Pavement Design Characteristics of In-Service Asphalt Mixtures

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This paper summarizes the findings of a pavement design study on evaluating fatigue and resiliency characteristics and their variations in asphalt materials from in-service pavements in Texas. Cores from seven recently constructed highway pavements in Texas were tested with the repeated load indirect tensile test. Mean values of fatigue life, resilient modulus of elasticity, and resilient Poisson's ratio were determined, and their variations were estimated. In addition, stress-fatigue life relations were evaluated in terms of applied tensile stress and applied stress difference. The relations between repeated load fatigue properties and static properties were also evaluated. Fatigue lives were found to be essentially the same as those reported by other investigators. The mean resilient moduli of elasticity were fairly consistent for the various projects and ranged from 1520 to 4240 MPa (221 000 to 615 000 lbf/in^2). The majority of the Poisson's ratios were in the 0.10 to 0.22 range. The coefficient of variation for fatigue life, which was relatively large, ranged from 30 to 80 percent; the amount of variation was stress and project dependent. The coefficient for resilient modulus was relatively small, from 4 to 28 percent. No correlations for estimating purposes were found, although the relation between fatigue life and tensile strain looked promising.

Most current pavement design procedures are largely empirical and deterministic in nature. The state of the art, however, has advanced to the point at which attempts are being made both to apply elasticity concepts to design and to understand the fatigue behavior of various pavement layers and materials. Probabilistic concepts also need to be included. While theories are being developed and integrated into design and analysis systems, we still need to determine elastic and fatigue properties and their variations in pavement materials.

This paper summarizes the findings of a study on estimating these properties and variations in asphalt materials from actual pavements in Texas.

EXPERIMENTAL PROGRAM

The principal objectives of this investigation were to characterize in-service black-base materials in terms of fatigue life and of resilient elastic properties under repeated applications of low tensile stresses, to estimate the amount of expected variation in these properties, and to investigate possible correlations between behavior under a single load and that under repeated loading.

Therefore, field cores of black-base and asphalt surfacing materials from recently constructed highway pavements in Texas were tested with the static test and the repeated load indirect tensile test. The fatigue lives, elastic properties, and the variations among these properties were estimated by using the repeated load indirect tensile test; values of strength, modulus of elasticity, and Poisson's ratio were determined by using static loading.

Projects Tested and Core Sampling

Cores from seven projects in five locations in Texas were tested. General information on the projects is contained in Table 1.

Normally, black-base pavement layers are cored at equally spaced longitudinal intervals. Even though they were obtained in this systematic fashion, these cores can be considered to have been randomly sampled, because the sampling location function does not coincide with any variation distribution function known to exist in the pavement.

All cores were obtained with either a 102- or a 152-mm (4- or 6-in) inside diameter core barrel. The cores were sawed at the interface between lifts so that each specimen represented its respective lift. At least 10 specimens from each project were selected randomly and tested with the repeated load indirect tensile test; 3 to 5 specimens were tested under a single, slowly applied load to determine static strengths and static elastic properties of the black base and the asphalt concrete. Before testing, the specimen dimensions were carefully measured, and each specimen was weighed for density.

Test Method

In the indirect tensile test, a cylindrical specimen is loaded with either static or repeated compressive loads that act parallel to and along the vertical diametral plane. The load is distributed and the loading area maintained a constant by applying the compressive load through a 13-mm (0.5-in) wide steel loading strip curved at the interface to fit the specimen. This loading configuration develops a relatively uniform tensile stress, perpendicular to the plane of the applied load and along the vertical diametral plane, that ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter.

By monitoring the applied load and the horizontal and vertical deformations of the specimen, one can estimate the specimen's tensile strength, Poisson's ratio, and modulus of elasticity. Under repeated loads, one can estimate the resilient modulus of elasticity and Poisson's ratio for any given application of load, the permanent deformation accumulated for any given number of load applications, and the fatigue life, by continuously or periodically monitoring load, horizontal deformation, and vertical deformation.

Static Testing

The indirect tensile test procedure for static loading was the same as that used by Marshall and Kennedy (1). The basic testing apparatus included a loading system and a means of monitoring the applied loads and the specimen's horizontal and the vertical deformations.

The loading system consisted of a loading apparatus, a load-aligning device, and loading strips. In this study, a closed-loop electrohydraulic system was used to apply the load and to control the deformation rate. A deformation rate of 51 mm/min (2 in/min) at approximately 24°C (75°F) was used. A special loading device ensured that the loading platens and strips remained parallel during the test.

The load was monitored with a load cell, and the horizontal deformation was measured with a device with two cantilevered arms having attached strain gauges. Vertical deformation was measured with a DC linear variable differential transformer (LVDT). The loads and deformations were monitored by two X-Y plotters,

Table 1. Black-base and asphalt concrete projects.

