INVESTIGATION OF FATIGUE FAILURE IN BITUMINOUS BASE MIXES

by

G. W. Maupin, Jr.
Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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Summary

A correlation between the results obtained with the fatigue test and those from the indirect tensile test on two base mixes was attempted in anticipation of the possible use of the latter test to design base mixes for maximum fatigue life. Two base mixes at several asphalt contents were tested at two test temperatures. Flexural fatigue tests and indirect tensile tests were performed for each mix and temperature condition.

Unexpectedly, there was a very poor correlation between the constants of the fatigue equations and the strength and stiffness values from the indirect tensile tests. However, the asphalt content corresponding to the maximum fatigue life agreed generally with the asphalt content corresponding to maximum work in the indirect tensile test. The work computed from the indirect tensile test might be useful in selecting the asphalt content for the maximum fatigue life of base mixes.

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INTRODUCTION

In bituminous pavements, fatigue often necessitates premature rehabilitation and unnecessary expenditures. Repeated bending under wheel loads ultimately causes cracks to develop if the permissible level of strain is exceeded. The strain level depends primarily upon the support strength provided by underlying layers and the stiffness of the bituminous concrete. The latter, in turn, is dependent on the temperature, loading rate, and properties of the bituminous mixture such as void content, asphalt content, and aggregate type. Therefore, it is obvious that predicting fatigue life is very difficult. Many of the factors mentioned have been investigated in the laboratory using a variety of testing equipment and specimens of various geometries. Beam specimens[1,2,3], circular plate specimens,[4] trapezoidal specimens,[5,6] and cylindrical specimens have been used under several types of fatigue tests.

Because of the stochastic nature of fatigue test results, from 8 to 10 specimens usually have to be tested at various levels of stress to adequately define the fatigue behavior of a bituminous mix. The lengthy time period required to test 8 or 10 specimens prohibits fatigue testing on a routine basis; however, a great deal of general knowledge has been gained from research on the effects of factors such as asphalt content and void content. Routine testing would require a simple and quick test method that could be performed as part of the routine design procedure.

A recent investigation of surface mixes by the author established a correlation between results of fatigue tests and those of the relatively simple indirect tensile test.[3] On the basis of the correlation, it was recommended that the indirect tensile test be used to obtain relative fatigue properties of bituminous mixes. Although the method, which is empirical, will not yield absolute fatigue values, the relative fatigue values are useful for mix design. In the investigation cited, tests were made on surface mixes having a 1 in. (25 mm) top size aggregate; however, since base mixes, with a larger top size aggregate of 1 1/2 in. (38 mm), also were known to experience fatigue failures, the research was extended to develop a testing procedure for these mixes.

PURPOSE AND SCOPE

The purpose of the investigation was to correlate the results of fatigue tests with those of indirect tensile tests on base mixes, in anticipation of the possible use of the indirect tensile test to design for maximum fatigue life.

Two base mixes at high, medium, and low asphalt contents were tested in the laboratory at two test temperatures. Tests were extended to include a very low asphalt content for one of the mixes, because of the abnormal high strengths and fatigue lives obtained at the low asphalt content.

GENERAL APPROACH

It was desirable to utilize mix designs and test temperatures that would provide a broad range of strength and stiffness values; therefore, aggregate source, asphalt content, and testing temperature were varied.

Fatigue tests were performed for each variable, and basic fatigue relations were obtained in the form

$$N_f = K_1 \ (1/\sigma)^{n_1}, \text{ and} \quad (1)$$

$$N_f = K_2 \ (1/\varepsilon)^{n_2}, \quad (2)$$

where

N_f = number of cycles to failure;

σ = maximum applied stress, psi (Pa);

ε = applied tensile strain, in./in. (mm/mm); and

K_1, K_2, n_1, n_2 = constants.

Indirect tensile tests were performed on each mix at each test condition. An attempt was then made to correlate the constants K_1, K_2, n_1, and n_2 to indirect tensile test results.

LABORATORY PROCEDURE

Materials

The sources of aggregates and the mix gradations are listed in Tables 1 and 2, respectively. Limestone aggregate was used in mix no. 1 and basaltic greenstone in mix no. 2. The asphalt cement was an AC-20 manufactured by Exxon.

Table 1. Sources of Aggregates

Mix No.	Type	Percentage by weight	Source
1	#357	15	Augusta Stone - Staunton, Va.
	# 57	40	Augusta Stone - Staunton, Va.
	# 10	45	Augusta Stone - Staunton, Va.
2	#357	25	Moore Brothers Co. - Linden, Va.
	# 68	25	Moore Brothers Co. - Linden, Va.
	# 10	50	Moore Brothers Co. - Linden, Va.

Table 2. Mix Designs

	Percentage Passing	
Sieve	Mix No. 1	Mix No. 2
1 1/2	100	100
3/4	78	82
#4	43	38
#8	28.5	28
#200	4.0	4.5
Percent asphalt by weight of total mix	4.5	4.5

Fatigue Testing

Constant stress fatigue tests were performed on 3 in. (76 mm) x 3 in. (76 mm) x 15 in. (381 mm) sawed beam specimens. The beams were prepared according to ASTM Designation D 3202-73; however, the compactive effort was modified to yield a void content similar to that obtained in field construction.

An electrohydraulic, closed loop test system was used to apply repetitions on third point loading to the simply supported beams. The haversine loads were of 0.1-second duration separated by a 0.4-second rest period. A negative load was applied during the rest period to return the beam to its original position. Collapse of the beam was defined as failure.

The stress, strain, and stiffness were computed as

$$\sigma = \frac{Mt}{2I},$$

$$\varepsilon = \frac{12td}{3l^2 - 4a^2}, \text{ and}$$

$$E = \frac{Pa\ (3l^2 - 4a^2)}{48\ Id},$$

where

σ = tensile stress, psi (Pa);
ε = tensile strain, in./in. (mm/mm);
E = flexural stiffness, psi (Pa);
P = applied load, lb. (N);
M = bending moment, in.·lb. (m·N);
I = beam moment of inertia, in.^{4} (m^4);
t = depth of beam, in. (m);
d = centerline deflection at neutral axis, in. (m);
l = length between centerlines of end supports, in. (m); a
a = distance between centerline of end support and nearest third point load, in. (m).

A linear variable differential transformer (LVDT) attached to the neutral axis of the beam at midspan was used to monitor the deflection, d, and the flexural stiffness was calculated from the load and deflection recorded at 200-300 cycles. The tests were performed at 72°F. (22°C) and 55°F. (13°C) in a temperature-controlled cabinet.

