Fatigue Characteristics of Alaskan Pavement Mixes

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Mechanistic analysis procedures for pavement evaluation have been simplified with recent development in microcomputers. These procedures require pavement fatigue models to make them useful for evaluation of pavement life. Although numerous models exist, their applicability to cold climates requires further investigation. The purpose of this study was to determine the applicability of existing fatigue models in Alaska, determine if different asphalt concrete mixes used in Alaska differed in performance, and determine whether laboratory-prepared samples perform differently than field-compacted samples. Testing consisted of three-point bending tests with temperatures ranging from 80°F to −15°F. A materials testing system modified for the test procedure was used with computerized data acquisition systems. All tests were displacement controlled. None of the existing fatigue relationships were adequate. As a result, a new equation was developed that better fits AC-2.5 and AC-5 at temperatures below 45°F. This equation is much more sensitive to strain than the Asphalt Institute equations. AC-2.5 and AC-5 performed similarly at temperatures below 20°F. At temperatures as low as −15°F, no difference in performance was noted. Laboratory-prepared samples and field samples showed equivalent performance. The data indicated a difference between the time at which the maximum load occurred and the time at which the maximum strain occurred. This difference, or phase lag, was greatest at the beginning of the test and almost in phase at the end of the test. This phenomenon should be explored further, because it may provide a method of determining remaining life.

Application of state-of-the-art mechanistic analysis procedures to pavement design and evaluation have been simplified with developments in microcomputers. These procedures are based on fundamental engineering principles that require a knowledge of material response parameters. The approach is often used for estimating remaining life for existing pavements and expected life of new pavements, based on fatigue concepts. A number of sources of fatigue relationships for asphalt concrete (AC) are available (*1–6*). However, it is not clear if these relationships are applicable in Alaska during low-temperature periods. This project investigated the applicability of typical fatigue relationships to the pavement design process in Alaska. The project also investigated whether laboratory-compacted samples provided similar fatigue results to field-compacted samples. The generated fatigue equations have been compared with the relationship developed by the Asphalt Institute (AI) because this relationship is widely used.

Preliminary analyses were performed on the generated data in terms of simplistic energy or work approaches to fatigue in asphalt concrete. On the basis of limited data from these initial analyses, this approach holds promise for future development.

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TESTING EQUIPMENT AND PROGRAM

A modified material testing system (MTS) universal testing machine was used to perform the cyclic loading tests. A load application system was developed to use with the MTS load frame to apply third-point bending to beam specimens. Environmental control chamber dimensions restricted specimen size to 2 × 2 × 15 in.

The basic equipment consisted of a model 810 MTS system, with a model 413 master control panel, 442 controller, and 410 digital function generator. A trigger generator acting as gate to the MTS function generator produced the load pulse—a 0.1-sec haversine load cycle with a 0.9-sec rest period. The relaxation period of 0.9 sec was chosen to ensure that full recovery was achieved by the material between applied loads. Loads were applied in the typical third-point loading used for this type of test, ensuring a constant bending moment over the middle third of the beam. Tests were run in a displacement control mode using a displacement gauge to monitor center deflections of the beam. This information provided feedback for the MTS load system control. Loads were measured using a 5,000-lb load cell. Strains were measured directly using an extensometer attached to the beam with adhesive. Stresses were calculated from load, deflection, and beam dimensions using beam theory. Modulus was calculated from computed stress and measured strain.

During testing, strain was measured only in the tension region of the beam. Initial tests using two extensometers to measure strains on both sides of the beam confirmed that the system was functioning adequately. Stresses based on these measurements were compared with theoretical calculations, as plotted in Figure 1, and show good agreement, with minor errors developing mainly in the failure zone at approximately 375 psi. Additional assumptions were checked during this phase. Calculated modulus, plotted against stress level, remained relatively insensitive to stress level for most of the stress range. As expected, major deviations occurred during failure. Variations also occurred in the calculated modulus at the low end of the stress scale because of a number of factors, including load system friction.

