Development of Fatigue Failure Criterion for Hot-Mix Asphalt Based on Dissipated Energy and Stiffness Ratio

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ABSTRACT

Fatigue in hot-mix asphalt is the accumulation of damage under the effect of repeated loading. Flexural beam fatigue testing in the laboratory has been used for several decades and is expected to be an integral part of the new superpave advanced characterization procedure. Current fatigue failure criteria are based on a simple relation between the tensile strain in the beam *versus* the number of load repetitions to failure. Failure in the beam has relied on an arbitrary criterion such as 50 percent reduction of stiffness. This method does not provide a consistent indication of the onset of failure when different modes of loading are used. The dissipated energy approach is a promising technique for fatigue characterization, since it provides a consistent indication of the level of deterioration in the specimen in terms of behavior, accumulated damage or remaining life. As a part of the superpave advanced characterization research, a new fatigue failure criterion for flexure fatigue test was developed in this study using the dissipated energy approach. This approach makes it possible to predict the fatigue behavior of hot-mix asphalt in the laboratory over a wide range of conditions from the results of a few simple fatigue tests. A fundamental energy-based fatigue failure criteria methodology was developed using the dissipated energy approach, which is independent of the type of load control, temperature and mix and binder type.

KEYWORDS: Dissipated energy, Hot-mix asphalt (HMA), Flexural beam fatigue, Fatigue failure criteria, Initial stiffness, Failure stiffness, Pavement design, Strain control, Stress control.

INTRODUCTION

Load associated fatigue cracking is one of the major distress types occurring in flexible pavements. The action of repeated loading caused by traffic induces tensile and shear stresses in the bound layers which lead to the gradual loss in the structural integrity of the material. Fatigue initiates cracks in the wheel path at points where critical tensile strains and stresses occur. Once the damage initiates at the critical locations, the action of traffic eventually causes these cracks to propagate through the entire bound layer.

Numerous models have been developed by various researchers to characterize fatigue in asphalt layers. The most common model form used to predict the number of load repetitions to fatigue cracking is a function of the tensile strain and mix stiffness. The basic structure for almost every fatigue model developed and presented in the literature for fatigue characterization is of the following form (Monismith, 1985):

$$N_f = k_1(\varepsilon_t)^{k_2}(S_o)^{k_3} \quad (1)$$

where:

N_f = Number of loading cycles to failure;

ε_t = Initial tensile strain;

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S_o = Initial stiffness of the material;

k_1,k_2,k_3 = Regression constants.

Flexure beam fatigue tests are conducted in the laboratory to simulate field conditions and to determine various parameters in Equation 1. Two types of controlled loading are generally used in fatigue testing: constant stress and constant strain. In the constant stress case, the repetitive constant load causes gradual damage in the test specimen and therefore the strain increases, which reduces the stiffness with time. In case of constant strain, the stiffness is reduced as a function of load repetitions and the stress must be reduced to maintain constant strain. The constant stress type of loading is applicable to thick pavement layers, whereas the constant strain loading is applicable to thin layers. For medium-thickness layers, fatigue behavior is governed by a mixed mode of loading, mathematically expressed as some model yielding intermediate fatigue prediction to the constant strain and stress conditions.

In either cases of loading, specimen failure has not been well defined since cracks cannot be easily observed or tracked during the test. Current test procedure, therefore, arbitrarily defines failure as the number of loading cycles at which the stiffness of the beam is reduced to 50 percent of its initial value or when the specimen breaks. The fatigue failure criterion is typically developed as the straight line best fit between the tensile strain in the beam *versus* number of load repetitions to failure on a log-log scale. Although several researchers have made some attempts to improve the fatigue failure criterion, no reliable method has been developed that can be applied under various conditions. Research is still needed to properly interpret the fatigue behavior of the material and understand how the energy dissipates through the test until failure.

OBJECTIVE

The main objective of this study is to develop a fatigue failure criterion based on the dissipated energy approach to be used with the flexure fatigue tests. The developed method shows the similarity between the two types of loading: constant strain and constant stress. This method has the potential for unifying the current phenomenological description with a more rational energy-based description.

