Effect of Additives on Bituminous Highway Pavement Materials Evaluated by the Indirect Tensile Test

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The use of the indirect tensile test to investigate the effects of ethylene vinyl acetate, polypropylene fiber, rubber, and sulfur as additives on the fatigue and strength characteristics of bituminous mixtures is discussed. The test apparatus, preparation of specimens, and selection of binder contents using the Marshall procedure are described. Experimental results on the effects of stress level, binder content, and additive on the mean load cycles to failure are given and compared with the work of other investigations. Relationships between fatigue life and applied stress difference are developed and compared with experimental results. The addition of additives in most cases increased fatigue life; significant improvements were observed when the bitumen incorporated ethylene vinyl acetate and when a 50/50 sulfur/bitumen blend was used. Some improvement in fatigue properties was noted for rubber-modified mixes and 20/80 sulfur/bitumen mixes. Fiber-reinforced specimens had lower fatigue lives because of sample preparation difficulties.

Progress in the structural design of highway pavements has led to a need to characterize highway pavement materials by laboratory testing. This in turn has made it possible to investigate the effect of mix composition and additives on such important characteristics as fatigue resistance and creep in the laboratory before full-scale road trials are carried out.

SCOPE OF RESEARCH

The work described in this paper used the indirect tensile test employed extensively by Adedimila and Kennedy *(1)* to investigate the effects of ethylene vinyl acetate, polypropylene fiber, rubber, and sulfur on fatigue and strength characteristics. The objects of the research program were

- To use the indirect tensile test to obtain relationships between the number of load repetitions to failure and the resilient characteristics of bituminous mixtures and
- To investigate the effects of incorporating additives in bituminous mixes.

Mixes used in the experimental program were made from hard limestone aggregate with the continuous grading shown in Figure 1; the binder was a 50-pen bitumen supplied by Croda Hydrocarbons, Ltd.

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PREPARATION OF SPECIMENS

Ethylene vinyl acetate was Evatane 18-150 supplied by Imperial Chemical Industries in the form of pellets approximatey 2 to 3 mm in diameter. Polypropylene fiber was manufactured by Don Fibres (Scotland), Ltd.; the 500-denier fiber staples had a length of 50 mm and a tensile strength of from 4.5 to 5.5 g per denier. Melting point of the fiber was given as 167°C with some softening to be expected at 150°C; 10 g of fiber were incorporated into each of the fiber-modified specimens.

Rubber additive was in the form of Pulvatex rubber powder supplied by Rubber Latex, Ltd., an unvulcanized rubber powder manufactured from concentrated natural rubber latex with 60 percent natural rubber and 40 percent by mass of a separator to keep the rubber particles from agglomerating. The rubber/bitumen ratio was 5/95 by mass.

The aggregate and filler were heated for a minimum of 2 hr at 165°C before mixing. For the specimens containing fiber it was noted that the fibers were susceptible to temperatures above 125°C, and mixing and compacting were achieved without exceeding this temperature. In the preparation of the sulfur-modified specimens, the heated sulfur powder was mixed with the bitumen before addition to the aggregate.

Compaction of specimens was carried out in standard Marshall molds, and compaction was achieved by 50 blows of the standard Marshall compaction hammer. Samples were cured for 3 weeks before testing. It has been suggested that with end-compacted specimens differences in density may occur along the specimen length. To determine the extent, if any, of these differences, the compacted specimens were cut into three equal discs and their densities determined. Four specimens were divided in this way, and the maximum density difference observed was 4.1 percent.

TESTING OF SPECIMENS

The indirect tensile testing of specimens was carried out by applying a repeated compressive load that acted parallel to and along the vertical diametral plane. Load was transmitted to the specimen through a 20-mm-wide curved loading strip of the same curvature as the specimen being tested.

The repeated compressive loads were applied to the specimen by a hydraulic ram, and the duration and value of the applied load were determined by signals from an electrical

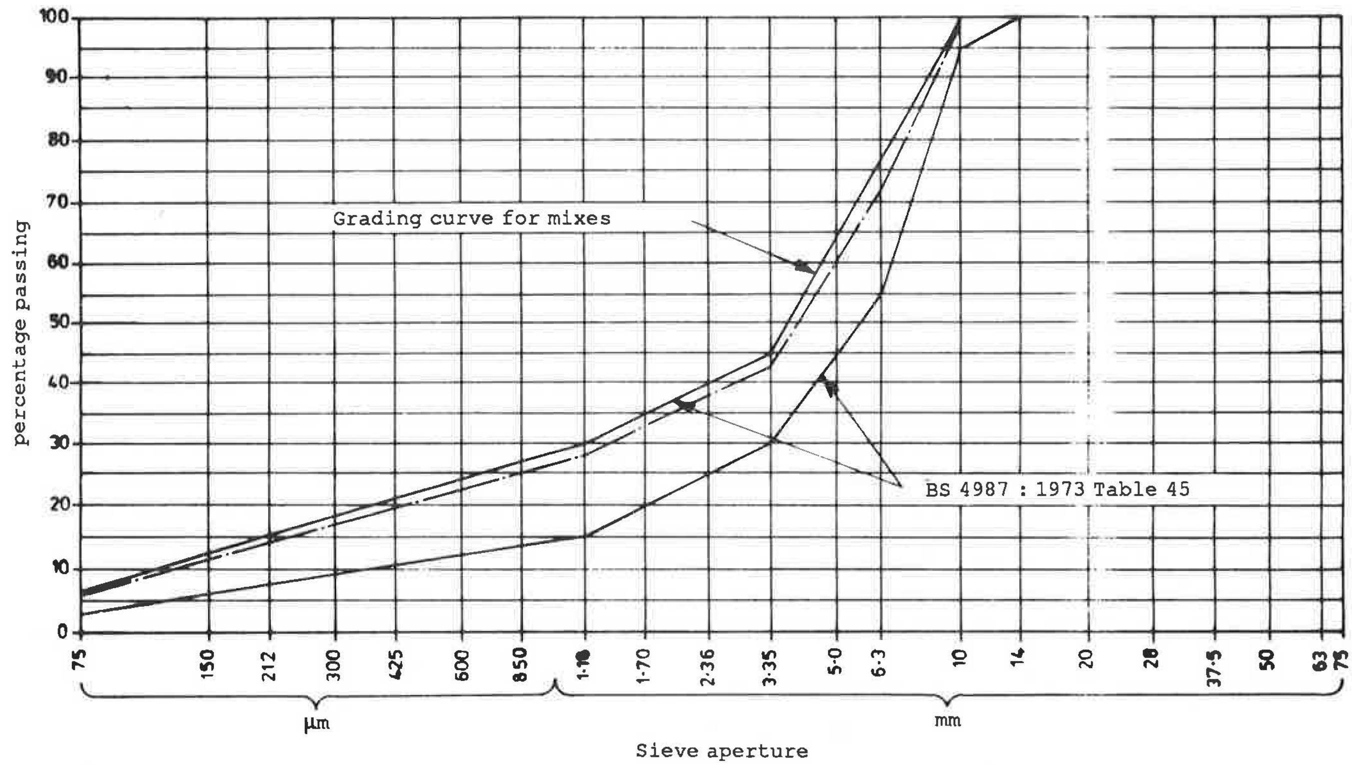

FIGURE 1 Aggregate grading curve for test specimens.