Load, deflection, and strain measurements were monitored and recorded using a Hewlett-Packard HP85 microcomputer and HP7090A measurement plotting system, or recording plotter. This plotter can monitor three channels at one time

and has the ability to record, digitize, and store approximately 1,000 data points per channel per scan. The computer was programmed to scan and record a 4-sec window, covering the 0.1-sec load pulse plus 0.9-sec rest period, at specified load strokes throughout a test sequence.

Strokes for recording were closely spaced initially, but the intervals increased as the test progressed. The HP85 recorded a complete digitized record for each specified stroke on magnetic tape. The data were then transferred to a microcomputer diskette. Data can be plotted directly by the recording plotter or computer. Resolution as shown in Figure 2 is excellent, but is affected by the base length of the record, because the points sampled remain constant at 1,000.

The time lag between load and response peaks, shown in Figure 2, is an interesting feature of the test record. A lag is not unexpected because of the viscoelastic nature of the AC being tested, a factor observed by other researchers. The time lag decreases as damage accumulates until load and response are in phase at failure. This finding may be useful for determining condition of in-service pavement materials in terms of total accumulated damage, and for estimating remaining life.

Testing included two grades of asphalt cement, AC-5.0 and AC-2.5, which are commonly used in Alaska. The range of temperatures focused on lower temperatures to provide information for the Alaskan pavement design process. The program involved tests under the conditions presented in Table 1.

The intent of this program was to

- Determine if typical existing fatigue equations are applicable at low temperatures, and if not, to develop such equations.
- Determine if typical AC mixes used in Alaska perform significantly differently at low temperatures.
- Determine if laboratory prepared samples perform differently than field-compacted samples.

Originally, the intended minimum temperature was −40°F for the project. The maximum that could be achieved within the project budget was −15°F. However, the −15°F appears to be adequate, because the data collected seemed to indicate that both AC-5.0 and AC-2.5 mixes behave similarly below about 20°F.

An axial extensometer, a displacement gauge, and a thermocouple were used with test specimens. The extensometer,

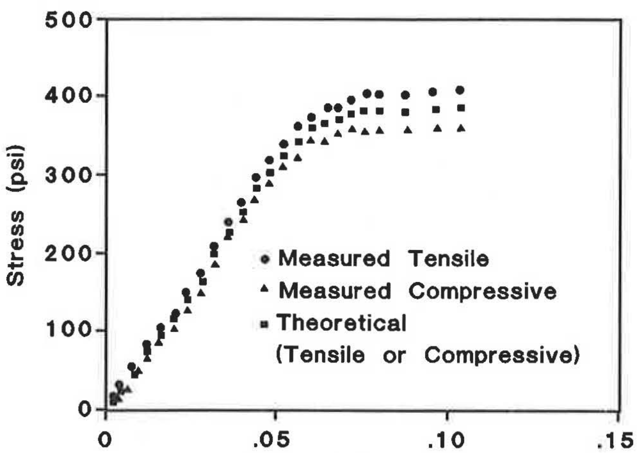

FIGURE 1 Comparison of measured (computed) and theoretical stresses.

TABLE 1 TEST PROGRAM

Temperature (°F)	Asphalt Grade AC 5.0	AC 2.5
80	Field samples	Field samples
40	Field and lab samples	Field samples
20	Field samples	Field and lab samples
10	Field samples	Field samples
-15	Field samples	Field samples