DISSIPATED ENERGY APPROACH

Dissipated energy is defined as the damping energy or the energy loss per load cycle in any repeated or dynamic test (Van Dijk, 1975; Van Dijk and Visser, 1977; SHRP, 1995). Flexure center and third-point beam fatigue tests are normally used when applying such a method with either controlled stress or controlled strain. At each loading cycle, the strain, stiffness and phase angle are determined by software. The dissipated energy can be calculated using the following equation:

$$w_i = \pi \varepsilon_i^{\,2}\, S_i\, Sin\phi_i \qquad (2)$$

where:

w_i= Dissipated energy at load cycle i;

ε_i = Strain amplitude at load cycle i;

S_i = Mix stiffness at load cycle i;

ϕ_i = Phase shift between stress and strain at load cycle i.

This dissipated energy is then summed over load cycle increments.

$$W_N = \sum_{i}^{N_f} w_i \qquad (3)$$

where W_N is the cumulative dissipated energy over N cycles. The use of dissipated energy for fatigue life prediction has been investigated over the past three decades (Van Dijk, 1975; Van Dijk and Visser, 1977; SHRP, 1995; Chomton and Valayer, 1972; Van Dijk et al., 1972). A unique relationship exists between the number of cycles to failure and cumulative dissipated energy to failure as follows (SHRP, 1995; Chomton and Valayer, 1972; Van Dijk et al., 1972; Carpenter and Jansen, 1997; Tayebali et al., 1992):

$$W_N = A\left(N_f\right)^z \qquad (4)$$

where A and z are experimentally determined coefficients.

In the constant strain fatigue test, the dissipated energy per cycle decreases with increasing the number of load repetitions, whereas for the constant stress fatigue test, the dissipated energy per cycle increases as the number of load repetitions increases. A higher cumulative dissipated energy has generally been associated with a higher fatigue life.

It was further found that crack initiation in a given mix is related to the stress or strain level or the energy dissipated during an initial loading cycle (w_o) as follows (SHRP, 1995; Tayebali et al., 1992; Tayebali et al., 1993):

$$N_f = e\left(\frac{1}{w_o}\right)^f \qquad (5)$$

where w_o is the dissipated energy during an initial loading cycle and e and f are experimentally determined coefficients.

The energy dissipated during each loading cycle is an excellent indicator of fatigue response. Furthermore, dissipated energy has greater conceptual appeal than a simple strain indicator because it captures both the elastic and viscous effects.

CURRENT FATIGUE FAILURE CRITERIA

AASHTO Method (AASHTO, 1994)

The 50-percent reduction in the initial stiffness is the most common definition for fatigue failure in the constant strain mode, which is widely used by asphalt professionals and researchers (AASHTO, 2010). It was originally defined by (Van Dijk and Visser, 1977). (Pronk and Hopman, 1990; Tayebali et al., 1992 and 1993; Abojaradeh et al., 2007; Shen and Lu, 2011) also defined the 50-percent reduction in the initial modulus as fatigue failure. Consequently, the 50-percent reduction in stiffness was later on adopted to define the fatigue failure point by the AASHTO as a provisional standard TP8-94 (AASHTO, 2010). However, the fatigue failure point based on the 50-percent reduction in stiffness was randomly chosen, and it does not represent the true fatigue failure in many cases and can provide ambiguous results. Rowe, in fact, showed that the stiffness of a tested cantilever beam tested in the controlled strain mode was below 50 percent of its original value without any clear sign of a crack on the beam (Rowe, 1993).

Pronk and Hopman Method (Pronk and Hopman, 1990)

In 1990, Pronk and Hopman developed the concept of energy ratio for the constant strain test to define failure as the ratio of the initial dissipated energy to the i^{th} cycle dissipated energy multiplied by the load cycle value n (Energy Ratio = n * w_o/w_i).