Indirect Tensile Tests

The primary difference in indirect tensile tests for base mixes as compared to surface mixes was the requirement for a larger diameter specimen to accommodate the larger aggregate. While the study of surface mixes utilized 4-in. (100-mm) diameter test specimens, 6-in. (150-mm) diameter specimens were used for the base mixes on the assumption that the diameter needed to be 4 times the maximum aggregate size.

The indirect tensile test was performed by the procedure reported by Anagnos and Kennedy[7] using cylindrical specimens 3.75 in. (95.2 mm) thick x 6 in. (152 mm) in diameter. The specimens were constructed with a mechanical drop hammer with a 22-lb. (10-kg) weight dropped 18 in. (457 mm) for the required number of blows to duplicate the density of the corresponding beam. Curved loading strips 0.75 in. (19 mm) wide with a 3.0-in. (76-mm) radius were used. The radial deformation was measured perpendicular to the direction of loading with two LVDTs and recorded with a visicorder oscillograph.

The load was applied at a vertical deformation rate of 2 in. (51 mm) per minute with an automatic recording Marshall stability testing device that recorded the load and vertical deformation. The tensile strength and stiffness were computed as

$$\sigma = \frac{.104\ P}{t}, \text{ and}$$

$$E = \frac{P}{xt}\,[0.2699 + 0.977\nu],$$

where

σ = indirect tensile strength, psi (Pa);
E = indirect tensile stiffness, psi (Pa);
P = load, lb. (N);
t = thickness of specimen, in. (m);
x = horizontal deformation, in. (m);
ν = Poisson's ratio $= \frac{0.318\ DR - 4.207}{-1.175\ DR - 0.167}$; and
DR = ratio of vertical to horizontal deformation.

The "work" involved in testing a specimen was also computed for possible correlation with the fatigue results. Work was defined as the area under the load-vertical deformation curve as shown in Figure 1.

RESULTS

Fatigue Tests

The stress-fatigue life curves for each mix tested at 55°F. (13°C) and 72°F. (22°C) are illustrated in Figures 2 and 3.

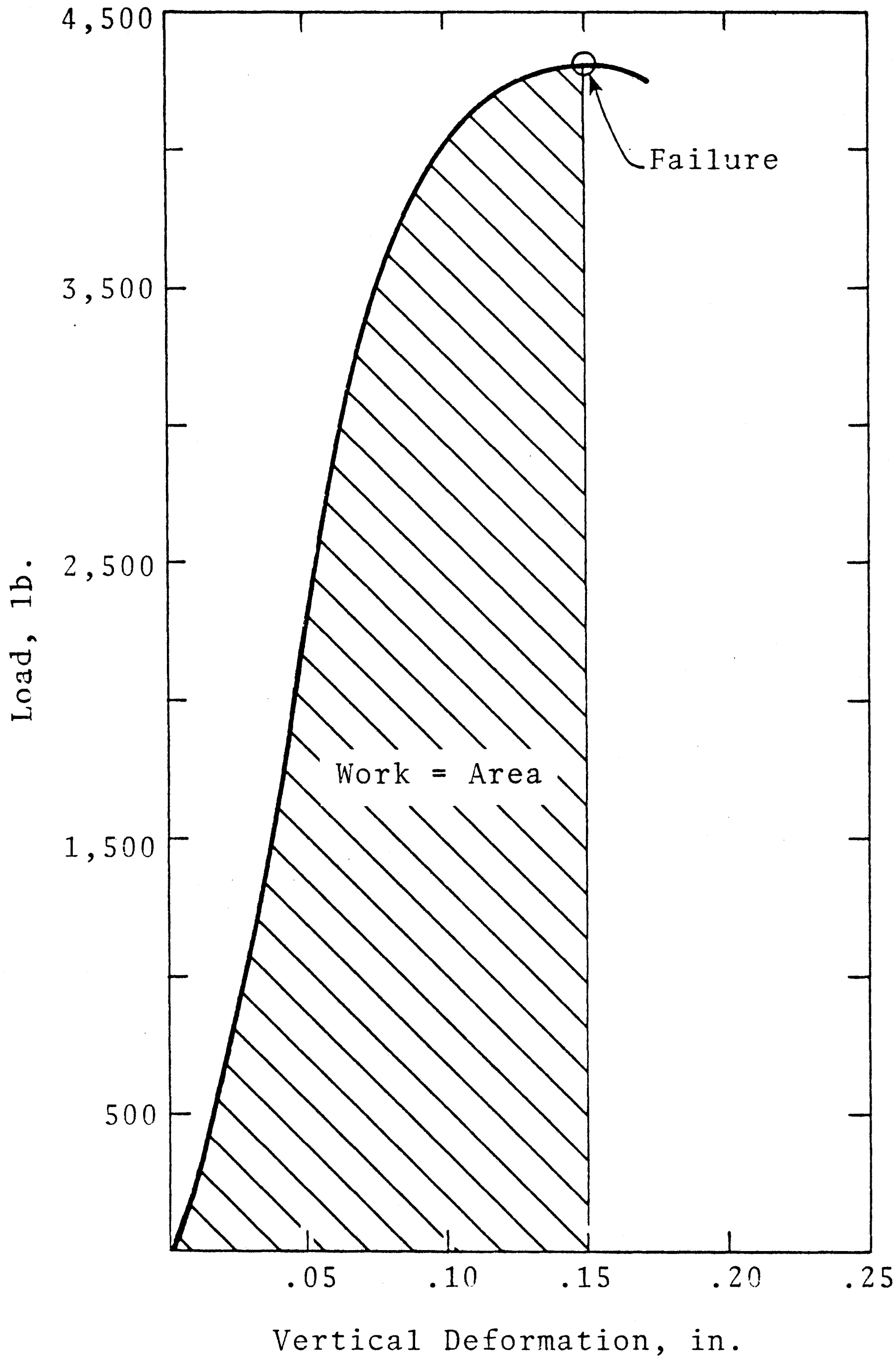

Figure 1. Indirect tensile test "work",
1 lb. = 4.45 N; 1 in. = .0254 m.