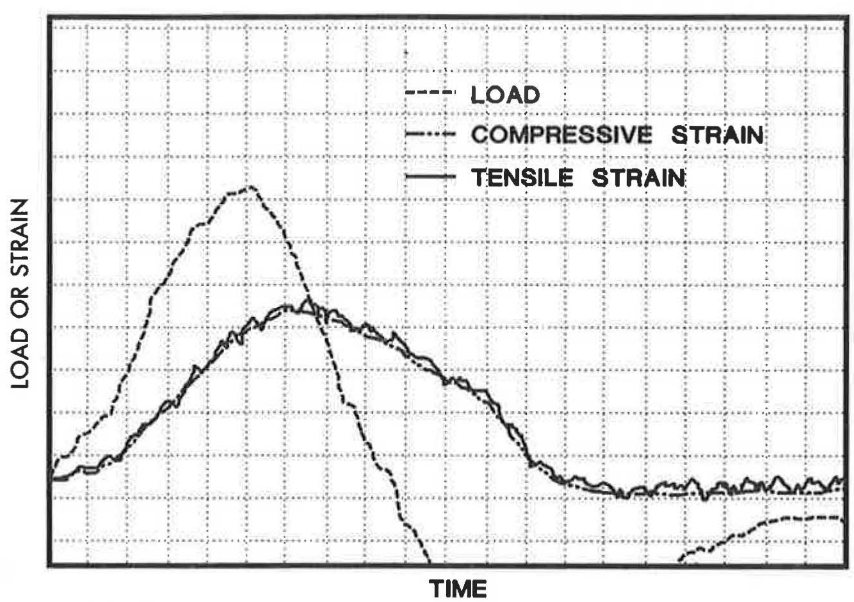

FIGURE 2 Typical data record.

used to measure tensile strain, was affixed with contact cement to the top surface of the specimen. The displacement gauge was used to measure and control the center deflection. Specimen and load frame temperatures were monitored using thermocouples. The cooling equipment was activated, and sufficient time was allowed for the sample and load system to reach thermal equilibrium. At low temperatures, monitoring loads induced by thermal contraction of the steel testing fixture and adjusting the position of the center clamps were necessary. Testing began after the load assembly had reached thermal equilibrium. The system was preprogrammed to deliver a predetermined deflection at the center of the AC once every second.

TEST PROCEDURE

Typical AC samples and materials were collected from Fairbanks and Anchorage. Testing focused on AC-5.0 hot-mix material using Fairbanks Sand and Gravel (FSG) aggregate, and AC-2.5 material using EarthMovers (EM) aggregate. Both field- and laboratory-compacted specimens were tested. Field compaction involved the use of forms at the paving site, into which the job-mix was placed and compacted using rollers. Laboratory compaction involved the use of a Cox kneading compactor and a laboratory duplication of the job-mix specifications, following the ASTM D3202 test procedure. Both laboratory and field samples were sawed into 2- × 2- × 16-in. nominal samples for testing.

Equipment was programmed to record all information in the stroke sequence 1, 11, 30, 62, 126, 254, 510, 1022, 2046, 4094, 8190, 16382, etc. Test data are shown in Figure 3. The load-deflection curves are not produced, but the energy values are listed. These energy or work values are the areas under the load-deflection curves shown, in in.-lb, and are a measure of the work done on the sample during a load pulse. The first curve in Figure 3, or Energy Input (1), is a measure of the work done by the load from the undeflected position to the