By plotting the energy ratios for different cycles *versus* the number of load cycles, the transition between micro- and macro-crack formation is defined as the number of load cycles as the energy ratio deviates from a straight line. Under controlled stress, the fatigue life was defined as the peak of the curve. Thus, the definition of failure in this method does not have a unifying nature for both modes of loading. Also, under strain conditions the value of failure is somewhat arbitrary, since it is not easy to judge where the energy ratio deviates from a straight line in view of the fact that the early part of the curve is not truly a straight line.

Pronk Method (Pronk, 1997)

In 1997, Pronk suggested a different expression of energy ratio for the constant strain test to define failure as the ratio of the cumulative dissipated energy up to cycle n to the dissipated energy for cycle n (W_n/w_n). Plotting the energy ratio for different cycles *versus* the number of load cycles for each specimen, the fatigue life was defined as the number of load cycles as the energy ratio deviates from a straight line. Similar to the previous method, when the energy ratio is plotted *versus* the number of load cycles, two different curves are obtained for both modes of loading. Also, it is not easy to accurately locate where the curve deviates from a straight line.

Rowe and Bouldin Method (Rowe and Bouldin, 2000)

Rowe and Bouldin improved the definition of failure by developing a function that produces the same format for both test types. The developed function produces a peak value, which can easily be identified. This point represents the formation of cracks rather than fitting an arbitrary straight line through the data set for the controlled strain test. The expression of energy ratio was simplified for both controlled stress and controlled strain as the load cycle value multiplied by the stiffness at that cycle (Energy Ratio = n * Si).

By plotting the energy ratio for different cycles *versus* the number of load cycles, the fatigue life was defined as the peak of the curve for both controlled stress and controlled strain testing. The main advantage of this method is that the peak value of n*S can be easily determined by fitting a high-order polynomial function to the data and differentiating. Fatigue failure is defined as the point when the curve switches from the micro-crack formation regime to the crack formation and propagation regime. It was concluded that in general the 50 percent stiffness reduction rule does not capture this point. This point falls generally in a range between 35 and 65 percent of the initial modulus. It was recommended that fatigue analysis is based upon the evaluation of the parameter n*S to determine the life for a given specimen. Results can be combined to define the fatigue performance of the mixture.

Ghuzlan and Carpenter Method (Ghuzlan and Carpenter, 2001)

Ghuzlan and Carpenter proposed a method that shows the similarity between the two types of loading: constant strain and constant stress. A new failure criterion was defined as the change in dissipated energy between cycles a and a+1 (or ΔDE) divided by the dissipated energy of load cycle a (or DE). This change was calculated approximately every 100 load cycles. A newly defined energy ratio (ΔDE/DE) plotted *versus* load cycles gives a curve that decreases rapidly during the first number of cycles then stays constant for a large number of cycles and then increases rapidly at the end. This trend was the same for both constant stress and constant strain tests. The failure point (N_f) is defined as the number of load cycles at which the change in the energy ratio begins to increase rapidly. It was found that under the same load control, the location of the 50 percent reduction in initial stiffness varied considerably from test to test. Also, for the same initial conditions, but different load controls, it was found that the location of the 50 percent reduction in initial stiffness is not the same. It was also concluded that the change in dissipated energy ratio represents typical material behaviors and shows the point at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading.

In this method, the authors went one step further to create a new fatigue failure criterion. The results of tests performed on several specimens were compiled in one graph by plotting the constant plateau values of ΔDE/DE (which represents the value of the constant energy ratio ΔDE/DE for each load cycle) and the corresponding number of cycles at the failure point N_f for each specimen. This relation produced a straight line on the log-log scale similar to the traditional fatigue curve. There was no significant difference between the lines of constant strain and constant stress, and thus, it was possible to plot both lines as one line. This concept was validated for three different asphalt mixes (Ghuzlan and Carpenter, 2001). It was concluded that the change in dissipated energy between two load cycles provides a more fundamentally correct indication of damage being done by one load cycle to the next one than does cumulative dissipated energy. This approach, however, has some limitations in such a way that the failure point cannot be accurately located and may differ from one operator to another. It is also not practical to have the values of energy damage accumulation ratio every 100 cycles, especially for long-life specimens. Finally, the constant plateau value of ΔDE/DE is not easy to determine because of the data scatter.