Project	Material	Number of Specimens: Fatigue	Number of Specimens: Static	Asphalt: Type	Asphalt: Percentage by Weight	Aggregates	Specimen Diameter (mm)
2	Black base	18	5	AC-20	6.2 to 6.5	Limestone	152
5	Black base	15	5	AC-10	6.9 to 7.2	Limestone	152
8B	Black base	15	5	AC-20	4.6 to 5.3	Caliche conglomerate gravel	152
8C	Black base	11	3	AC-20	5.6 to 5.9	Limestone	152
17B(1)	Black base (first lift)	15	100[a]	AC-10 and AC-20	4	River gravel	102
17B(2)	Black base (second lift)	15		AC-10 and AC-20	4	River gravel	102
25 to 97(1)	Black base (first lift)	12	3	AC-20	6	Sandstone	102
25 to 97(2)	Black base (second lift)	11	3	AC-20	6	Sandstone	102
25 to 97(3)	Black base (third lift)	12	3	AC-20	3.5	Gravel	102
25 to 97(S)	Asphalt concrete (surface course)	12	3	AC-20	5	Gravel	102
25 to 100 (1,2)	Black base (first and second lifts)	12	4	AC-20	4.5	Gravel	102
25 to 100(3)	Black base (third lift)	10	2	AC-20	3.2	Gravel	102
25 to 100(S)	Asphalt concrete (surface course)	10	2	AC-20	4.7	Gravel	102

Note: 1 mm = 0.039 in.
[a] From Moore and Kennedy (1).

one recording load and horizontal deformation and one recording load and vertical deformation.

Points picked from the X-Y plots and other weight and volume information were used as input for computer program MODLAS 9, which calculates the tensile and elastic properties of the materials by using the indirect tensile test.

Repeated Load Testing

The basic test equipment used in the repeated load tests was the same as that used for the static loading tests, except for an additional horizontal deformation transducer consisting of two LVDT's that were used to monitor the horizontal deformation of the specimen for any particular load application.

Loads were applied at one cycle per second for 0.4 s followed by a rest period of 0.6 s (Figure 1). All tests were conducted at approximately 24°C (75°F).

Figure 1. Load time pulse for repeated load indirect tensile test.

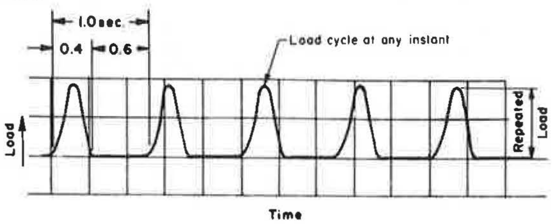
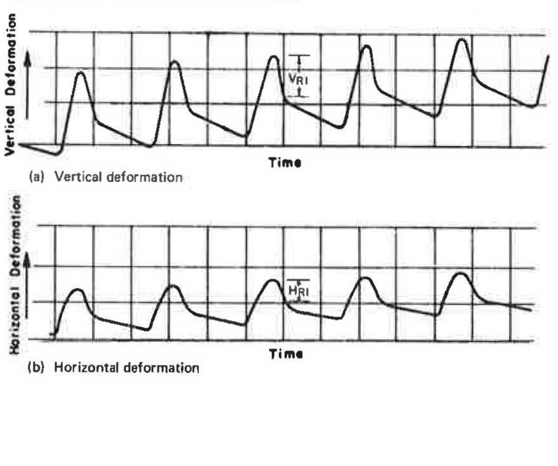
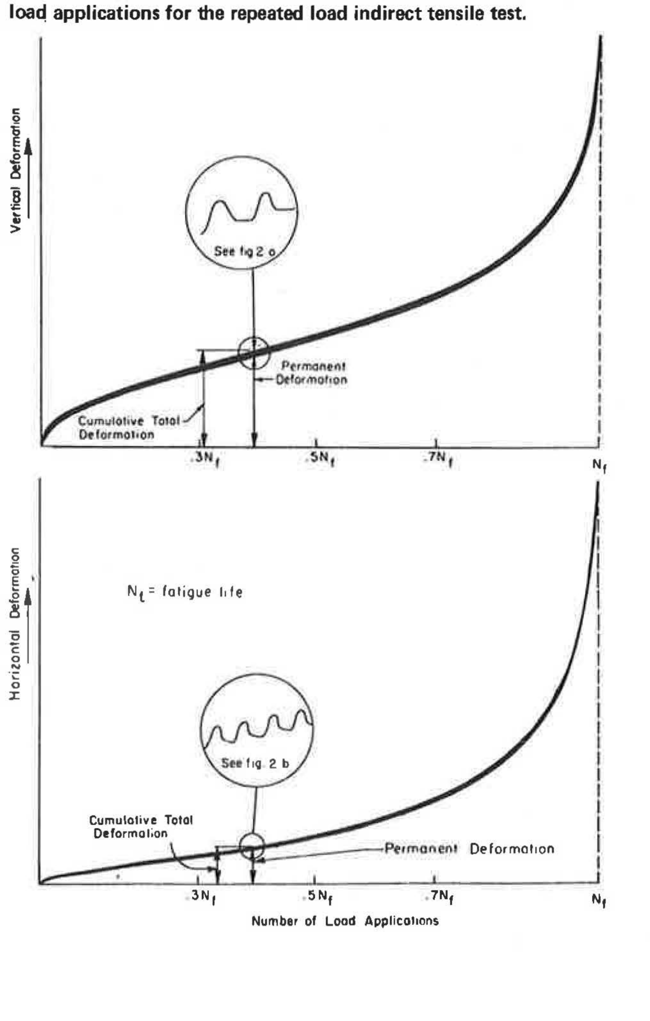