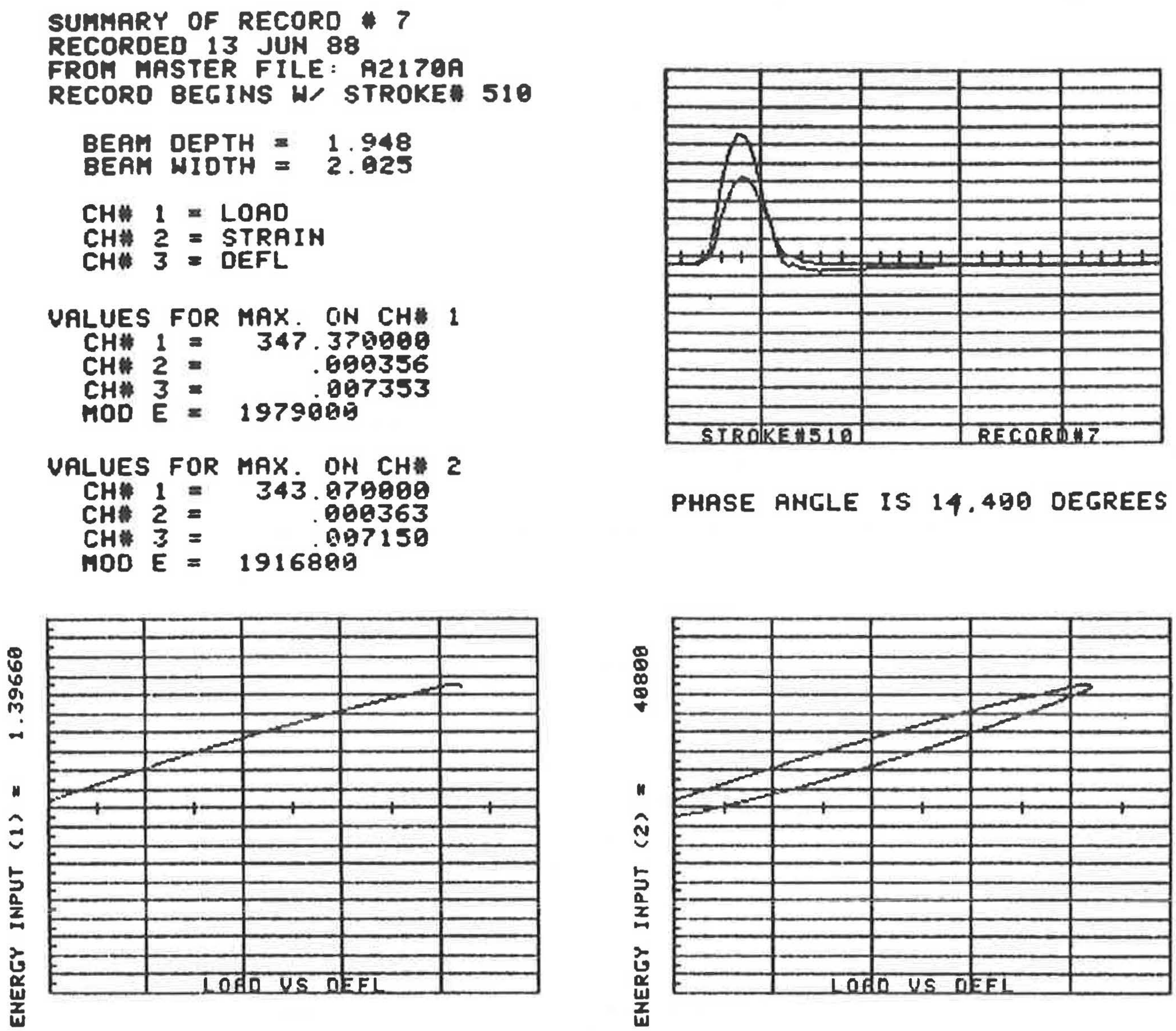

FIGURE 3 Typical reduced load, strain, and deflection data.

point of maximum deflection. Energy Input (2) in Figure 3 is the area within the hysteresis loop, which assumes that the machine provides Energy Input (1). However, the elastic rebound of the sample uses up stored energy to return to its original position. Therefore, only the net work represented by the hysteresis loop area is imparted to the sample during the load cycle. This net work contributes to accumulated damage. This may be the case for AC at low temperatures where the viscous component of the viscoelastic response is minor. A third energy, now shown in Figure 3, was also calculated. The loading arrangement is such that the MTS loading ram applies the desired deflection, and then performs a positive return to the undeflected position. A load cycle of 0.1 sec can allow a significant viscous strain to occur in AC at higher temperatures. As a result, the sample has work performed on it again by the machine positive return stroke in restoring it to the undeflected position. Energy Input (3) is considered to be representative of this situation, and is calculated from the equation Energy 3 = 2 * (Energy 1) − Energy 2. This energy relates to the work done in deforming the beam plus the additional work required to return it to the undeformed shape. For any AC sample, not one of these work estimates would reflect exactly the sample and system interaction. However, they do provide a beginning point to consider the material behavior. Some preliminary analyses indicated good correlation between energy, strain, and the number of cycles to failure.

All essential fatigue data are available, as shown in Figure 3, including measured loads, strains and deflections, and calculated moduli. Two sets of maximum values for load, strain, and deflection are recorded, and these are related to the phase angle.