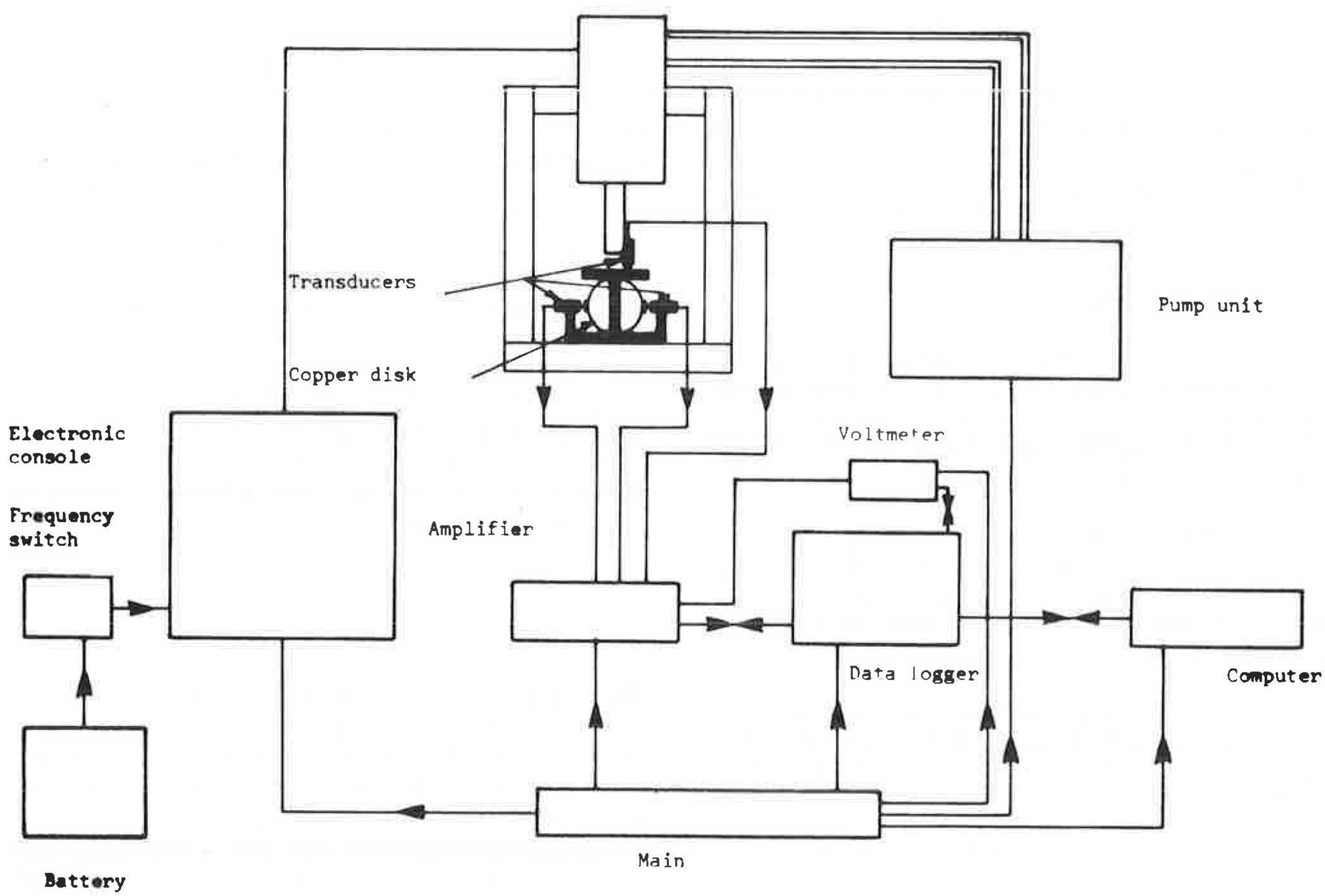

FIGURE 2 Setup of test equipment.

TABLE 1 TEST SPECIMENS USED IN EXPERIMENTAL PROGRAM

Bituminous Specimens			Bituminous Specimens Containing Fiber			Bituminous Specimens Containing Evatane (copolymer)			Bitumen Specimens Containing Sulfur (20 percent of bitumen weight)			Bituminous Specimens Containing Sulfur (50 percent of bitumen weight)			Rubber-Modified Bituminous Specimens (5 percent of bitumen weight)		
Bitumen Content (%)	No. of Speci-mens	Stress Level (kPa)	Bitumen Content (%)	No. of Speci-mens	Stress Level (kPa)	Binder Content (%)	No. of Speci-mens	Stress Level (kPa)	Binder Content (%)	No. of Speci-mens	Stress Level (kPa)	Binder Content (%)	No. of Speci-mens	Stress Level (kPa)	Binder Content (%)	No. of Speci-mens	Stress Level (kPa)
5	3	283	5	3	283	5.0	4	283	5.5	4	283	5.0	4	283	4.8	4	283
	3	496		3	496		4	496		4	496		4	496		4	496
	3	662		3	662		4	662		4	662		4	662		4	662
6	3	283	6	3	283	6.0	4	283	6.0	4	283	6.0	4	283	5.2	4	283
	3	496		3	496		4	496		4	496		4	496		4	496
	3	662		3	662		4	662		4	662		4	662		4	662
7	3	283	7	3	283	6.5	4	283	6.5	4	283	6.5	4	283	5.6	4	283
	3	496		3	496		4	496		4	496		4	496		4	496
	3	662		3	662		4	662		4	662		4	662		4	662
8	3	283				7.0	4	283	7.0	4	283	7.0	4	283	6.0	4	283
	3	496					4	496		4	496		4	496		4	496
	3	662					4	662		4	662		4	662		4	662
						8.0	4	283									
							4	496									
							4	662									

TABLE 2 MARSHALL TEST DATA: DENSITY AND MARSHALL QUOTIENT AT OPTIMUM BINDER CONTENT FOR BITUMINOUS AND MODIFIED BITUMINOUS MIXES

Type of Specimen	Optimum Binder Content (%)	Stability (kN)	Flow (mm)	Density (g/mL)	Percentage of Voids	QM[a] (kN/mm)
Bituminous	6	10.2	5.0	2.40	3.8	2.04
Bituminous containing fiber	6	9.7	5.6	2.26	9.1	1.72
Evatane-modified bituminous (5:95 EVA:bitumen ratio)	6.5	13.6	4.3	2.42	2.4	3.21
Sulfur S20–modified bituminous (20:80 sulfur:bitumen ratio)	5.5	10.0	3.1	2.42	1.3	3.22
Sulfur S50–modified bituminous (50:50 sulfur:bitumen ratio)	6.5	18.4	3.0	2.42	3.7	6.13
Rubber-modified bituminous (5:95 rubber:bitumen ratio)	5.2	9.5	3.0	2.40	3.6	3.22

[a]QM = Marshall quotient.

console that was part of the data acquisition and control system.