Figure 2. Typical load and deformation versus time relation for repeated load indirect tensile test.



The loads and elastic deformations from a given load application were recorded on a two-channel strip chart recorder. The permanent deformations were recorded on a digital data logging system. The specimen's load, elastic deformations, and permanent deformations were measured continuously during the first 200 cycles and were then monitored at increments of approximately 100 cycles. Typical vertical and horizontal deformation-time relations for a given load impulse are shown in Figure 2, and typical relations between total and permanent deformation and the number of cycles are shown in Figure 3.

Figure 3. Typical relation between deformation and number of load applications for the repeated load indirect tensile test.



Instantaneous resilient deformations, or recoverable deformations V_{RI} and H_{RI} (Figure 2), and the repeated load were used to calculate the resilient elastic properties under repeated loading.

Because of time restrictions, only a limited number of fatigue tests could be conducted. In some cases the stress level was raised in order to complete the testing program within a reasonable time, to establish the relation between tensile stress and fatigue life, and to determine whether this relation was essentially linear, as shown by previous work. Relatively high stress levels resulted in very low fatigue lives.

Fatigue Failure

Failure was considered to occur when the specimen fractured completely or, in terms of permanent horizontal (tensile) deformation, when deformation increased without additional load applications (Figure 3). Fatigue life (N_f), therefore, is the number of cycles corresponding to this large increase in deformation.

Resilient Elastic Characteristics

Permanent and total deformations increase substantially during the first few load cycles, and then the rate becomes essentially constant until failure (Figure 3). After analyzing a large number of permanent deformation relations, I concluded that the essentially linear portion of the curve occurred between about 15 and 85 percent of fatigue life. Because this range represents a significant portion of the material's design life, estimates of instantaneous resilient modulus and Poisson's ratios were calculated at 30, 50, and 70 percent of the fatigue life. These values were then averaged to obtain a representative value for each specimen.

Variation

One of the objectives of this study was to estimate variations in fatigue life and elastic properties of black-base and asphalt materials from in-service pavement. The coefficient of variation, which is the sample standard deviation divided by the sample mean, was therefore used because it related variation to mean.

Correlations

Possible correlations between the repeated load properties and the static or mixture properties were investigated with a view to developing techniques for estimating fatigue life and elastic properties under repeated loads without having to conduct costly and time-consuming repeated load tests.

ANALYSIS AND EVALUATION

Summaries of the test results for the seven projects are shown in Tables 2 and 3.

Fatigue Life

The black-base specimens for each project were subjected to a minimum of three stress levels to define the stress versus fatigue life relation and to measure the inherent variation in expected fatigue life.

Fatigue Life and Stress Relations

The mean fatigue life and coefficient of variation obtained for the specimens from each project are given in Table 2. The relations between the logarithm of tensile stress and the logarithm of fatigue life were essentially linear, but the slopes and relative positions varied, which indicated that the relations were material or project dependent. The linear relation can be expressed in the form

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

where

- N_f = fatigue life in cycles to failure;
- σ_T = repeated tensile stress in kilopascals;
- $\Delta\sigma$ = stress difference, approximately $4\sigma_T$, in kilopascals;
- n_2 = slope of the logarithmic relation between fatigue life and the tensile stress or stress difference;
- K_2 = antilog of the intercept of the logarithmic relation between fatigue life and tensile stress; and
- K_2' = antilog of the intercept of the logarithmic relation between fatigue life and stress difference.

As shown in Table 2, except for the four projects 5, 8B, 17B(1), and 17B(2), the slopes were fairly consistent. Values ranged from 1.50 to 5.08, and most slopes ranged from 3.18 to 5.08. Values for projects 5, 8B, 17B(1), and 17B(2) were smaller and varied from 1.58 to 2.66.

Monismith and others (2) reported values of K_2 and n_2 from previous work on field cores. Values of n_2 ranged from 1.85 to 6.0, and it was suggested that n_2 was a function of stiffness of the mixture.