Al-Khateeb and Shenoy Method (Al-Khateeb and Shenoy, 2004; Al-Khateeb and Shenoy, 2011)

In this method, the fatigue failure is determined directly from load-deformation (or stress- strain) raw data by observing the load-deformation hysteresis loop or the output waveform of the fatigue test. The stress and strain signals (waveforms) before fatigue failure are highly correlated, and after failure these signals are not correlated any longer. The point of first fatigue failure is therefore identified when the shape of the hysteresis loop starts to show some distortion from its original smooth oval shape. The distorted shape in its early stage normally lasts for a long period before a very distorted shape of the hysteresis loop or waveform shows up. At this point, the complete fatigue failure (the ultimate fatigue failure) of the beam has been reached.

The fatigue failure criteria described in Al-Khateeb and Shenoy method (Al-Khateeb and Shenoy, 2004) is not limited to the 4-point bending beam that was used in their studies, but rather, their concept can be used in any type of fatigue testing configuration or even for any other material including non- bituminous materials.

Later on, Al-Khateeb and Shenoy (Al-Khateeb and Shenoy, 20011) based on their distinctive fatigue failure criteria have also used, to identify quantitatively the points of fatigue failure, the concept of a simple “R- squared” statistic for the relationship between the stress (output) signals for successive cycles with respect to the first sinusoidal cycle in a strain-controlled test or for the relationship between the strain (output) signals for successive cycles with respect to the first sinusoidal cycle in a stress-controlled test. When the R^2 value starts to decrease sharply, that indicates the occurrence of the point of first fatigue failure, and at the end when the R^2 value reaches zero, the complete fatigue failure occurs.

Abojaradeh, Witszak and Mamlouk Study (Abojaradeh et al., 2007)

The main objective of this study was to validate the criteria used to define the initial and the final stiffness in flexure fatigue testing. In this study, extensive flexure fatigue tests were performed on five typical dense-graded mixtures and an asphalt rubber gap-graded mixture. An optimization approach was used, in which different initial and failure conditions were assumed. Fatigue models were developed using linear regression curve fitting and the conditions that produced the best fit were selected. Both the phenomenological and the dissipated energy approaches were used. Test results conclusively indicated that the initial stiffness should be defined at cycle number 50. In addition, when a phenomenological approach for fatigue is employed, the fatigue failure stiffness should be taken at 50 percent of the initial stiffness. A stiffness degradation model was developed, which provided an independent proof that failure occurs when the stiffness of the beam is reduced to 50 percent of the initial stiffness. This model represents a basic material property at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading. In contract to the tensile strain-failure approach, data analysis with the energy approach showed that fatigue failure stiffness, taken at 30 percent of the initial stiffness, provided identical fatigue energy failure regardless of constant stress or strain mode of loading. The results show that the phenomenological and the energy approaches provide different definitions of failure and that the test should be consistent with the method of analysis used.

Shen and Lu Review (Shen and Lu, 2011)

Shin and Lu conducted a review of three different energy based fatigue failure criteria and evaluated their applicability for fatigue data from asphalt binders and mixtures and under both stress and strain controlled loading modes. A macroscopic failure criterion is recommended, which is defined as the sudden change of the dissipated energy evolution curve and is consistently related to the beginning of macrocrack propagation. In addition, by comparing different failure criteria, the traditional 50 % initial modulus reduction criterion was found to have a strong correlation with energy based macroscopic fatigue failure for both mixtures and binders. It is thus suggested that the 50% initial modulus reduction failure can be used as a simple but reasonable fatigue criterion, which indicates the transition from microcrack to macrocrack.