Plotting of the load and the horizontal and vertical displacement patterns, and recording values of load and strain, was carried out by an HP 85A computer. Readings and graphic plots were made at preset time intervals under computer instruction. A schematic layout of the apparatus is shown in Figure 2.

Testing was carried out in a controlled-temperature laboratory with temperature maintained in the 22°C to 24°C range for all tests. Loading frequency was at a rate of one cycle per second with a load duration of 0.4 sec and a rest period of 0.6 sec.

Previous research *(2, 3)* has indicated that fatigue life, modulus of elasticity, tensile strength, and Poisson's ratio are affected by stress level and mix composition. In the present study the effect of binder content and stress level on the fatigue characteristics of mixes modified by additives was investigated. A range of binder contents, chosen with reference to the optimum binder content as determined by the Marshall testing procedure, was selected. Details of the mixes selected are given in Table 1, and the results of the Marshall test procedure are given in Table 2.

To carry out a fatigue test all measuring devices were calibrated before testing, the specimen was placed in the test rig, and the upper platen was brought into light contact with the specimen. Vertical and horizontal transducers were fixed in place and a 222.5-N (50-lb) preload was applied to remove any slack between the upper platen and the specimen. The HP 85 was loaded with the control program and its first action zeroed the transducer and load cell readings. The additional load required to produce the required stress level for the test (283, 496, or 662 kPa) was then applied at a frequency of one cycle per second. Load and vertical and horizontal strain patterns were accurately traced by taking 20 readings per cycle. These were made at preset time intervals as shown in Figure 3. Testing continued until complete fracture occurred.

Experimental Results

Details of the fatigue test results for all the specimen types obtained by indirect tensile testing are given in Table 3 and shown graphically in Figures 4–6. It can be seen that polymer-modified binders offer an improvement in fatigue life compared with mixes that contain the other additives evaluated or unmodified mixes.

Fatigue and Applied Stress Relationship

The relationships between the logarithm of applied stress and the logarithm of fatigue life for bituminous and additive-modified bituminous specimens were investigated in this program. As in previous studies, a linear relationship is found to exist between the logarithm of applied stress and the logarithm of fatigue life, which was expressed as

$$Nf = K_2\left(\frac{1}{\sigma}\right)^{n_2} \quad (1)$$

where

Nf = fatigue life,
σ = applied stress, and
K_2, n_2 = constants that depend on mixture properties and temperatures.

The values of the constants K_2 and n_2 for all types of specimens are given in Table 4. The K_2-values range between 4.50×10^{10} and 4.03×10^{13}. The n_2-values for all fatigue test results vary between 2.62 and 3.75.

Table 5 gives typical values of K_2 and n_2 obtained by Pell and Cooper *(2)*, Monismith et al. *(4)*, Kennedy and Moore *(5)*, and Raithby and Sterling *(6, 7)*.

Table 6 gives typical values of K_2 and n_2 and K_1 and n_1 obtained by Adedimila and Kennedy *(1)* for the repeated-load indirect tensile test.

Figure 7 shows typical logarithmic stress–fatigue life relationships for a variety of mixtures tested under different conditions by a number of investigators (including this research group) using various types of fatigue tests; Figure 7 shows typical values of K_2 and n_2. It can be seen that there are large differences in fatigue lives obtained in the various studies especially for the indirect tensile test. A comparison of K_2- and

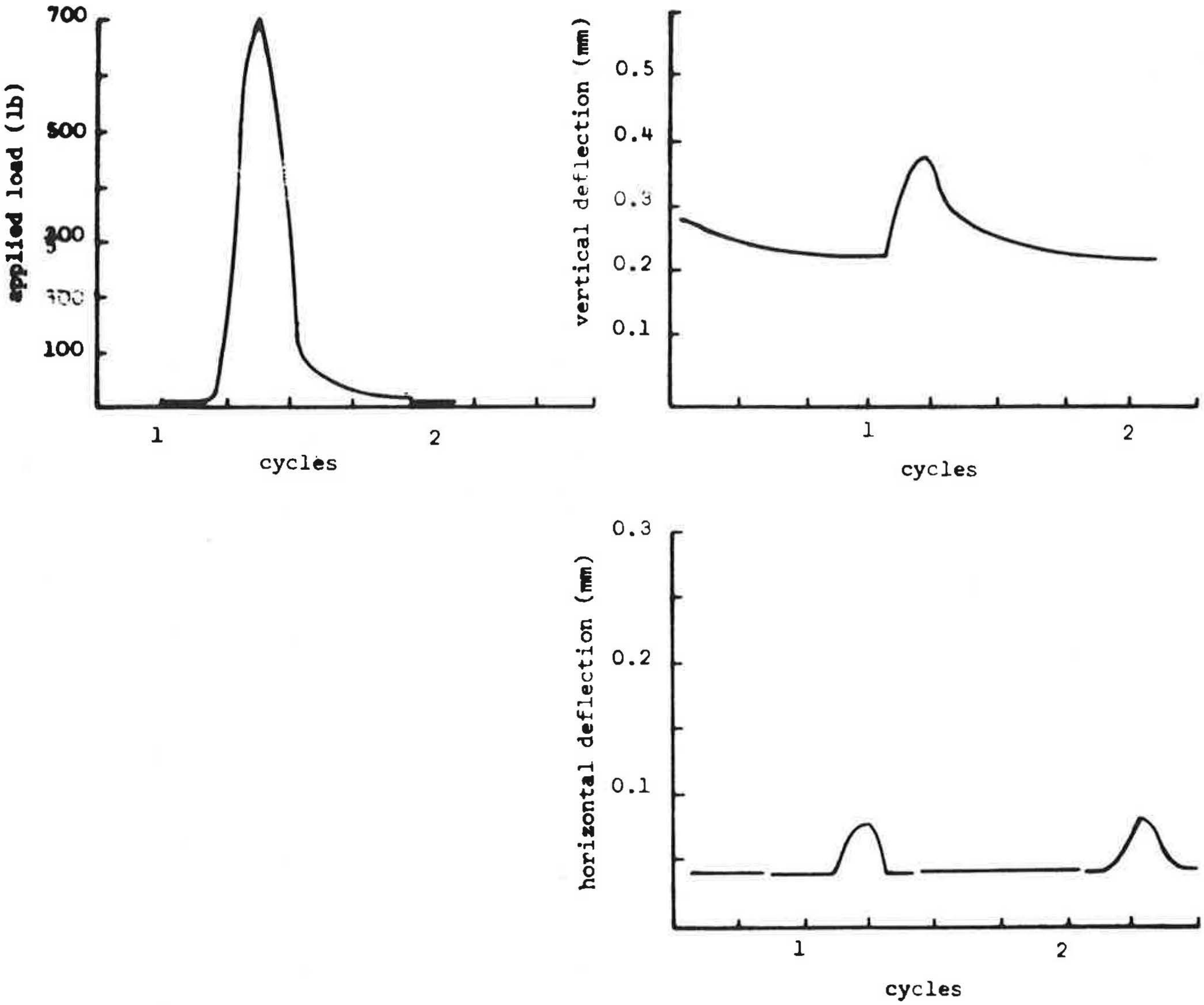

FIGURE 3 Typical load and vertical and horizontal deflection during the repeated-load indirect tensile test.

n_2-values indicates that the differences are mainly in K_2-values and that the values of n_2 are approximately the same. Values of K_2 range from 6.19×10^5 to 2.24×10^{21}, with the lower values associated with the repeated-load indirect tensile test (6.19×10^5 to 1.9×10^{13}) and with higher testing temperatures. Values of n^2 ranged from 2.56 to 6.43.