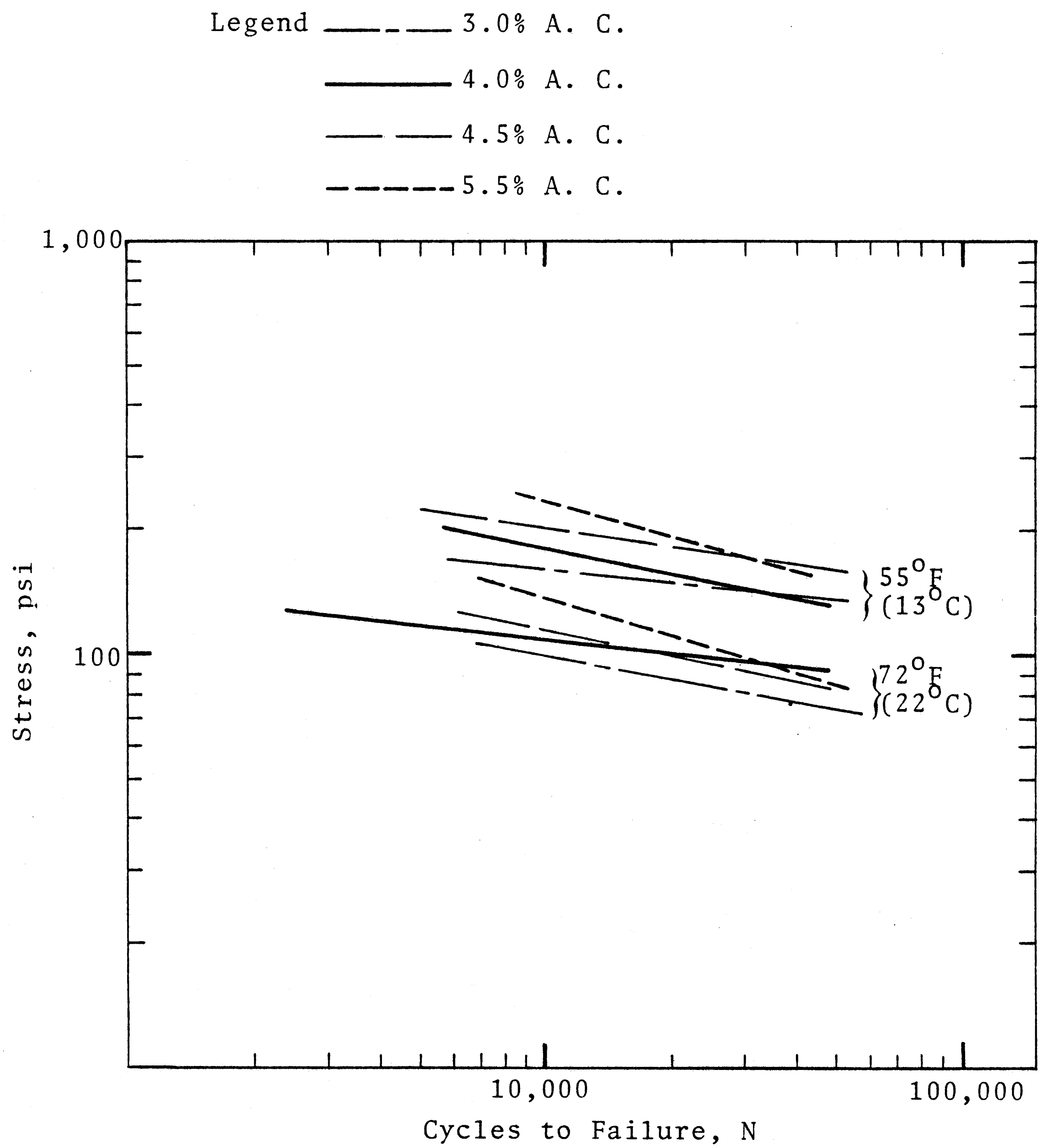

Figure 2. Stress vs. cycles to failure for mix no. 1.
1 psi = 6.89 kPa

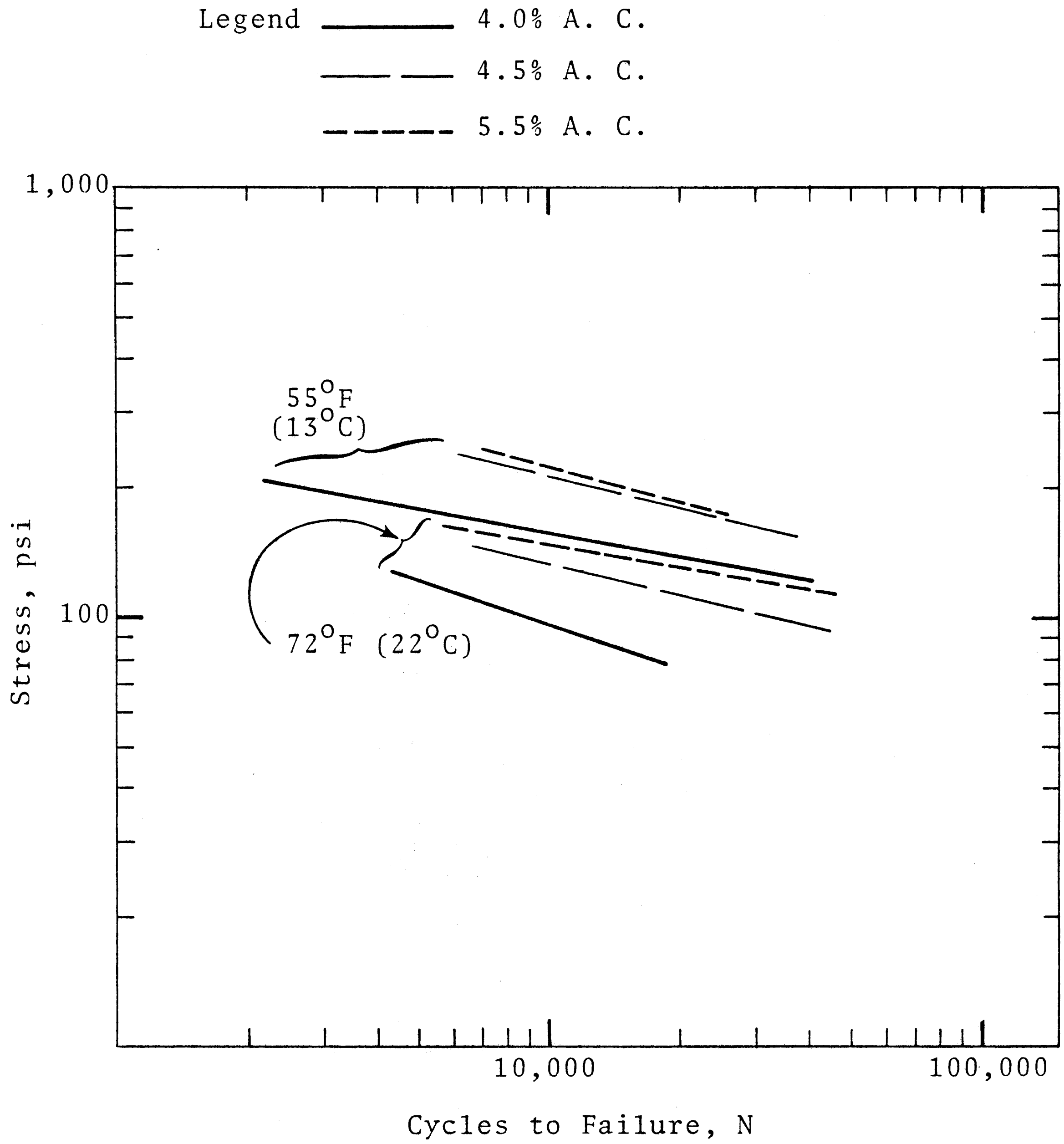

Figure 3. Stress vs. cycles to failure for mix no. 2.
1 psi = 6.89 kPa

There it can be observed that at a given stress level, a longer fatigue life was obtained for both mixes at the lower temperature because of the increased flexural stiffness. There was not a significant difference in the fatigue curves for mix no. 1 at various asphalt contents; however, the asphalt content did appear to affect the fatigue life of mix no. 2. For this mix, a low asphalt content resulted in a lower fatigue life than did the medium and high asphalt contents. Figure 4 illustrates the overlap of results at 72°F. (22°C) for high and low asphalt contents for mix no. 2, and Figure 5 demonstrates a similar overlap of the results for low and medium asphalt contents for mix no. 2 tested at 55°F. (13°C). The inherent variability of fatigue results demonstrates that fatigue curves must be widely separated to be considered different at a high level of significance. An analysis revealed that the apparent differences in the fatigue curves for mix no. 2 at various asphalt contents were not significant at a 95% confidence level.