SPECIMEN PREPARATION AND FATIGUE TESTING

Specimen Preparation

In this study, a total of six Arizona Department of Transportation (ADOT) mixtures were tested, five of which were conventional hot-mix asphalt (HMA) and one modified gap-graded asphalt rubber mixture (ARM). The five conventional HMA mixtures contain two different aggregate sources as shown in Table 1. The volumetric mixture design properties for all the six mixtures are shown in Table 1.

In this study, beams were prepared using vibratory loading applied by a servo-hydraulic loading machine. A mold was used with inside dimensions larger than the required dimensions of the beam to allow for sawing. A top loading rigid platen was connected to the loading shaft assembly for compaction.

After mixing and short-term aging, the mixture is placed in the mold, which is in turn placed in the loading machine. A stress-controlled sinusoidal load was then applied for compaction until the pre-determined density is reached. After compaction, specimens were left to cool to ambient temperature. The specimens were brought to the required dimensions for fatigue testing by sawing 1/4 inch (6 mm) from each side. The air void was measured using the saturated surface dry procedure (AASHTO T-166, Method A). Any specimen with an air void of 1 percent or larger deviation from the target value of 7 percent was rejected. The details of the beam preparation procedure are presented elsewhere (Witszak et al., 2001).

Table 1. Design Properties of Mixtures Used in the Study

Item	**Hot-Mix Asphalt**					**Asphalt Rubber Mix**
Binder Type	Chevron PG 76-16	Chevron PG 64-22	Navajo PG 70-10	Paramount PG 58-28	Chevron PG 64-22	PG 58-22
Binder Content (%)	4.20	4.55	4.25	5.00	5.25	7.50
Type of Aggregate	Salt River Base	Salt River Base	Salt River Base	Bidahochi Base	Bidahochi Base	Salt River Base
Specific Gravity	2.270	2.280	2.269	2.483	2.484	2.200
Max. Theoretical Specific Gravity	2.441	2.456	2.440	2.671	2.672	2.389
Air Void (%)	7.0	7.0	7.0	7.0	7.0	8.0