Values obtained in this study were in the range previously reported. A review of Table 1 shows that three of the four projects with the smaller values of n_2 involved mixtures containing AC-10 rather than AC-20. In addition, project 8B mixtures, which contained an AC-20, used a different basic aggregate type.

Previously reported values of K_2 (2) were 2.85×10^9 and 4.41×10^{23} kPa (8.00×10^7 and 4.10×10^{18} lbf/in^2). Values in this study were smaller, ranging from 5.90×10^7 to 1.30×10^{17} kPa (2.79×10^5 to 7.13×10^{12} lbf/in^2). Thus, the fatigue lives for the materials tested were generally shorter than those previously reported.

Porter and Kennedy (3) compared the fatigue relations obtained by various investigators using different test methods. This comparison indicated that the fatigue life obtained with the repeated load indirect tensile test was significantly shorter than that obtained with other test methods. A large portion of the difference was attributed to the fact that the indirect tensile test involves a biaxial state of stress. It was suggested that stress be expressed in terms of a stress difference, i.e., the maximum principal stress minus the minimum principal stress, which is approximately $4\sigma_T$ in the failure zone.

The relations between the logarithm of fatigue life and the logarithm of stress difference are shown in Figure 4. Values of n_2 did not change, because the relations merely shifted along the x axis. Values of the K coefficient (K_2'), however, were significantly larger than K_2 and ranged from 5.26×10^7 to 1.49×10^{20} kPa (2.49×10^6 to 8.18×10^{15} lbf/in^2), with the majority of the values in the range of 10^{10} to 10^{17} (Table 2). These values are consistent with the previously reported values of K_2.

Variations in Fatigue Life

The coefficients of determination (R^2) for the various relations shown in Figure 4 are summarized in Table 2. These values indicate that a great deal of the variation in data could not be explained by linear relations. In addition, the coefficients of variation were not constant but were stress and project dependent. Coefficients ranged from 26 to 84 percent; however, some of this can

Table 2. Fatigue results for in-service black base and asphalt concrete.

Project	Tensile Stress, σ_T[a] (kPa)	No. of Specimens	Fatigue Life, N_f: Mean (cycles)	Fatigue Life, N_f: CV (%)	$N_f = K_2(1/\sigma_T)^{n_2} = K_2'(1/\Delta\sigma)^{n}$: K_2 (kPa)	K_2' (kPa)	n_2	R^2 (%)[b]
2	110	3	16 984	—	1.85×10^{13}	9.14×10^{15}	4.48	85
	165	5	1 842	29				
	221	5	869	52				
	276	5	252	78				
5	110	5	3 179	30	8.02×10^{8}	3.20×10^{10}	2.66	73
	165	5	1 063	49				
	221	5	567	52				
8B	165	5	5 277	60	8.11×10^{8}	2.02×10^{10}	2.32	42
	221	4	4 281	40				
	276	5	2 586	84				
8C	276	4	7 124	38	4.43×10^{14}	2.08×10^{17}	4.44	84
	331	2	3 513	—				
	386	4	1 678	65				
17B(1) first lift	110	5	3 582	26	5.90×10^{7}	5.26×10^{7}	1.58	50
	165	5	1 985	40				
	221	5	1 374	65				
17B(2) second lift	110	5	3 253	49	8.61×10^{7}	1.77×10^{9}	2.18	53
	165	5	1 593	45				
	221	5	748	52				
25-97(1) first lift (asphalt-stabilized base)	221	5	1 393	80	2.57×10^{10}	2.10×10^{12}	3.18	39
	276	2	382	—				
	331	5	313	61				
25-97(2) second lift (asphalt-stabilized base)	221	1	27 795	—	3.83×10^{14}	2.28×10^{17}	4.61	45
	276	5	1 582	75				
	331	2	924	—				
	386	3	1 081	—				
25-97(3) third lift (type A specimen)	276	5	1 015	69	1.61×10^{11}	1.77×10^{13}	3.39	56
	331	2	450	—				
	386	5	309	50				
25-97(S) surface course (type D specimen)	276	5	1 271	41	1.30×10^{17}	1.49×10^{20}	5.08	49
	331	2	460	—				
	386	5	297	74				
25-100(1, 2) first two lifts (asphalt-stabilized base)	110	4	12 223	66	4.14×10^{12}	1.42×10^{15}	4.21	89
	165	2	2 346	—				
	221	4	655	59				
	331	2	108	—				
25-100(3) third lift (type A specimen)	276	4	799	49	1.74×10^{14}	1.14×10^{17}	4.68	50
	331	2	296	—				
	386	4	180	64				
25-100(S) surface course (type D specimen)	110	1	38 157	—	9.30×10^{12}	2.90×10^{15}	4.14	89
	276	3	644	—				
	331	2	512	—				
	386	4	195	38				

Note: 1 kPa = 0.145 lbf/in^2.
[a] $\Delta\sigma = 4\sigma_T$.
[b] R^2 for regression equation expressed in the form $\log N_f = \log K_2 - n_2 \log \sigma_T = \log K_2' - n_2 \log \Delta\sigma$.

be accounted for by stress, because the coefficients increased with increasing stress or decreasing fatigue life.