Because there is a time lag between applied load and resulting strain response, load and strain peaks occur at different times. The two sets of recorded values correspond to these two times. On the basis of behavior of the specimens tested, this time lag, quantified by the phase angle, reduces as damage accumulates. The tests were performed under deflection control, and the required load monitored. Fatigue failure was chosen as the point where the applied load dropped to 50 percent of the initial load required to generate a given strain level. At this point, the phase angle, or time lag, was typically zero (i.e., the load and response peaks occurred at the same time).

This phenomenon warrants additional study to determine if it is possible to estimate the amount of accumulated damage for in-service materials by measuring the time lag between load and response. The data from individual tests provide some insight into material behavior during testing. Figure 4 shows data from an AC-5 mix tested at 20°F. This test illustrates, for instance, that the choice of 50 percent of original load as a failure criterion is reasonable, because rapid damage appears to occur in that region. All three measures of work or energy are shown in Figure 4, and all exhibit similar characteristics to the load curve. Although these tests are referred to as strain control, the control variable is deflection, and some strain variation is typical. The large strain variation in Figure 4, however, is atypical.

DATA ANALYSIS

The experimental data were used to develop fatigue relationships as a function of the number of repetitions, the initial applied strain, and modulus. Figures 5–7 show typical log of initial strain versus log of load repetitions plots developed from the test data. As expected, the plots show relatively consistent linear relationships between log strain and log repetitions for specific temperature ranges. The correlation coefficients for Equations 1–6 (Table 3) support this. Actual data analysis sequence is indicated by the regression equation number sequence shown in Tables 2 and 3. Analysis involved use of a statistics software package for microcomputers to perform multiple linear regression analyses (*7*).

For instance, each of Equations 1–6 (Table 3) considered a set of AC-5 test data at a specific temperature, while Equation 7 (Table 3) combined AC-5 field and laboratory samples with AC-2.5 samples, all at 40°F. This sequential analysis allowed combination of the data sets while determining whether obvious differences exist between data sets. In some cases, decisions were based on visual inspection of plotted data. As an example, a combined plot of the data for Equations 4

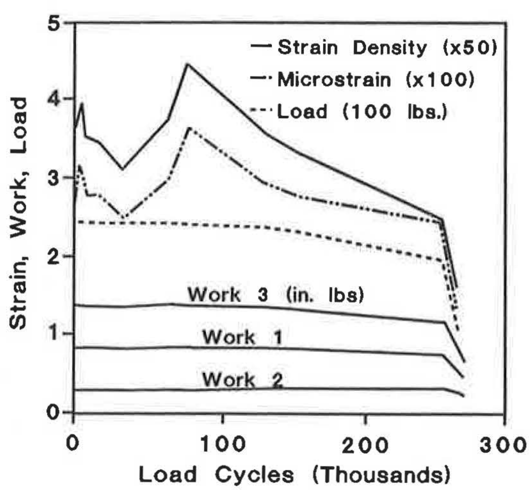

FIGURE 4 Typical data available from specific tests.

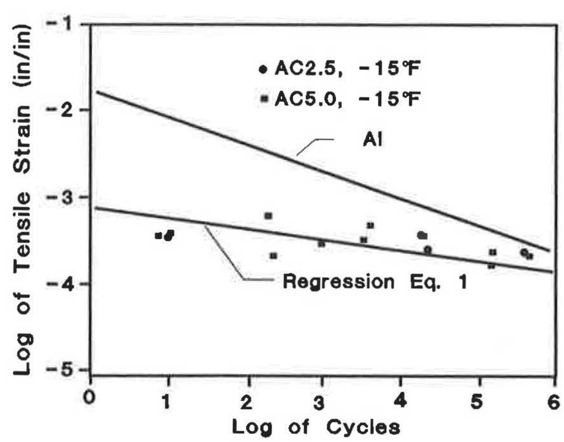

FIGURE 5 Test data for −15°F, showing Regression Equation 1 (Equation 1, Table 3) and the Asphalt Institute equation.

and 5 revealed little or no difference between field- and laboratory-compacted AC-5 samples at 40°F. Further, inclusion of AC-2.5 data at 40°F (i.e., the data used for regression Equation 7, Table 3) indicates that these mixes respond similarly at this temperature, with a correlation coefficient of 0.922 for Equation 7 (Table 3).