It is thought that the differences in the fatigue results obtained by different test methods are due to differences in loading and environmental testing conditions and the composition of the specimens.

Previous findings *(8)* have indicated that, because of the biaxial state of stress developed in the indirect tensile specimen, fatigue life should be evaluated in terms of stress difference, which for the indirect tensile test is equal to $4\sigma t$. Expressing fatigue life in terms of stress difference changes the values of K_2. The relationship can be expressed as

$$Nf = K_2'\left(\frac{1}{\Delta\sigma}\right)^{n_2} \tag{2}$$

where $\Delta\sigma$ is the stress difference; K_2' is a constant, dependent on mixture properties and testing temperature; and n_2 is as previously defined.

The relationships between the logarithm of applied stress and the logarithm of fatigue life have been shifted to the right so that values of K_2' are larger than values of K_2. Values of K_2' ranged from 1.69×10^{12} to 7.00×10^{15} (Table 4). The obtained values of K_2' are generally smaller than those reported for flexural and axial load tests for other mixtures *(4, 8)*. Many researchers have found that temperature change and different load durations and types of binder and aggregate affect the values of K_2', and K_2. Adedimila and Kennedy *(1)* have reported that factors such as temperature and aggregate bitumen content influence values of K_2 and K_2'. Increased test temperature has the main effect on values of K_2' and K_2. These values generally decrease with an increase in temperature. For this research program the test temperature, type of aggregate, and type of bitumen used have been kept constant for all specimens. The main mix variable is the bitumen content, which has a limited effect on the value of K_2 and K_2'. The combined effect

TABLE 3 MEAN, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION OF FATIGUE LIFE FOR BITUMINOUS SPECIMENS

Type of Specimen	Bitumen Content (%)	Stress Level (kPa)	No. of Specimens	Mean Cycles to Failure	Standard Deviation	CV (%)
Bituminous	5	283	3	18,193	12237	67.0
	5	496	3	4,740	779	16.4
	5	662	3	2,050	292	14.2
	6	283	3	22,322	10113	45.3
	6	496	3	2,863	742	25.9
	6	662	3	1,247	54	4.3
	7	283	3	27,956	9503	34.0
	7	496	3	4,790	714	14.9
	7	662	3	1,380	212	15.4
	8	283	3	20,519	3229	16.0
	8	496	3	2,930	453	15.5
	8	662	3	1,130	61	5.4
Bituminous containing fiber	5	283	3	26,826	1861	6.9
	5	496	3	3,500	320	9.1
	5	662	3	880	162	18.4
	6	283	3	17,200	2040	11.9
	6	496	3	4,200	1407	33.5
	6	662	3	1,536	418	27.3
	7	283	3	21,941	1846	8.4
	7	496	3	3,105	740	23.8
	7	662	3	1,288	423	32.8
Bituminous containing 5% EVA	5	283	4	39,100	3158	8.0
	5	496	4	5,195	1388	26.7
	5	662	4	2,560	723	28.2
	6	283	4	46,030	3210	7.0
	6	496	4	5,790	1151	20.0
	6	662	4	2,750	633	23.0
	6.5	283	4	41,300	2786	6.7
	6.5	496	4	6,100	729	12.0
	6.5	662	4	2,020	396	19.5
	7	283	4	35,731	2439	6.8
	7	496	4	5,160	386	7.5
	7	662	4	1,855	253	13.6
	8	283	4	27,700	3558	12.8
	8	496	4	3,570	620	17.4
	8	662	4	1,497	105	7.0
Bituminous containing 20% sulfur/80% bitumen	5.5	283	4	18,457	1770	9.6
	5.5	496	4	3,354	453	13.5
	5.5	662	4	1,101	195	17.7
	6	283	4	20,596	2938	14.3
	6	496	4	3,707	463	12.5
	6	662	4	1,215	232	19.1
	6.5	283	4	17,819	1935	10.8
	6.5	496	4	3,492	416	11.9
	6.5	662	4	1,441	188	13.0
	7	283	4	15,976	3535	22.1
	7	496	4	3,315	662	20.0
	7	662	4	1,297	451	34.7
Bituminous containing 50% sulfur/50% bitumen	5.5	283	4	24,025	2731	11.4
	5.5	496	4	4,393	1041	23.7
	5.5	662	4	1,375	294	21.4
	6.0	283	4	26,277	2895	11.0
	6.0	496	4	4,900	1631	33.3
	6.0	662	4	1,645	420	25.5
	6.5	283	4	36,956	2575	7.0
	6.5	496	4	5,290	1347	25.5
	6.5	662	4	2,390	960	40.0
	7.0	283	4	31,500	3286	10.4
	7.0	496	4	4,012	603	15.0
	7.0	662	4	1,850	263	14.0
Bituminous containing rubber	4.8	283	4	20,533	2856	14.0
	4.8	496	4	3,578	577	16.0
	4.8	662	4	1,350	209	15.5
	5.2	283	4	23,474	3437	14.6
	5.2	496	4	3,232	477	14.7
	5.2	662	4	1,422	168	11.8
	5.6	283	4	26,540	2777	10.5
	5.6	496	4	4,202	737	17.5
	5.6	662	4	1,600	366	22.6
	6.0	283	4	22,181	3613	16.3
	6.0	496	4	3,820	1285	33.6
	6.0	662	4	1,410	320	22.7