Table 3 lists the constants, K and n, of the fatigue curves obtained by regression analysis. There were good correlations between the intercept, K, and slope, n, of both the stress and strain fatigue curves.

To ensure that the fatigue tests were performed properly and that the equipment was functioning properly, a control specimen made from a mix that had been tested in a previous study[3] was tested concurrently with each group of test specimens. A regression of the stress fatigue curve was obtained on the fatigue results for the control specimens and compared to the regression obtained for the same mix in the previous study. There was not a significant difference between the control regression, $N = 1.4 \times 10^{18} (1/\sigma)^{6.1}$, and the previous regression, $N = 1.0 \times 10^{17} (1/\sigma)^{5.9}$; therefore, proper testing procedure and equipment performance were confirmed.

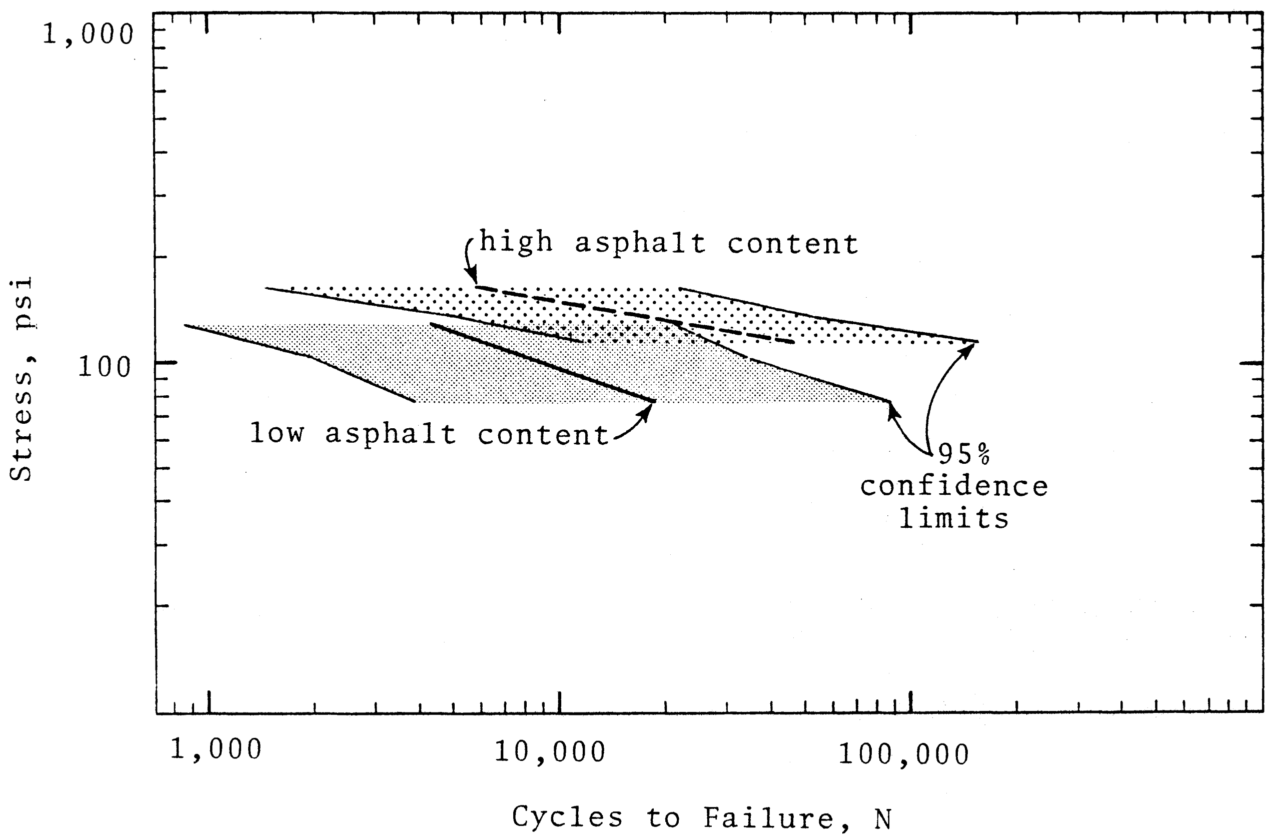

Figure 4. Overlap of fatigue results of mix no. 2 at 72°F (22°C).
1 psi = 6.89 kPa