The complete analysis sequence provided the following general conclusions:

1. Laboratory- and field-compacted samples responded similarly.
2. Below about 20°F, the AC-5 and AC-2.5 mixes responded similarly.
3. Fatigue behavior below about 20°F is not significantly affected by temperature, which is consistent with the work reported by Salam (*8*).

Two basic relationships are available as current common approaches in the literature (*1–3*):

$$N = a\varepsilon^b \tag{1}$$

$$N = a\varepsilon^b E^c \tag{2}$$

where

N = load repetitions to failure,
ε = tensile horizontal strain resulting from each load application, and
a,b,c = material constants found by regression analysis.

Fifteen combinations of the data were considered. The results are shown in Tables 2 and 3 for Equations 1 and 2, respectively, while the relevant relationships are also plotted on Figures 5–7. The AI equation, which is commonly used for design purposes, has also been plotted for comparison purposes. This equation takes the form

$$N = 18.4C\,(4.32 \times 10^{-3})\ \varepsilon^{-3.29}(E^*)^{-0.854} \tag{3}$$

where

$C = 10^M$,
$M = 4.84\left(\frac{V_b}{V_v + V_b} - 0.69\right)$,
N = number of load repetitions to failure,
ε = tensile strain (in./in.),
E^* = dynamic modulus (psi),
V_v = volume of air voids in mix (%), and
V_b = volume of asphalt cement in mix (%).

For this project, V_v and V_b came from the mix design information. The plots in Figures 5–7 show that, generally, the equations developed for this project tend to have a significantly flatter slope than the comparable AI relationship, and that the estimates are more conservative for low repetitions (less than approximately 1 million) and less conservative at high repetitions. The derived slopes decrease to some extent with temperature and the match with the AI relationship is better at higher temperatures than at lower temperatures. Table 3 indicates generally higher correlation coefficients than Table 2. This is not surprising because Equation 2 includes a modulus term E that is highly correlated with temperature and can thus deal effectively with data sets containing data from tests with widely varying temperature conditions, whereas Equation 1 does not. On the basis of these findings, the equations in Table 2 should be discarded and those in Table 3 retained. Typically, Equations 1 through 15 (Table 3) match the experimental data as shown in Figures 5–7, and from the correlation coefficients in Table 3.

DISCUSSION OF RESULTS

Testing Capabilities

The fatigue testing equipment developed and used for this project hampered, to some extent, the process of data collection. However, at this point, the system is functional, reliable, and capable of producing high-quality data that can provide useful information for application in mechanistic design procedures. A continuing fatigue testing program should be initiated. Of particular interest would be tests on samples from in-service pavements that would allow investigation of aging

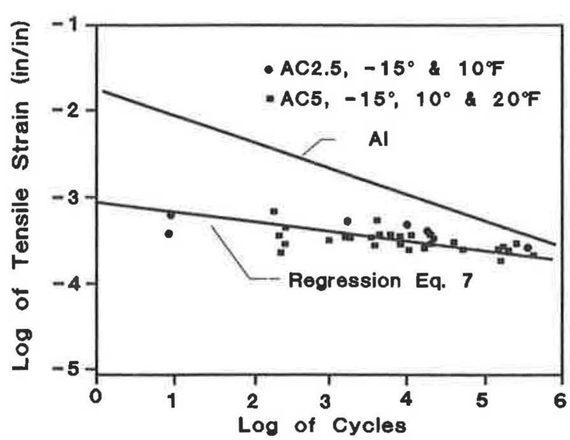

FIGURE 6 Test data for 40°F, showing Regression Equation 7 (Equation 7, Table 3) and the Asphalt Institute equation.