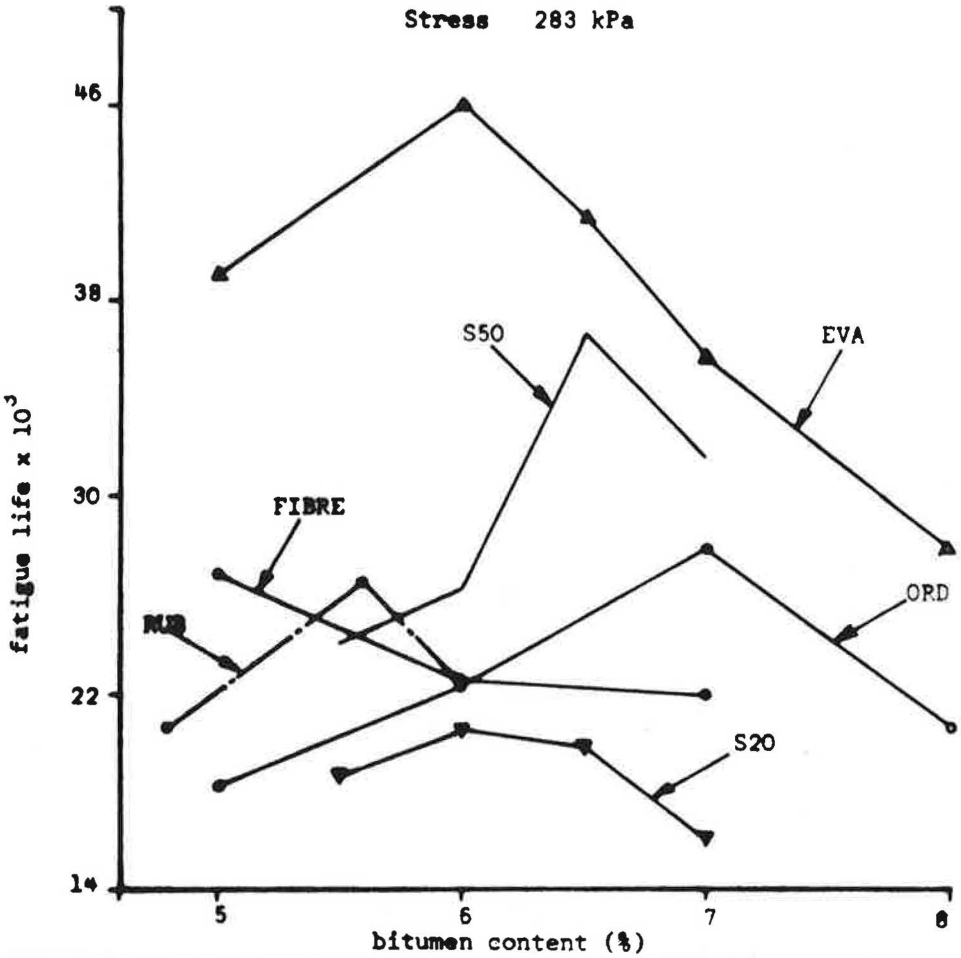

FIGURE 4 Effect of bitumen content on fatigue life (stress = 283 kPa).

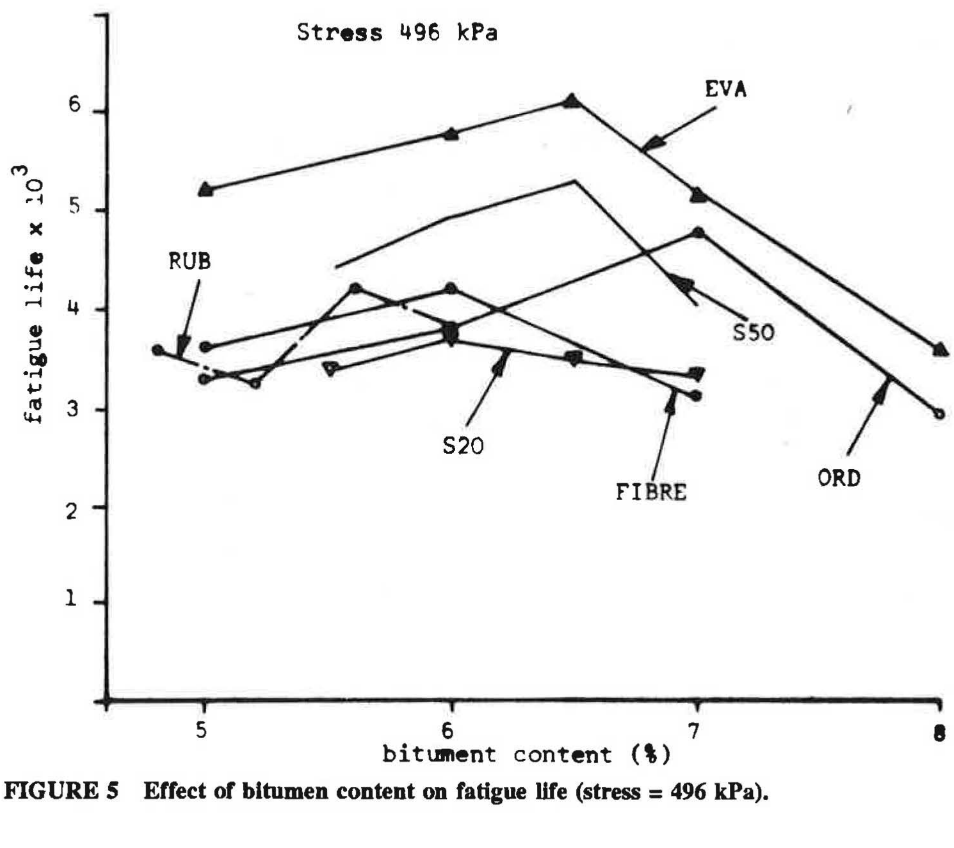

FIGURE 5 Effect of bitumen content on fatigue life (stress = 496 kPa).

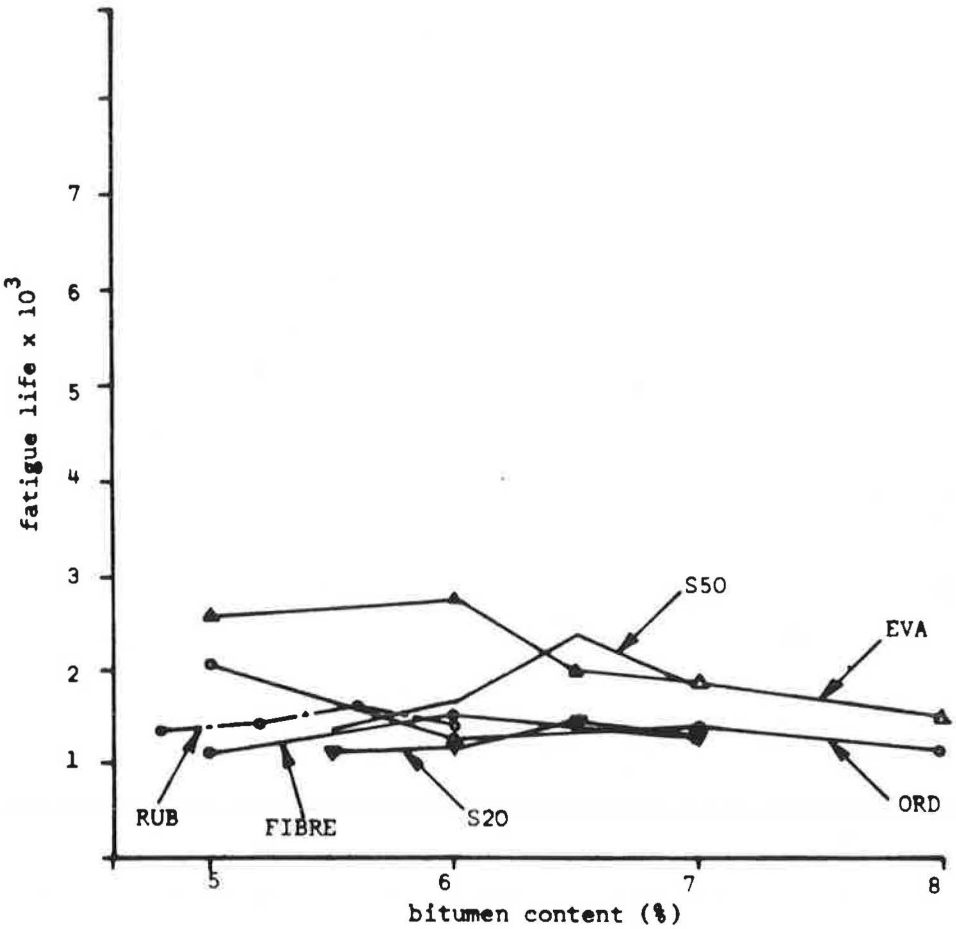

FIGURE 6 Effect of bitumen content on fatigue life (stress = 662 kPa).