A portion of the within-project variation for projects 8B and 8C might be attributed to the larger aggregates used in them. In addition, the cores from project 25-100 (1, 2) were very rough, which would contribute to the total variation by increasing testing error.

There were significant differences in the coefficients of variation for the various projects and stress levels, so no definite recommendation can be made for an exact value for the expected coefficient of variation. It is possible, however, to establish a range of expected values. This study seems to indicate that the coefficients of variation would range from about 30 to 80 percent.

Comparison Between Layers

Comparing the top and bottom layers for projects 17B and 25-97, which had an adequate number of specimens for comparison, indicates that the top layers (2) generally had longer fatigue lives than the lower layers (1). In Figure 4, the stress difference and fatigue life relation for project 25-97(2) is above that for project 25-97(1), but for projects 17B(2) and 17B(1) the reverse is true. However, if the K coefficients for the two projects are compared, the upper lifts exhibit larger values; this indicates that at lower stress values the fatigue lives would be longer for both projects. However, the slope value (n_2) is larger for the upper lifts, indicating that fatigue life shortened more rapidly with increased stress.

Elastic Characteristics

Mean values of the instantaneous resilient modulus of elasticity and Poisson's ratio and the coefficients of variation for each project and stress level are summarized in Table 3. The static values of tensile strength, modulus of elasticity, and Poisson's ratio obtained for the same projects are contained in Navarro and Kennedy (4).

Instantaneous Resilient Modulus of Elasticity

The mean instantaneous resilient moduli were consistent for the various projects and ranged from 152 to 424 MPa (221 000 to 615 000 lbf/in^2). More important, however, are the consistency within each project and the fact that

Table 3. Elastic properties for repeated load indirect tensile tests.

Project	Tensile Stress (kPa)	No. of Specimens	Instantaneous Resilient Modulus of Elasticity		Instantaneous Resilient Poisson's Ratio	
			Mean (MPa)	CV (%)	Mean	CV (%)
2	110	3	1960	–	0.31	–
	165	5	1830	7	0.27	31
	221	5	1920	9	0.44	46
	276	5	2060	4	0.58	12
5	110	5	1550	8	0.11	47
	165	5	1580	4	0.13	39
	221	5	1770	9	0.18	28
8B	165	5	2650	14	0.12	53
	221	4	2810	12	0.06	10
	276	5	3300	28	0.18	54
8C	276	4	3540	12	0.11	23
	331	2	3640	–	0.13	–
	386	4 (3[a])	3140	9	0.16	–
17B(2) top lift	110	5	3030	25	0.09	49
	165	4	3760	5	0.13	37
	221	5 (4[a])	3100	22	0.22	76
17B(1) bottom lift	110	5	3560	17	0.11	18
	165	4	4240	14	0.13	50
	221	5	3340	17	0.11	18
25-97(1) first lift (asphalt-stabilized base)	221	5	1730	17	0.32	33
	276	2	1850	–	0.46	–
	331	5	1720	4	0.39	38
25-97(2) second lift (asphalt-stabilized base)	276	5	1990	21	0.28	37
	331	2	2430	–	0.31	–
	386	3	2110	10	0.31	27
25-97(3) third lift (type A specimen)	276	5 (2[a])	2650	9	0.16	–
	331	2	3430	–	0.22	–
	386	5	2790	9	0.23	33
25-97(S) surface course (type D specimen)	276	5	2780	8	0.18	44
	331	2	2670	–	0.33	–
	386	4 (3[a])	2990	16	0.41	57
25-100(1, 2) first two lifts (asphalt-stabilized base)	110	3	1520	–	–	–
	165	2	1780	–	0.24	–
	221	2	2080	–	–	–
	331	1	2140	–	–	–
25-100(3) third lift (type A specimen)	276	3	2370	–	0.13	–
	331	2	2470	–	0.15	–
	386	3 (2[a])	2370	–	0.14	–
25-100(S) surface course (type D specimen)	276	3	2120	–	0.16	–
	331	2	2370	–	0.15	–
	386	3	2270	–	0.29	–

Note: 1 kPa = 0.145 lbf/in^2 and 1 MPa = 145 lbf/in^2.

[a] Number of specimens analyzed to determine the instantaneous resilient Poisson's ratio.

the modulus value was not overly sensitive to the magnitude of the applied stress, for the range of stresses used in testing. The coefficients of variation for any given project and stress level were low, ranging from 4 to 28 percent, as a result of this consistency.