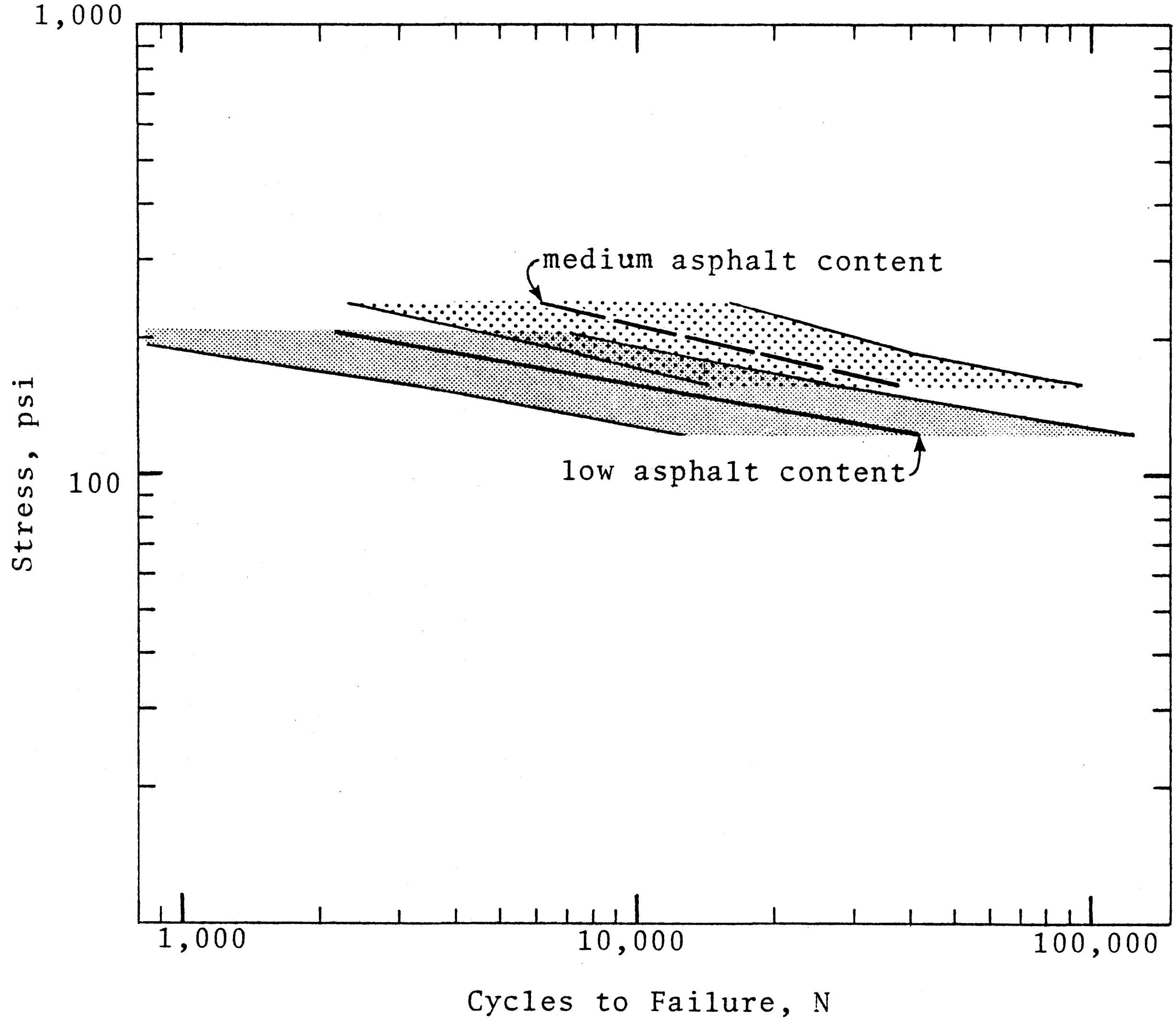

Figure 5. Overlap of fatigue results of mix no. 2 at 55°F (13°C).
1 psi = 6.89 kPa

Table 3. Fatigue Relationships.

Mix No.	Asphalt Content, percent	Test Temp., °F	$N = K_1 (1/\sigma)^{n_1}$		$N = K_2 (1/\varepsilon)^{n_2}$	
			K_1	n_1	K_2	n_2
1	3.0	72	1.920×10^{14}	5.14	1.032×10^{-5}	2.72
1	4.0	72	1.188×10^{22}	8.86	5.414×10^{-8}	3.56
1	4.5	72	1.450×10^{14}	4.92	3.096×10^{-6}	3.03
1	5.5	72	2.321×10^{11}	3.46	5.279×10^{-4}	2.45
1	3.0	55	1.190×10^{26}	10.00	1.851×10^{-8}	3.41
1	4.0	55	1.298×10^{15}	4.93	9.239×10^{-11}	4.20
1	4.5	55	3.232×10^{20}	7.17	9.263×10^{-6}	2.74
1	5.5	55	8.893×10^{12}	3.79	2.431×10^{-3}	2.06
2	4.0	72	3.867×10^{9}	2.82	1.099×10^{-5}	2.83
2	4.5	72	4.790×10^{12}	4.08	1.697×10^{-3}	2.18
2	5.5	72	4.798×10^{16}	5.86	3.120×10^{-7}	3.45
2	4.0	55	4.695×10^{15}	5.31	6.068×10^{-10}	3.97
2	4.5	55	8.169×10^{13}	4.25	4.407×10^{-4}	2.27
2	5.5	55	2.195×10^{12}	3.55	6.745×10^{-7}	3.16

Indirect Tensile Tests

The results of the indirect tensile tests are listed in Table 4. As expected, the strength and stiffness values were greater at 55°F. (13°C) than at 72°F. (22°C). The influence of asphalt content on the strength is illustrated in Figures 6 and 7. Mix no. 2 displayed distinct optimum strength-asphalt content curves with the maximum strength values occurring at 4.5% asphalt content. There were significant differences between the average values at each asphalt content for both the 55°F. (13°C) and 72°F. (22°C) curves when evaluated by the t test at the 95% confidence level. Therefore, the curves are truly optimum type curves and do not represent chance occurrences. Mix no. 1 displayed a decrease of values as asphalt content was increased from 3.0% to 5.5% at the 72°F. (22°C) test temperature.

Figures 8 and 9 illustrate that for mix no. 2 there was an optimum asphalt content for the ultimate stiffness. The curves for mix no. 1 repeat the previously noted trend of decreasing values with increases in the asphalt content.

The plots of work versus asphalt content in Figures 10 and 11 reveal optimum curves for both mixes at 55°F. (13°C); however, the curves at 72°F. (22°C) do not demonstrate optimum work - optimum asphalt content characteristics. Mix no. 2 was more sensitive to changes in asphalt content than mix no. 1, especially below the 4.5% design value. A 0.5% decrease in the asphalt content resulted in a significant reduction in strength and stiffness for mix no. 2, but in only a very slight change for mix no. 1.

