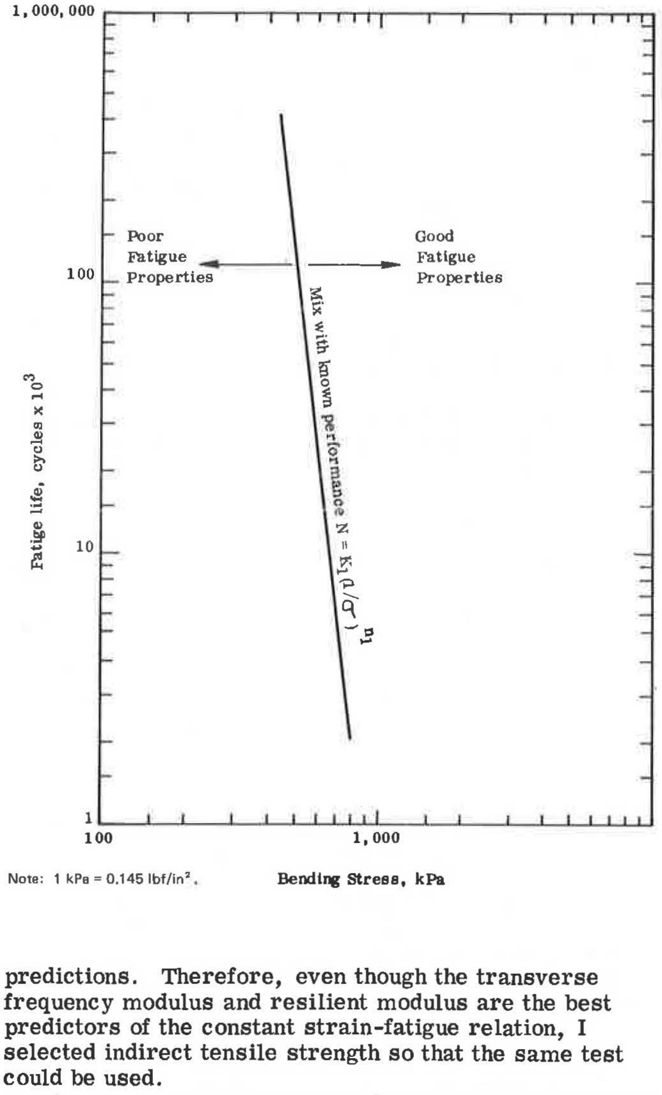
Table 4. Correlation between constant stress fatigue test and simple tests.

Equation	Fatigue Characteristic	Stiffness[b]						Strength[b]			Vertical Deformation[a]	
		Indirect Tensile	Punch	Flexure	Resilient Modulus	Transverse Frequency	Wave Velocity	Indirect Tensile	Punch	Flexure	Indirect Tensile	Punch
$N = k_1 (1/\sigma)^{n_1}$	n_1	0.87 (0.67)	0.88 (0.64)	0.51 (1.15)	0.52 (1.15)	0.34 (1.26)	0.61 (1.07)	0.70 (0.96)	0.79 (0.82)	0.45 (1.20)	0.08 (1.34)	0.18 (1.32)
	log k_1	0.79 (1.74)	0.83 (1.60)	0.37 (2.66)	0.35 (2.68)	0.09 (2.85)	0.52 (2.44)	0.53 (2.43)	0.68 (2.10)	0.26 (2.76)	0.18 (2.81)	0.41 (2.61)
$N = k_2 (1/\epsilon)^{n_2}$	n_2	0.53 (0.79)	0.62 (0.73)	0.28 (0.90)	0.09 (0.93)	0.14 (0.92)	0.45 (0.84)	0.23 (0.91)	0.34 (0.88)	0.05 (0.93)	0.40 (0.86)	0.47 (0.82)
	log k_2	0.45 (2.49)	0.52 (2.38)	0.16 (2.76)	0.03 (2.79)	0.23 (2.71)	0.31 (2.65)	0.12 (2.77)	0.24 (2.71)	0.08 (2.78)	0.50 (2.42)	0.56 (2.32)
$\sigma_{n=1}$[a]		0.91 (187)	0.81 (258)	0.72 (308)	0.76 (287)	0.77 (282)	0.55 (371)	0.93 (161)	0.81 (259)	0.71 (315)	0.39 (409)	0.10 (442)

[a] Refer to definition for Equations 3 and 4.

[b] Standard error of estimate listed in parentheses.

Figure 6. Fatigue design of bituminous concrete in the constant stress failure mode.



Note: 1 kPa = 0.145 lbf/in².

predictions. Therefore, even though the transverse frequency modulus and resilient modulus are the best predictors of the constant strain-fatigue relation, I selected indirect tensile strength so that the same test could be used.

The relations that can be used to determine the fatigue Equation 2 for constant strain fatigue are

$$n_2 = 0.0374\sigma_{IT} - 0.744 \quad (5)$$

$$\log K_2 = 7.92 - 0.122\sigma_{IT} \quad (6)$$

where σ_{IT} is indirect tensile strength.

The correlations would not allow a reasonable prediction of the fatigue Equation 1 for constant strain fatigue tests.

USE OF THE SIMPLE TEST PROCEDURE

The indirect tensile test procedure is primarily a tool for designing mixes that will have desirable fatigue characteristics. Rather than being used for routine design, the method should probably be used for special situations. An example might be designing a mix for a location having expected high deflections and needing a layer of asphalt concrete approximately 150 mm (6 in) thick. I assumed that the constant strain test is applicable to an asphalt concrete thickness less than 76 mm (3 in) and that the constant stress test is applicable to a thickness greater than 76 mm (3 in). A 150-mm (6-in) layer indicates that the constant stress test analysis would be applicable. Because high deflections are expected, the mix should be designed for high stress magnitudes. The steps in the design procedure are outlined below.