In contrast, mean static moduli for similar material tested with the static indirect tensile test (1, 5) had much lower values of 266 to 631 MPa (38 600 × 10^3 to 91 500 lbf/in^2) and much higher (24 to 59 percent) coefficients of variation. Mean values in this study ranged from 381 to 1165 MPa (55 200 to 169 000 lbf/in^2), which is consistent with the previously reported values; the coefficient of variation ranged from 14 to 27 percent, which is smaller than previously reported static coefficients but somewhat larger than the coefficients of variation for the moduli resulting from repeated loads. Although it was not completely substantiated by these results, a large portion of the variation associated with static testing can probably be attributed to testing errors, caused by surface irregularities, that would not have much effect on repeated load tests.

A comparison of the mean static moduli and the mean resilient moduli is shown in Figure 5. This figure shows the dynamic moduli to be significantly larger than the static moduli. The ratio of the resilient and static moduli ranged from 10.5 to 2.3, the higher values being associated with the materials with low static moduli.

Instantaneous Resilient Poisson's Ratio

Except for projects 2 and 25-97, resilient Poisson's ratio values were fairly consistent at 0.06 to 0.29, the majority ranging from about 0.10 to 0.22 (Table 3). Values for projects 2 and 25-97 were much higher, from 0.16 to an indicated value of 0.58, with the majority from 0.22 to 0.46.

These values tend to be lower than those for similar materials, which were tested previously with the static indirect tensile test and ranged from 0.16 to 0.34 (1, 5). A comparison of the static and resilient Poisson's ratios obtained from this study indicates that these ratios are of essentially the same magnitude. In most projects, the mean values tended to increase with increasing stress.

Coefficients of variation for Poisson's ratio were much higher—from 10 to 76 percent—than those for resilient modulus of elasticity; the majority ranged between 18 and 57 percent. Nevertheless, these coefficients are lower than the static Poisson's ratios for similar materials, for which coefficients ranged from

39 to 67 percent (1, 5). Coefficients of variation for the static Poisson's ratios from this study ranged from 25 to 41 percent.

Correlations With Fatigue Life

Possible correlations between fatigue life and static properties and between fatigue life and repeated load properties were explored, because repeated load tests are time consuming and costly to conduct. If correlations do exist, it is possible to estimate fatigue properties with either the much simpler static test or the short-term repeated load test. Such correlations could also lead to a better understanding of the fatigue behavior of pavement materials.

Stress-Strength Ratio

Previous work reported by Moore and Kennedy (6, 7) found a relatively good linear correlation between the

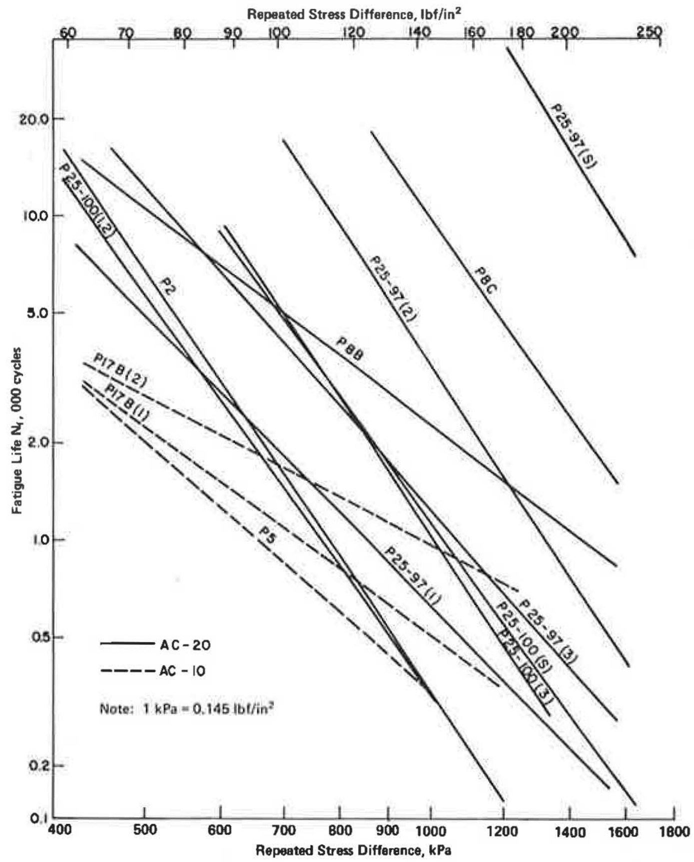


Figure 4. Relations between the logarithms of stress difference and fatigue life.