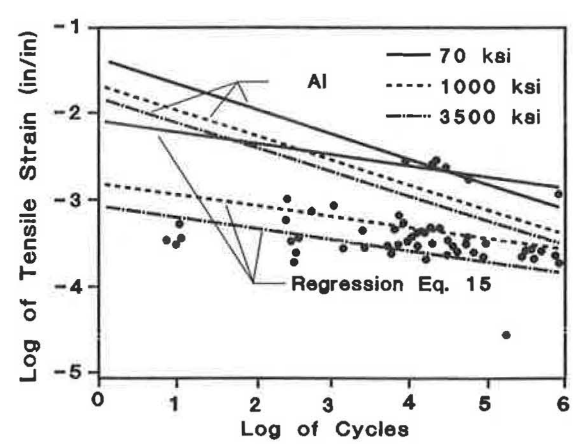

FIGURE 7 All test data, showing Regression Equation 15 (Equation 15, Table 3) and the Asphalt Institute equation.

effects, including the effect of freeze-thaw cycles on pavement materials, as well as those of damage accumulation during service.

Fatigue Analyses

Data were analyzed using statistical regression methods, and a series of regression equations was developed that are presented in Tables 2 and 3. It is recommended that only Table 3 be considered for use in design applications. The simplest approach would be to use Equation 15 (Table 3) as a general equation, i.e.,

$$N = (3.364 \times 10^{6})\ \varepsilon^{-7.370}\ E^{-4.470} \quad (4)$$

where

ε = tensile strain, and
E = modulus (psi).

Equation 4 has the advantage of being based on the largest data sample, but it should be noted that additional verification testing is desirable. There is a difference between the measured data and typical fatigue equations, such as the AI equation, particularly at lower temperatures. A number of factors could contribute to this difference, such as the effect of air voids. The AI equation takes this effect into account, but the values assumed in the AI equation for comparison purposes were design air voids at optimum asphalt content, because no air void measurements were made during the project. Typical measured densities were close to design densities so that the assumption appears reasonable. Inclusion of measured void data could have a significant effect. Also, the fatigue data measured during the project were predominantly at lower temperatures, which is not the case for the AI equation. Further, the project data base of approximately 65 tests was smaller than that for the AI equation, which should thus be generally more reliable than the developed equations. However, for low-temperature analysis, the developed equations may be more applicable, but field verification is necessary. In particular, the shift factor between laboratory and field response needs to be determined and verification at a higher number of load cycles, i.e., in excess of one million cycles or more, would be desirable. It is recommended that Equation 15 be applied only in cases where the resilient modulus of the asphalt concrete exceeds 1,500,000 psi.

Energy or Work Approaches

A few preliminary analyses were performed considering total energy input to (or work done on) the sample. The approach

TABLE 2 REGRESSION EQUATION COEFFICIENTS FOR EQUATION 1

Data	Equation #	a	b	Correlation coefficient	Asphalt Institute a	Asphalt Institute b
AC 5(-15°F)	16	5.741×10^{-16}	-5.333	.555		
AC 5(10°F)	17	7.396×10^{-30}	-9.303	.682	1.480×10^{-6}	-3.29
AC 5(20°F)	18	4.315×10^{-29}	-9.261	.622	1.848×10^{-6}	-3.29
AC 5(40°F)	19	7.367×10^{-10}	-4.004	.890	3.330×10^{-6}	-3.29
AC 5(40°F) (lab)	20	4.909×10^{-12}	-4.623	.951	3.330×10^{-6}	-3.29
AC 5(80°F) AC 5 (40°F - field & lab)	21	5.741×10^{-8}	-4.462	.959	1.585×10^{-5}	-3.29
AC 2.5(40°F) AC 5 (10°F)	22	6.933×10^{-15}	-5.487	.922	3.330×10^{-6}	-3.29
AC 2.5(10°F) AC 5(10°F,20°F)	23	6.353×10^{-18}	-5.977	.679	1.480×10^{-6}	-3.29
AC 5(10°F,20°F)	24	3.508×10^{-23}	-7.507	.576	Varies	-3.29
AC 2.5(10°F) AC 5(-15°F,20°F)	25	1.875×10^{-19}	-6.461	.656	Varies	-3.29
AC 5 (-15°F,10°F,20°F)	26	4.477×10^{-17}	-5.742	.545	Varies	-3.29
AC 2.5(10°F) AC 5(40°F,80°F)	27	1.945×10^{-17}	-5.843	.593	Varies	-3.29
AC 2.5(40°F) AC 5 (20°F,40°F,80°F)	28	1.542×10^{2}	-0.600	.213	Varies	-3.29
AC 2.5 (20°F,40°F)	29	1.535×10^{2}	-0.544	.175	Varies	-3.29
ALL DATA	30	1.271×10^{2}	-0.491	.120	Varies	-3.29