TABLE 4 EXPERIMENTAL VALUES OF K_2, K_2', AND n_2

Type of Specimen	Bitumen Content (%)	No. of Specimens	K_2	K_2'	n_2	Correlation Coefficient
Bituminous	5.0	9	4.50×10^{10}	1.69×10^{12}	2.62	0.98
	6.0	9	3.54×10^{12}	3.73×10^{14}	3.34	0.99
	7.0	9	9.97×10^{12}	1.24×10^{15}	3.48	0.99
	8.0	9	3.65×10^{12}	3.74×10^{14}	3.36	0.99
Fiber-modified bituminous	5.0	9	4.03×10^{13}	7.00×10^{15}	3.74	0.99
	6.0	9	1.22×10^{12}	9.73×10^{13}	3.15	0.98
	7.0	9	4.54×10^{12}	4.69×10^{14}	3.39	0.98
Polymer-modified bituminous	5.0	12	4.11×10^{12}	3.90×10^{14}	3.28	0.99
	6.0	12	8.05×10^{12}	8.56×10^{14}	3.37	0.99
	6.5	12	2.00×10^{13}	2.66×10^{15}	3.54	0.99
	7.0	12	1.18×10^{13}	1.45×10^{15}	3.47	0.99
	8.0	12	7.38×10^{12}	8.53×10^{14}	3.44	0.99
Sulfur-modified bituminous (20/80 sulfur/bitumen ratio)	5.5	12	2.11×10^{12}	1.97×10^{14}	3.28	0.99
	6.0	12	2.47×10^{12}	2.42×10^{14}	3.29	0.99
	6.5	12	3.05×10^{11}	1.79×10^{13}	2.95	0.99
	7.0	12	2.93×10^{11}	1.82×10^{13}	2.96	0.98
Sulfur-modified bituminous (50/50 sulfur/bitumen ratio)	5.5	12	3.63×10^{12}	3.61×10^{14}	3.33	0.98
	6.0	12	1.81×10^{13}	2.40×10^{14}	3.60	0.98
	6.5	12	3.75×10^{12}	3.60×10^{14}	3.27	0.99
	7.0	12	6.78×10^{12}	7.65×10^{14}	3.40	0.99
Rubber-modified bituminous (5/95 rubber/bitumen ratio)	4.8	12	1.43×10^{12}	1.10×10^{14}	3.20	0.99
	5.2	12	2.82×10^{12}	3.14×10^{14}	3.30	0.99
	5.6	12	3.46×10^{12}	3.52×10^{14}	3.31	0.99
	6.0	12	1.93×10^{12}	1.69×10^{14}	3.24	0.98

TABLE 5 FATIGUE DATA FOR VARIOUS TESTS AND INVESTIGATIONS

Test and Investigator	Mixture	Binder Content (%)	Binder Penetration	Temperature (°F)	K_2	n_2
Flexure, Monismith et al. *(4)*	British 594	7.9	40–50	68	1.36×10^{11}	2.87
	California	6.0	85–100	68	1.55×10^{11}	3.51
	California	6.0	60–70	68	7.29×10^{12}	4.21
	California	6.0	40–50	68	1.97×10^{15}	4.93
	California	6.2	60–70	68	6.01×10^{10}	3.24
	Gonzales lab surface	6.0	85–100	40	1.78×10^{16}	5.09
	Surfaces 1 and 2	4.9	85–100	40	1.16×10^{18}	5.71
Axial loading Raithby and Sterling *(6, 7)*	Pell's mix G	6.5	38	50	2.59×10^{13}	4.11
	Pell's mix G	6.5	38	50	1.72×10^{19}	6.43
	Pell's mix G	6.5	38	50	2.24×10^{21}	5.97
	Pell's mix G	6.5	38	50	2.13×10^{17}	5.28
	Pell's mix G	6.5	38	77	3.65×10^{11}	3.87
	Pell's mix G	6.5	38	77	5.78×10^{13}	4.76
	Pell's mix G	6.5	38	77	2.49×10^{13}	4.09
Rotating cantilever, Pell and Cooper *(2)*	HRA base	6.0	40–50	50	3.7×10^{16}	5.40
	HRA base course A13	6.8	40–50	50	1.1×10^{12}	3.50
	AC wearing course B6	6.0	60–70	50	3.9×10^{15}	4.90
	DBH base	4.7	90–110	50	3.0×10^{12}	3.90
	DTH base course	6.0	40–60	50	7.5×10^{14}	6.40
Repeated-load indirect tension, Kennedy and Moore *(5)*	Limestone	4.0	88	75	6.19×10^{5}	2.56
	Limestone	5.0	88	75	8.11×10^{6}	2.84
	Limestone	6.0	88	75	6.9×10^{7}	3.23
	Limestone	7.0	88	75	4.76×10^{8}	3.88
	Limestone	8.0	88	75	5.88×10^{7}	3.42
	Gravel	4.0	88	75	2.74×10^{6}	3.24
	Gravel	5.0	88	75	9.4×10^{6}	3.14
	Gravel	6.0	88	75	6.62×10^{7}	3.34
	Gravel	7.0	88	75	3.56×10^{8}	3.80
	Gravel	8.0	88	75	1.9×10^{7}	3.13

TABLE 6 FATIGUE DATA FOR REPEATED-LOAD INDIRECT TENSILE TESTS REPORTED BY ADEDIMILA AND KENNEDY *(1)*

Mixture	Binder Content[a] (%)	Temperature (°F)	K_2	n_2	K_1	n_1
Limestone	6	50	4.59×10^{10}	3.74	1.29×10^{-11}	3.73
Gravel	6	50	1.9×10^{13}	5.14	5.65×10^{-17}	5.19
Limestone	4	75	9.36×10^{5}	2.67	9.97×10^{-8}	2.67
Limestone	5	75	8.75×10^{6}	2.86	4.49×10^{-8}	2.86
Limestone	6	75	5.63×10^{7}	3.14	3.67×10^{-9}	3.20
Limestone	7	75	4.29×10^{8}	3.84	5.48×10^{-11}	3.84
Limestone	8	75	4.20×10^{7}	3.33	6.24×10^{-9}	3.33
Gravel	4	75	1.62×10^{6}	3.06	2.10×10^{-9}	3.06
Gravel	5	75	5.43×10^{6}	2.96	6.82×10^{-9}	2.97
Gravel	6	75	1.09×10^{8}	3.46	9.31×10^{-11}	3.49
Gravel	7	75	8.68×10^{8}	4.11	2.9×10^{-11}	4.13
Gravel	8	75	1.86×10^{7}	3.13	3.71×10^{-9}	3.13
Limestone	6	100	5.27×10^{5}	2.66	5.01×10^{-7}	2.66
Gravel	6	100	3.26×10^{5}	2.72	5.75×10^{-8}	2.72

[a]The binder was an AC-10 asphalt cement with a penetration value of 88.

of aggregate grading and binder content and the manufacture of specimens may explain the variations in K_2-values. It has been reported by Monismith and Epps *(9)* that in controlled tests the greater the stiffness the flatter the slope (high n_2-values) of the regression line and the longer the fatigue life.