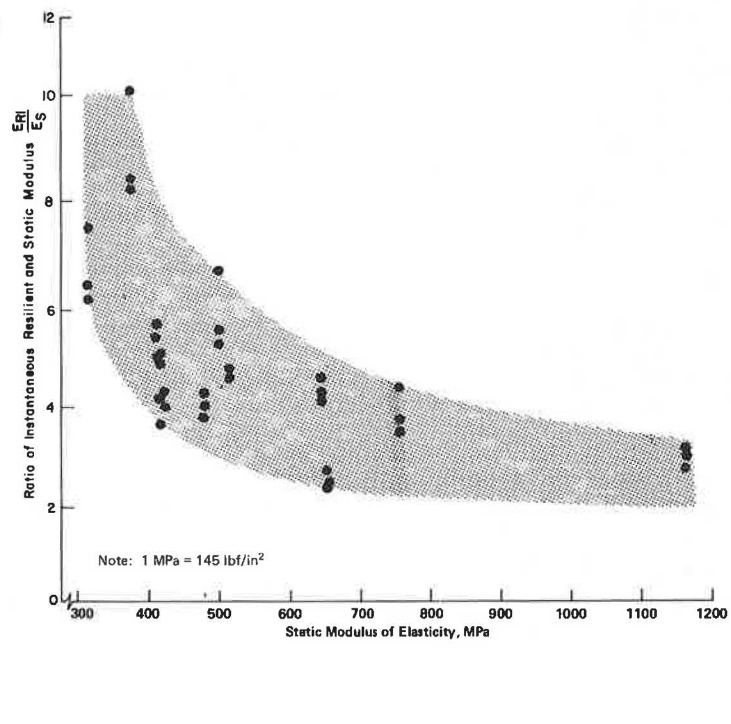
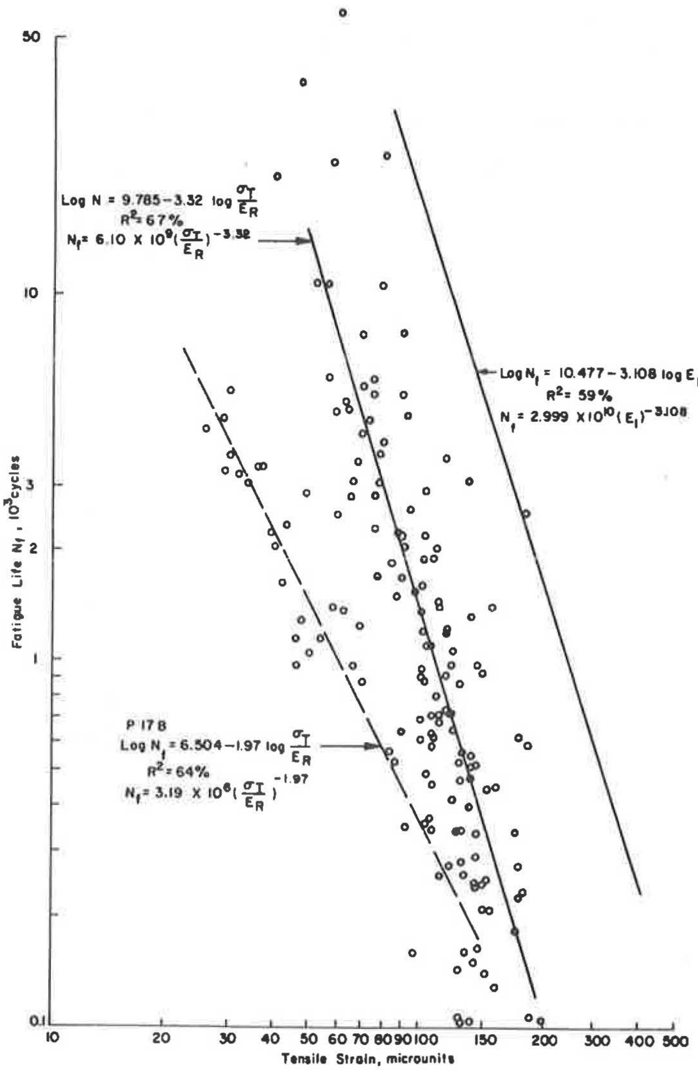


Figure 5. Relation between static modulus and the ratio of static and instantaneous resilient moduli.

Figure 6. Relations between the logarithms of fatigue life and tensile strain.



logarithm of the ratio of applied tensile stress to static tensile strength and the logarithm of fatigue life. Such a relation allows fatigue life to be estimated from static test results.

Navarro and Kennedy (4) described the relation between the logarithm of the estimated stress-strength ratio, defined as the ratio of the repeated tensile stress to the mean static tensile strengths, and the logarithm of fatigue life. A coefficient of determination (R^2) of 51 percent indicates that, although a correlation does exist, the reliability of a predicted fatigue life would be questionable and subject to large errors.