Table 4. Indirect Tensile Test Results

Mix No.	Asphalt Content, percent	Test Temp., °F	Indirect Tensile Strength, psi	Vertical Failure Deformation, in.	Horizontal Failure Deformation, in.	Work *, lb x in.	Ultimate Stiffness psi
1	3.0	72	113	.105	.037	274	35,900
1	4.0	72	94	.092	.012	210	34,000
1	4.5	72	94	.105	.030	208	30,400
1	5.5	72	85	.104	.042	218	27,400
1	3.0	55	178	.117	.033	444	51,300
1	4.0	55	193	.127	.036	555	49,500
1	4.5	55	183	.133	.031	535	46,300
1	5.5	55	158	.143	.037	480	39,600
2	4.0	72	69	.119	.014	216	19,400
2	4.5	72	98	.112	.015	268	29,600
2	5.5	72	85	.149	.013	278	18,300
2	4.0	55	120	.163	.030	488	25,300
2	4.5	55	183	.144	.032	590	43,400
2	5.5	55	160	.154	.029	585	34,800

Note: Metric equivalents are: °C = 5/9 (F° - 32); 1 psi = 6,890 Pa; 1 in. = 25.4 mm; 1 lb x in = 0.113 N x m.

*Work = Area under force-vertical deformation curve

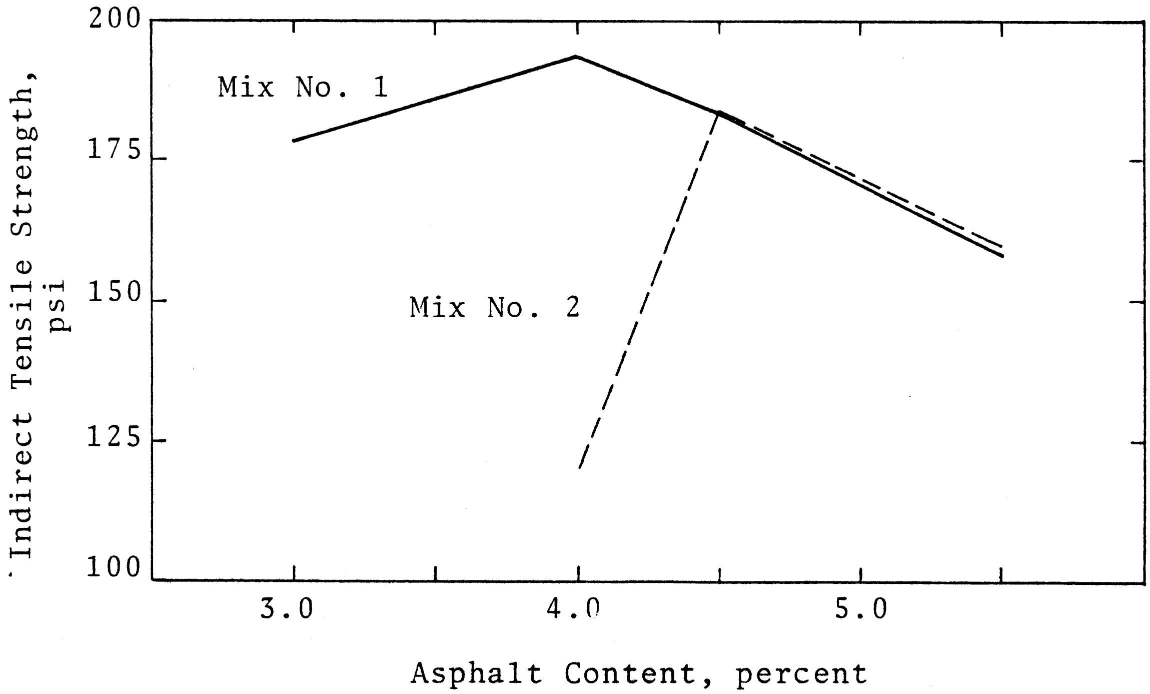

Figure 6. Indirect tensile strength at 55°F. (13°C) vs. asphalt content. 1 psi = 6.89 kPa.

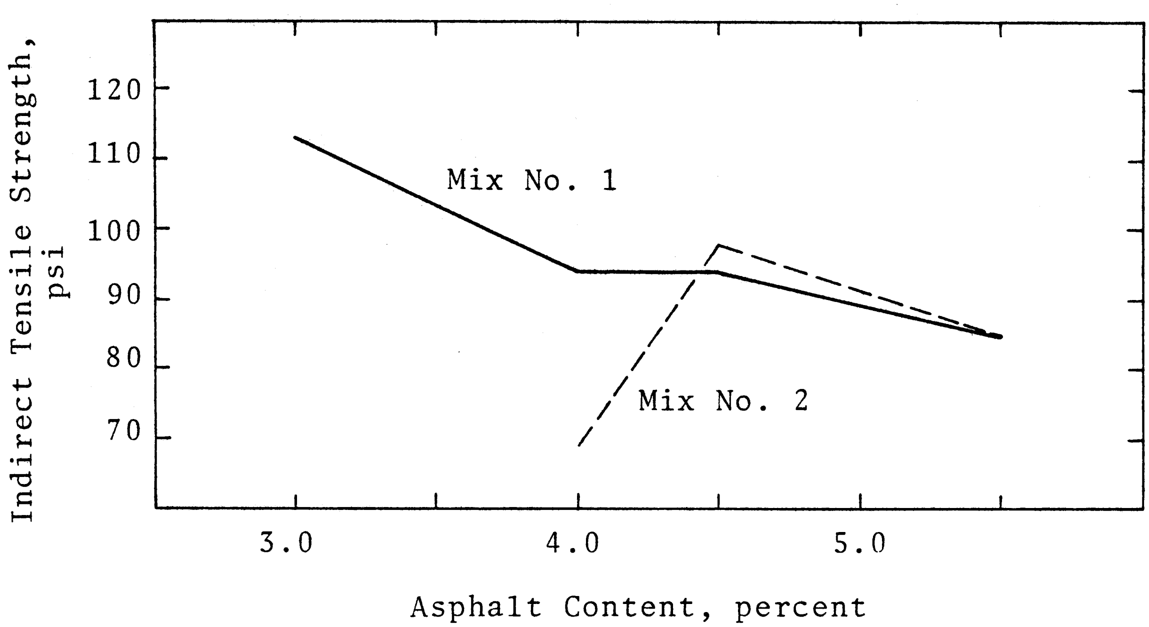

Figure 7. Indirect tensile strength at 72°F. (22°C) vs. asphalt content. 1 psi = 6.89 kPa.