Relationship Between Fatigue and Initial Strain

Fatigue life relationships are often expressed in terms of initial strain for controlled-stress tests and repeated strain for controlled-strain tests. The relationships between fatigue life and initial strain for bituminous specimens and additive-modified bituminous specimens are shown in Figure 8. A regression analysis is used to obtain values of the constants K_1 and n_1 for the general equation .

$$Nf = K_1\left(\frac{1}{\varepsilon_{\text{mix}}}\right)^{n_1} \tag{3}$$

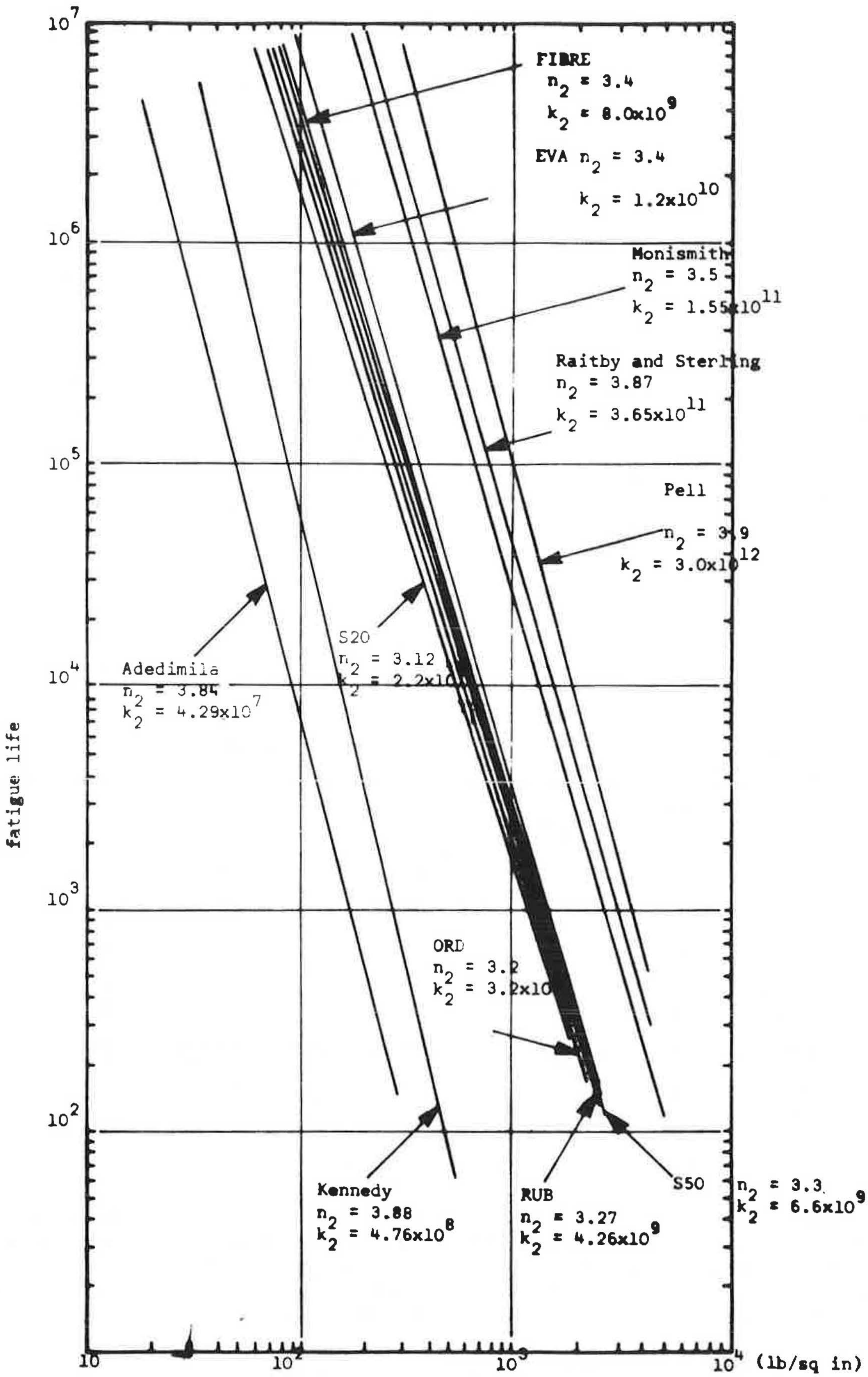

FIGURE 7 Typical stress-fatigue relationships for various tests.