Stiffness

Previous work has indicated that stiffness is an important characteristic related to fatigue life. Deacon and Monismith (8) stated that any factor affecting stiffness also affects fatigue behavior. Deacon (9) reported that the effect of stiffness is a function of the mode of loading: under controlled stress loading, a material with a high stiffness will perform well as long as the mixture is not brittle and is well proportioned, but the reverse is true under controlled strain loading.

Epps and Monismith (10) presented data that indicated that stiffness alters the slope of the logarithmic relations between fatigue life and bending stress and showed that a stiff mix had a longer fatigue life. There was an indication that this was true in my study; however, for the limited number of projects and conditions involved, there was no definite correlation, although materials with higher static moduli of elasticity tended to have longer fatigue lives.

Tensile Strain

Previous investigators have shown that fatigue life is related to strain (4, 6, 7, 11, 12). Figure 6, derived from Moore and Kennedy (6, 7), illustrates this relation. Tensile strains were estimated by dividing the repeated tensile stress (σ_T) by the resilient modulus of elasticity (E_R). Included for comparison is the relation previously established by Moore and Kennedy (6, 7).

As shown, there was a definite trend when the data for project 17B were excluded. The relation for all of the other projects exhibited a coefficient of determination (R^2) of 67 percent, which indicates that a great deal of variation could be accounted for by the relation but that substantial estimation errors could be expected if the relation were used to predict fatigue life. The relation, excluding project 17B, was essentially parallel to that previously established by Moore and Kennedy, but the fatigue lives for a given strain were shorter, possibly because of the difference between field cores and laboratory-prepared specimens.

CONCLUSIONS

Fatigue Life

Fatigue failures occurred at indirect tensile stresses ranging from 110 to 386 kPa (16 to 56 lbf/in^2), which was 15 to 65 percent of the indirect tensile strength.

The relation between the logarithm of tensile stress and the logarithm of fatigue life was essentially linear, and that between stress and fatigue life could be expressed as in Equation 1.

Values of n ranged from 1.58 to 5.08 and are approximately equal to those previously reported. In addition, it appeared that n was related to the viscosity of the asphalt, because mixtures containing stiffer asphalts exhibited lower n values.

Values of K ranged from 5.90×10^7 to 1.30×10^{17} when stress is expressed in kilopascals (2.79×10^5 to 7.13×10^{12} when stress is expressed in pound force per square inch). These values are significantly smaller than those previously reported, which is indicative of shorter fatigue lives.

Relating the logarithm of fatigue life to the logarithm of stress difference (i.e., the maximum principal stress minus the minimum principal stress) did not change the values of n, but the values of K′ were larger than the values of K. Values of K′ ranged from 5.26×10^7 to 1.49×10^{20} when stress is expressed in kilopascals (2.49×10^6 to 8.18×10^{15} when stress is expressed in pound force per square inch); the majority of the values ranged from 10^{10} to 10^{17}. These are consistent with previously reported values.

The coefficient of variation generally ranged from 30 to 80 percent, magnitude being stress and project dependent. Variation tended to increase with increasing stress or decreasing fatigue.

There was an indication that the upper layers had longer fatigue lives than the lower layers. However, because only two projects could be evaluated, additional study is required.

Elastic Properties Under Repeated Loads

The mean resilient moduli of elasticity were fairly consistent for the various projects and ranged from 1520 to 4240 MPa (221 000 to 615 000 lbf/in^2).

The resilient moduli of elasticity were significantly larger than the static moduli of elasticity. The ratio of the resilient and the static moduli ranged from 10.5 to 2.3, the higher values being associated with the materials with low static moduli.

The coefficients of variation for the resilient moduli of elasticity were low, from 4 to 28 percent.

The majority of mean resilient Poisson's ratios ranged from 0.10 to 0.22; however, for two projects the values were much higher, from 0.22 to 0.46. In general, Poisson's ratios tended to increase with increased stress.

Coefficients of variation for resilient Poisson's ratio were higher than for resilient modulus of elasticity; the majority of the values lay between 18 and 57 percent.

Correlations With Fatigue Life

A correlation between fatigue life and the ratio of the repeated tensile stress to the static tensile strength was found to exist. However, large errors could be expected if this correlation were used to estimate fatigue life.

No correlation was found to exist between fatigue life and stiffness, except that higher moduli tended to have longer fatigue lives.

A correlation between the logarithm of fatigue life and the logarithm of tensile strain (repeated tensile stress divided by the resilient modulus of elasticity) was found to exist. It was essentially parallel to a similar relation previously reported. This relation, however, should not be used to estimate fatigue life because of the relatively large errors that could be expected.

Recommendation

The information obtained from this study of the fatigue and repeated load characteristics of asphalt-treated mixtures can and should be used in the development and application of stochastic pavement design procedures based on elastic theory. This paper provides estimates of the engineering properties and variation characteristics of in-service asphalt mixtures, rather than those of laboratory-prepared mixtures, that can be used in design.

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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