is simple, shows significant promise, and is conceptually appealing from a fundamental material behavior standpoint. It is possible that the idea can be related to bond energy and fracture considerations. From an application point of view, use of work or energy per unit strain in a mechanistic design procedure is no more difficult than the use of strain alone. A correlation between this work or energy approach and some of the existing empirical pavement deflection basin parameter approaches would not be surprising, but is pure conjecture.

SUMMARY AND RECOMMENDATIONS

Flexural fatigue tests were performed at various temperatures on AC beams manufactured from typical Alaskan paving mixtures. Both AC-5 and AC-2.5 mixes were tested at temperatures ranging from −15°F to 80°F. Laboratory- and field-compacted specimens were used.

On the basis of the test data, it was concluded that

1. Laboratory- and field-compacted samples responded similarly in the tests,
2. The AC-5 and AC-2.5 mixes responded similarly below approximately 20°F,
3. Fatigue behavior below approximately 20°F does not appear to be significantly affected by temperature, and
4. The measured fatigue data are different from behavior predicted by typical fatigue equations such as the Asphalt Institute relationship.

A number of fatigue relationships developed from the test data are presented in Tables 2 and 3. It is recommended that Equation 15 in Table 3 be used for low-temperature applications in Alaska, but field verification needs to be carried out. A shift factor may be necessary to calibrate laboratory data to field conditions.

TABLE 3 REGRESSION EQUATION COEFFICIENTS FOR EQUATION 2

Data	Eq. #	a	b	c	Correlation coefficient	The Asphalt Institute a	b	c
AC 5(-15°F)	1	0.7513	-8.215	-3.720	.672	.5893	-3.29	-.854
AC 5(10°F)	2	2.897×10^{12}	-11.343	-7.620	.776			
AC 5(20°F)	3	1.324×10^{17}	-8.085	-6.501	.799			
AC 5(40°F)	4	3.292×10^{3}	-4.577	-2.411	.954			
AC 5(40°F) (lab)	5	9.528×10^{-52}	-5.201	6.324	.951			
AC 5(80°F) AC 5(40°F - field & lab)	6	6.368×10^{-5}	-4.739	-0.783	.961			
AC 2.5(40°F) AC 5(10°F)	7	1.241×10^{-15}	-5.464	0.137	.922			
AC 2.5(10°F) AC 5 (10°F,20°F)	8	6.040×10^{20}	-12.926	-9.792	.825			
AC 5 (10°F,20°F)	9	1.245×10^{19}	-9.131	-7.405	.757			
AC 2.5(10°F) AC 5 (-15°F,20°F)	10	3.006×10^{11}	-10.840	-7.156	.795			
AC 5 (-15°F, 10°F,20°F)	11	11.53	-8.673	-4.312	.714			
AC 2.5(10°F) AC 5 (40°F,80°F)	12	12.71	-9.015	-4.520	.730			
AC 2.5(40°F) AC 5 (20°F,40°F, 80°F)	13	6.565×10^{6}	-5.764	-3.640	.905			
AC 2.5 (20°F,40°F)	14	2.152×10^{6}	-6.047	-3.700	.866			
ALL DATA	15	3.364×10^{6}	-7.370	-4.470	.703			

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