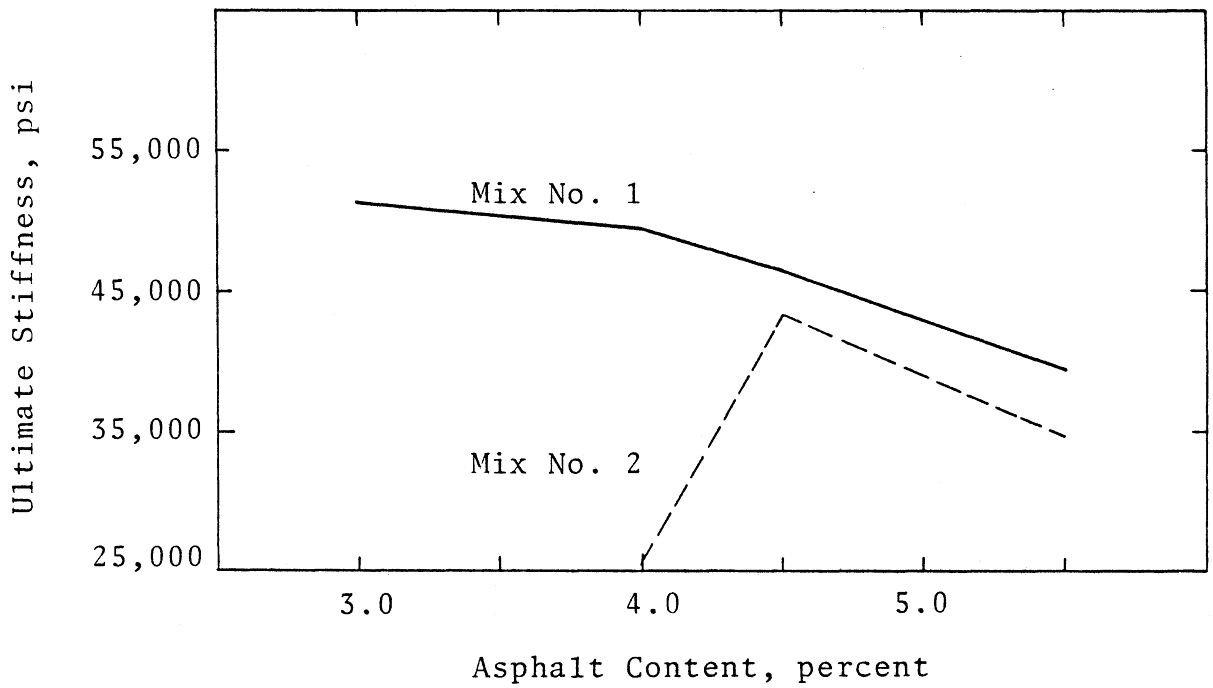

Figure 8. Ultimate stiffness at 55°F. (13°C) vs. asphalt content. 1 psi = 6.89 kPa.

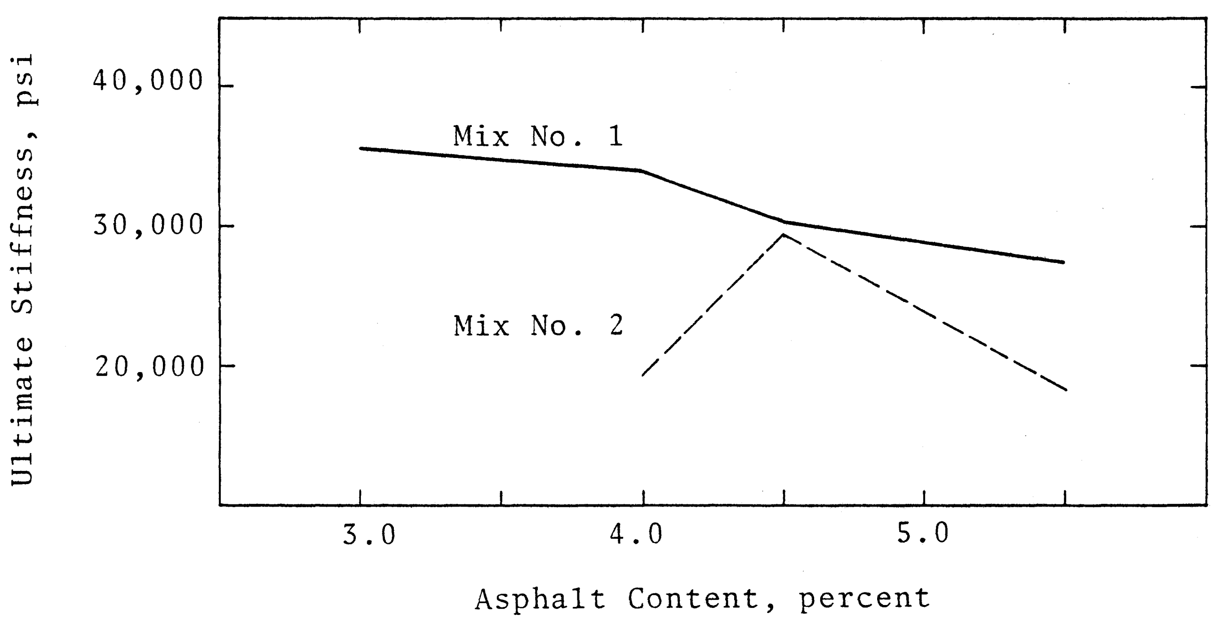

Figure 9. Ultimate stiffness at 72°F. (22°C) vs. asphalt content. 1 psi = 6.89 kPa.