1. Obtain the indirect tensile strength and stiffness of a mix with a known fatigue field performance.
2. From these data, compute the fatigue relation in Equation 1 from Equations 3 and 4.
3. Plot this relation on log-log paper as shown in Figure 6. (It is obvious that mixes located to the right of the relation will have better fatigue properties than those to the left.)
4. Design the potential mix, possibly using a hard asphalt cement.
5. Obtain the indirect tensile strength and stiffness.
6. Compute the fatigue relation in Equation 1 from Equations 3 and 4.
7. Plot this relation on log-log paper.
8. Compare the mix with a known fatigue performance.

If the fatigue properties are not improved, it may be necessary to try other mix designs.

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Table 5. Correlation between constant strain fatigue test and simple tests.

		Stiffness[a]						Strength[a]			Vertical Deformation[a]	
Equation	Fatigue Characteristic	Indirect Tensile	Punch	Flexure	Resilient Modulus	Transverse Frequency	Wave Velocity	Indirect Tensile	Punch	Flexure	Indirect Tensile	Punch
$N = k_1 (1/\sigma)^{n_1}$	n_1	0.15 (1.22)	0.15 (1.22)	0.74 (0.83)	0.44 (1.11)	0.62 (0.97)	0.50 (1.07)	0.53 (1.05)	0.08 (1.23)	0.73 (0.85)	0.64 (0.95)	0.68 (0.91)
	$\log k_1$	0.12 (3.29)	0.22 (3.24)	0.65 (2.51)	0.41 (3.03)	0.67 (2.48)	0.38 (3.07)	0.54 (2.79)	0.10 (3.30)	0.68 (2.45)	0.70 (2.36)	0.72 (2.29)
$N = k_2 (1/\epsilon)^{n_2}$	n_2	0.79 (0.63)	0.28 (0.98)	0.46 (0.90)	0.56 (0.84)	0.84 (0.56)	0.46 (0.90)	0.81 (0.59)	0.47 (0.90)	0.59 (0.83)	0.40 (0.94)	0.18 (1.00)
	$\log k_2$	0.82 (1.82)	0.34 (3.00)	0.64 (2.46)	0.95 (2.69)	0.85 (1.67)	0.51 (2.75)	0.85 (1.69)	0.51 (2.74)	0.64 (2.46)	0.41 (2.91)	0.19 (3.14)

[a] Standard error of estimate listed in parentheses.

supervisor, is acknowledged for scheduling and performing the many tests. And appreciation goes to S. A. Kelley, our computer programmer, for running the analysis program.

The contents of this report reflect my views, and I alone am responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policy of the U.S. Department of Transportation. The opinions, findings, and conclusions expressed in this paper are mine and not necessarily those of the sponsoring agencies.

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Laboratory Measurement of Permeability of Compacted Asphalt Mixtures

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An improved method for measuring the permeability of compacted asphalt mixtures in the laboratory was developed. It eliminates the difficulties encountered with using a rubber membrane for sealing the specimen in a metal cylinder. In the new method, the specimen wall is coated with a one-part silicone rubber sealer that is applied as a paste with a spatula and is permanently flexible and waterproof. After the coating has cured and been checked for leaks, a known pressure difference is created by a vacuum across the specimen. The rate of air flow through the specimen is obtained at various differential pressure values. Flow rate is plotted against pressure difference, and the slope of the straight line portion of the curve is calculated. Permeability is calculated by using this slope value and the specimen height. The technique measures the true permeability, eliminates the possibility of specimen deformation during testing and the problems associated with other methods, permits no asphalt contamination, and is versatile with respect to aggregate gradation and asphalt grade.

The importance of measuring permeability, the small openings in a medium that permit liquids or gasses to pass through it, has long been recognized in the field of asphalt concrete. In 1955 McLaughlin and Goetz (1) hypothesized that using permeability gives a better measure of durability than using void content alone. Permeability, in their opinion, can be used to measure the capacity of a porous medium to transmit fluid, whereas the normal measure using voids in a bituminous mixture does not directly measure the forces producing disintegration.

Hein and Schmidt (2), after conducting a study on air permeability of asphalt concrete, suggested that permeability measurements are essential to routine mix design studies. Their results indicated that the void content of mixtures is not necessarily proportional to permeability when the variation is caused by gradation.

An investigation to evaluate the effects of air permeability and air void content on the durability of asphalt concrete was conducted by Smith and Gotolski (3). One of their conclusions was that air permeability is a good indicator of the extent of accessibility of the air void system.

This literature review indicates a need for a laboratory permeability measuring technique for predicting asphalt concrete behavior from the standpoint of durability.

METHOD

Keyser and Gilbert (4) conducted a study of methods that were then (1973) being used to determine the permeability of bituminous mixtures. They reported that 15 types of permeameters were in use in North America and Europe, of which 9 could be used in the laboratory.

In general, air permeability is measured by creating a known pressure differential across a specimen and then measuring the amount of air flow over a known period of time. The test requires that the specimen be encased so that air flow is limited to passage through it. This has been accomplished by sealing the specimen in a metal cylinder with asphalt or other sealing material. This method, however, is destructive to the specimen; it is also difficult to be certain that a complete seal has been obtained.