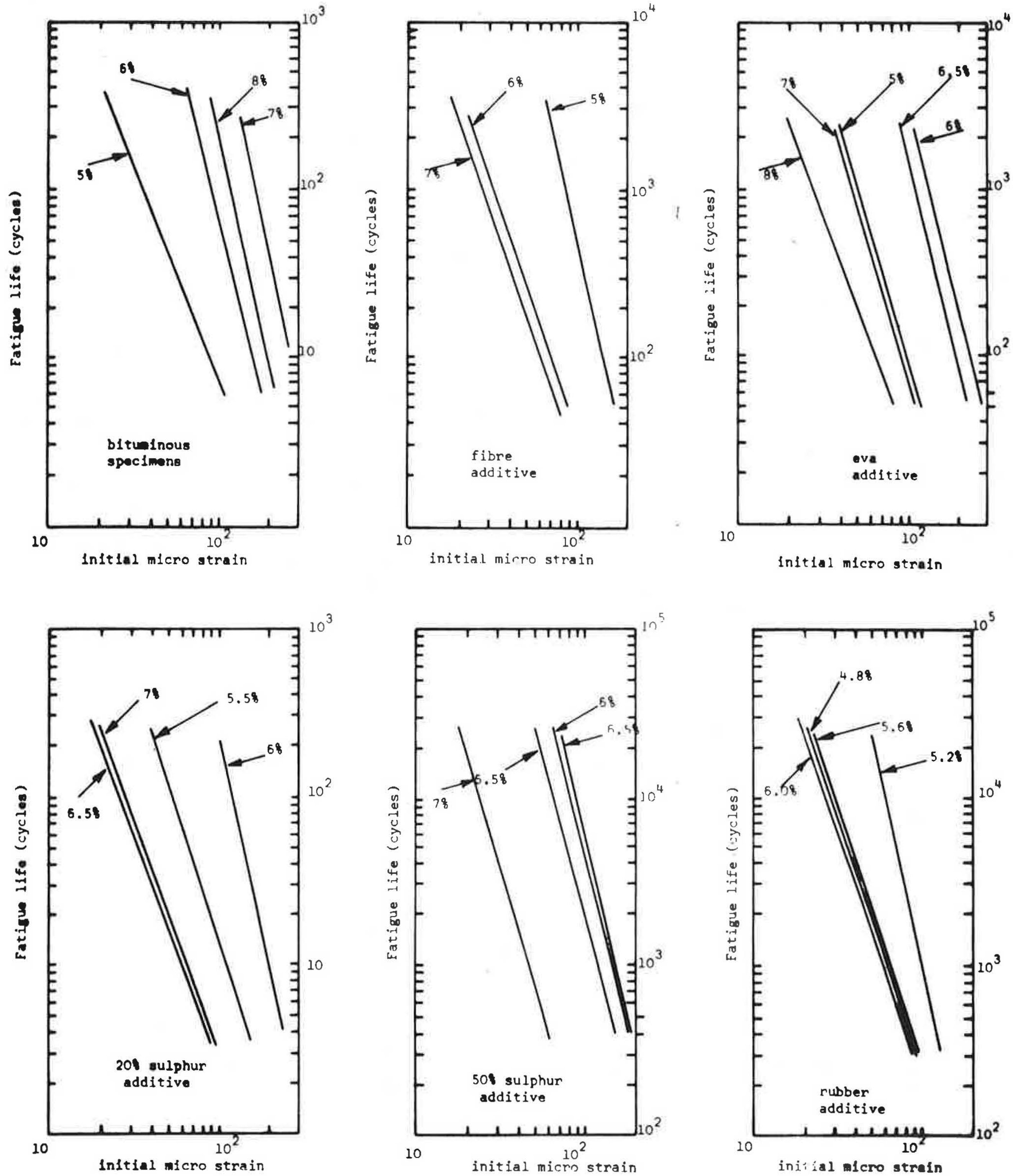

FIGURE 8 Relationships between fatigue life and initial strain.

where

Nf = fatigue life,
ε_{mix} = initial strain in the mixture, and
K_1, n_1 = constants.

A summary of values of K_1 and n_1 is given in Table 7. Values of K_1 range from 7.93×10^{-7} to 3.10×10^{-4} for bituminous and modified bituminous mixtures. Values of n_1 ranged from 2.61 to 3.74 for bituminous and modified bituminous specimens.

It is rather difficult to compare the values of K_1 and n_1 obtained in this research program with those obtained from previous flexural and axial load and dynamic indirect tensile tests because the mixtures, bitumen contents, testing temperatures, and testing procedures are different for each type of test.

Adedimila and Kennedy *(1)* conducted dynamic indirect tensile tests on bituminous mixtures that contained gravel or limestone. The reported values for K_1 and n_1 for the part of their test program that dealt with similar mixtures with the same bitumen contents and the same test temperature can, however, be compared with the values of K_1 and n_1 in Table 7. Their K_1-values ranged from 2.9×10^{-13} to 4.49×10^{-8}, and n_1 ranged from 2.67 to 4.13.

CONCLUSION

To predict fatigue life with respect to applied stress and mixture strain, regression analysis was used to obtain the best-fit values of the constants K_1, n_1, K_2, and n_2 in Equations 1 and 3. To compare the predicted and the actual mean fatigue values, the percentage of error for each bitumen content was calculated. Values of the actual mean fatigue life and the predicted mean fatigue life, along with the percentage of error for all types of mixtures, with respect to applied stress and mixture strain were determined, and the percentage of error for the bituminous and the modified bituminous mixes indicated that, in general, the difference between the actual and predicted mean fatigue life values were small; no particular trend was noticed in the degree of error with increase in binder content. Increased applied stress had little effect on the percentage of error. Some isolated cases for which the percentage of error reached 15 percent can be associated with the difficulty in maintaining high consistency in the manual preparation and manufacture of specimens.

The difference between the predicted values of applied stress and mixture strain were small. The percentage of error varied with binder content for both sets of analysis.

Marshall stability tests were used to determine optimum binder contents for fatigue testing, and it was noted that the addition of 20 percent sulfur to the binder did not increase stability compared with that of a normal bituminous specimen but did decrease the flow, which resulted in an increased Marshall quotient. Fiber specimens produced disappointing test values because of low densities caused by mixing and compacting difficulties. Mixtures with rubber-modified binders also had low stability values but decreased flow values. The two most successful mixes were those with ethylene vinyl acetate binders and those with binder modified by 50 percent sulfur.

An analysis of the indirect tensile test fatigue results indicated low coefficients of variation that exhibited a general decrease with an increase in binder content. Tests carried out at different binder contents showed that several mixes had an optimum binder content for maximum fatigue life. These binder contents were within ± 1 percent of the optimum derived by the Marshall test.

TABLE 7 EXPERIMENTAL VALUES OF K_1 AND n_1

Type of Specimen	Bitumen Content (%)	No. of Specimens	K_1	n_1	Correlation Coefficient
Bituminous	5.0	9	6.35×10^{-4}	2.61	0.98
	6.0	9	2.76×10^{-6}	3.34	0.99
	7.0	9	7.93×10^{-7}	3.48	0.99
	8.0	9	1.23×10^{-5}	3.36	0.99
Fiber-modified bituminous	5.0	9	1.59×10^{-6}	3.74	0.99
	6.0	9	6.18×10^{-5}	3.14	0.98
	7.0	9	4.41×10^{-5}	3.38	0.98
	7.0	9	4.41×10^{-5}	3.38	0.98
Polymer-modified bituminous	5.0	12	6.32×10^{-6}	3.26	0.99
	6.0	12	2.67×10^{-6}	3.37	0.99
	6.5	12	1.14×10^{-6}	3.55	0.99
	7.0	12	5.33×10^{-6}	3.48	0.99
	8.0	12	2.44×10^{-6}	3.44	0.99
Sulfur-modified bituminous	5.5	12	3.13×10^{-5}	3.28	0.99
(20/80 sulfur/bitumen ratio)	6.0	12	2.29×10^{-5}	3.30	0.99
	6.5	12	3.10×10^{-4}	2.94	0.99
	7.0	12	4.71×10^{-4}	2.95	0.98
Sulfur-modified bituminous	5.5	12	2.28×10^{-6}	3.32	0.98
(50/50 sulfur/bitumen ratio)	6.0	12	2.87×10^{-6}	3.26	0.98
	6.5	12	3.46×10^{-6}	3.27	0.99
	7.0	12	3.62×10^{-6}	3.41	0.99
Rubber-modified bituminous	4.8	12	5.51×10^{-6}	3.20	0.99
(5/95 rubber/bitumen ratio)	5.2	12	2.33×10^{-6}	3.32	0.99
	5.6	12	3.40×10^{-6}	3.32	0.99
	6.0	12	9.70×10^{-6}	3.22	0.98

In these tests at optimum binder content, the use of ethylene vinyl acetate as a binder additive produced the highest fatigue life improvement followed by the use of a 50 percent sulfur additive. Rubber-bitumen mixtures and 20 percent sulfur also gave an improvement in fatigue properties in these tests at some stress levels. Difficulty was experienced in the preparation of fiber-reinforced specimens; this resulted in low densities, high air void contents, and shorter fatigue lives.

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