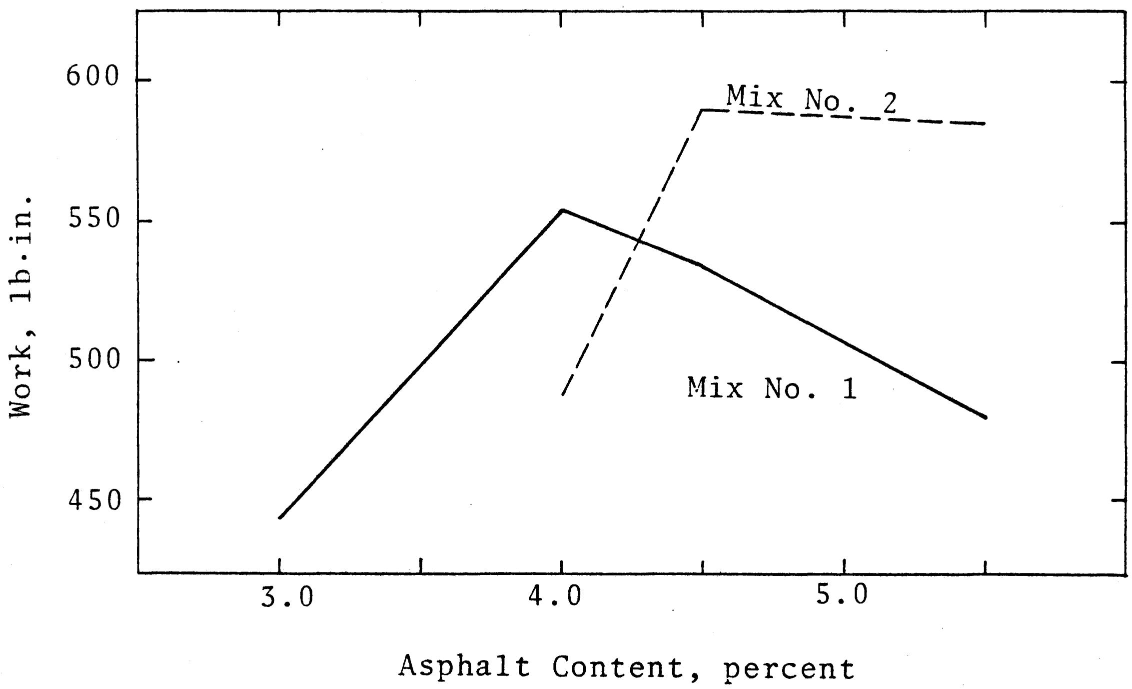

Figure 10. Indirect tensile test "work" at 55°F. (13°C) vs. asphalt content.
1 lb·in = 0.113 Nm

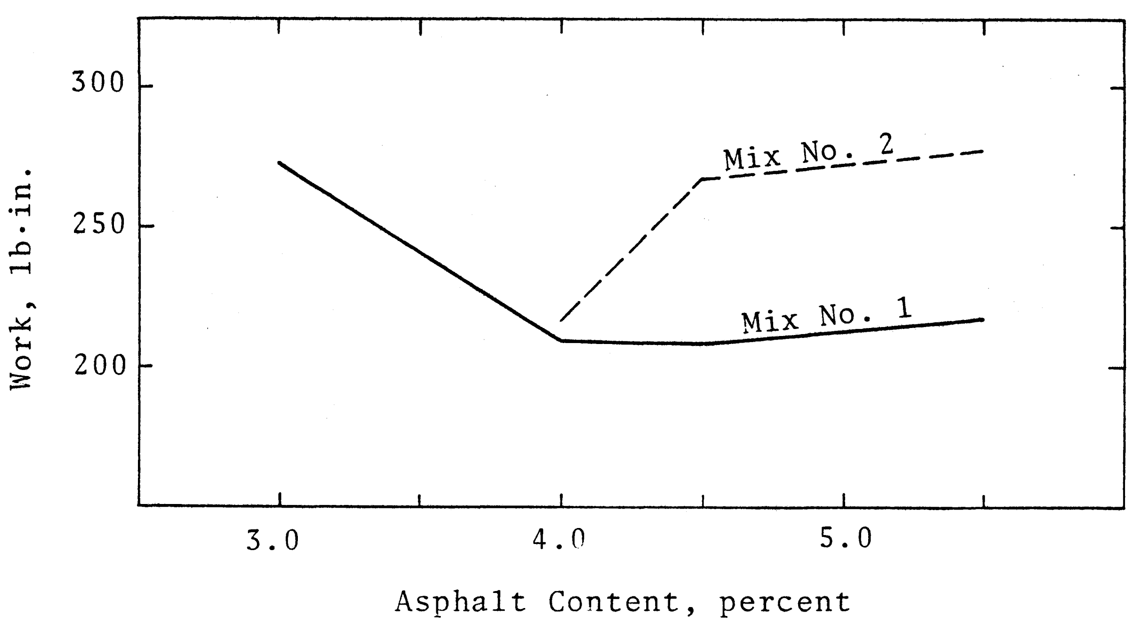

Figure 11. Indirect tensile test "work" at 72°F. (22°C) vs. asphalt content.
1 lb·in = 0.113 Nm

CORRELATION OF FATIGUE TEST AND INDIRECT TENSILE TEST RESULTS

The primary objective of the investigation was to correlate the results of the indirect tensile tests with the fatigue curves. In the previously cited study in which surface mixes were used, correlations were developed that permitted the constant stress-fatigue equations to be estimated from the indirect tensile strength and stiffness.(3) A similar correlation was attempted in the present study, but a poor one was obtained.

The strength, stiffness, and work plots were then compared with the fatigue curves to determine if the optimum asphalt content, i.e., the asphalt content corresponding to a maximum value of these mix characteristics, corresponded to maximum fatigue life.

As already discussed, under Indirect Tensile Tests, some of the plots, particularly those for mix no. 1, did not yield a convex optimum type curve; therefore, the optimum asphalt content was defined as that yielding the maximum value. Table 5 lists the optimum asphalt contents from the strength, stiffness and work curves and the asphalt contents yielding the maximum fatigue life at the 80-psi (550-kPa) stress level. There was good agreement between the optimum asphalt contents from the work curves and the asphalt contents yielding maximum fatigue life for mix no. 2. Although there was not exact agreement between the optimum asphalt contents for the work and fatigue curves of mix no. 1, there was general agreement that the optimum was 4.0% or less. One difficulty with attempting to correlate the results for mix no. 2 was the lack of a significant difference between the fatigue curves at various asphalt contents. Fatigue life did not appear to be influenced significantly by changes in asphalt content for mix no. 1. This behavior was probably caused by the surface texture, angularity and packing characteristics of the limestone. The asphalt content yielding maximum fatigue life corresponds to the optimum asphalt content of the work curves better than do the optimum asphalt contents of the strength and stiffness curves. Although the correlation was less than desired, the work curves might suffice as a guide for determining the optimum asphalt content for maximum fatigue life.

Table 5. Optimum Asphalt Contents

Mix No.	Test Temp., °F	Optimum Asphalt Content, percent			Asphalt Content Yielding Maximum Fatigue Life at 80 psi, percent
		Strength	Stiffness	Work	
1	72	3.0	3.0	3.0	4.0
1	55	4.0	3.0	4.0	3.0
2	72	4.5	4.5	5.5	5.5
2	55	4.5	4.5	4.5	4.5

Deg. C = 5/9 (°F-32)

1 psi = 6894 Pa

CONCLUSIONS

1. There was no direct correlation between the results from the indirect tensile tests and the fatigue curves.

2. The optimum asphalt content-work curves might be useful as a guide for determining the asphalt content for maximum fatigue life.

3. The limestone mix (mix no. 1) was not sensitive to changes in asphalt content.

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