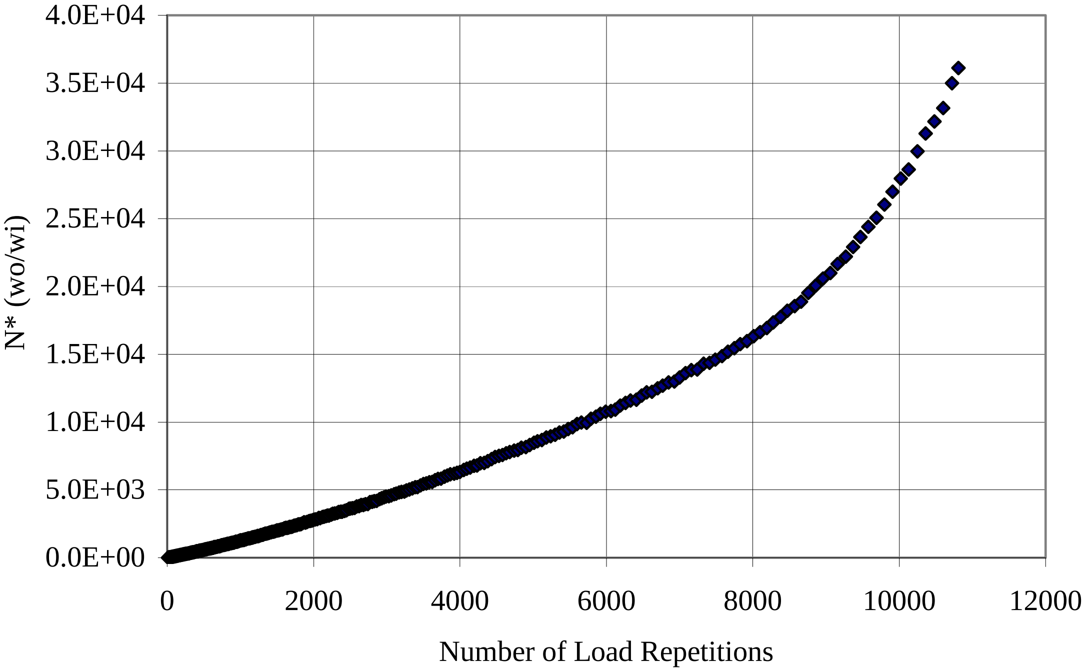

Figure 1: Example of Energy Ratio (N^*w_o/w_i) *versus* Number of Load Repetitions Using Pronk and Hopman Method (Salt River Base Aggregate, Chevron 76-16 Binder, Strain Control Test, 70°F)

Flexural Beam Fatigue Apparatus

Flexural fatigue tests were performed according to the AASHTO TP8 and T-321 procedures (AASHTO, 1994 and 2010). The device is typically placed inside an environmental chamber to control the temperature during the test. The cradle mechanism allows for free translation and rotation of the clamps. Pneumatic actuators at the ends of the beam center it laterally and clamp it. Servomotor driven clamps secure the beam at four points with a pre-determined clamping force. Haversine or sinusoidal loading is applied to the beam via the built-in digital servo-controlled pneumatic actuator. A "floating" on-specimen transducer measures and controls the true beam deflection irrespective of loading frame compliance.

Test Conditions

Specimens were stored in the environmental chamber for at least two hours to reach the required test temperature. The following factors were used in the beam fatigue test:

- Mix type: 6 different mixes as defined earlier.
- Mode of loading: Constant strain and constant stress.
- Wave shape: Haversine for constant strain and sinusoidal for constant stress.
- Load frequency: 10 Hz.
- Test temperature: 100, 70 and 40°F (37.8, 21.1 and 4.4°C).

At least 36 specimens covering all factor combinations were tested to establish representative fatigue curves.

DEVELOPMENT OF FATIGUE FAILURE CRITERION

Fatigue Failure Criteria Using Previous Methods

The results of the flexure fatigue lab tests obtained in this study were analyzed using five dissipated energy methods reported earlier to develop fatigue failure criteria and to assess their applicability and accuracy. The assessment criteria used were: 1) to ensure that the number of cycles to failure is clearly defined for individual specimens, 2) a good fit exists between the defined energy parameter and the number of cycles to failure for all specimens and 3) the two types of loading produce the same relation. The following steps were used for each method:

1. The energy ratio parameter defined in each method was determined and plotted *versus* the number of loading cycles for each specimen. The energy ratio at failure and the number of cycles at failure were determined for each specimen.
2. A fatigue failure criterion was developed by plotting the energy ratio at failure *versus* the number of load cycles at failure on a log-log scale for all specimens.
3. A linear regression equation was fitted to the data points for each mode of loading separately and the corresponding coefficients of determination (R^2) were determined.
4. Step 3 was repeated for both modes of loading combined.
5. A rating system of R^2 values was assumed as:
   - Excellent ≥ 0.90.
   - Good 0.70 - 0.89.
   - Fair 0.40 – 0.69.
   - Poor 0.20 – 0.39.
   - Very poor <0.20.

Table 2 shows a summary of goodness of fit of test results for strain control and stress control separately and combined for methods used in the study.

Figure 1 shows an example of energy ratio as defined by the Pronk and Hopman method (Pronk and Hopman, 1990) *versus* the number of load cycles. As indicated earlier, it was not easy to determine the number of cycles to failure. Figure 2 shows the fatigue failure criteria for constant stress and constant strain modes of loading separately. Although an excellent fit was obtained for each mode separately, the results for the two modes of loading resulted in a good rating as shown in Table 2.

Table 2. Goodness of Fit of Test Results for Strain and Stress Modes of Loading for Dissipated Energy Methods

Mode of Loading	Pronk and Hopman	Pronk	Rowe and Bouldin	Ghuzlan and Carpenter	Abojaradeh New Method
Constant Strain	Excellent	Excellent	Good	Very Poor	Excellent
Constant Stress	Excellent	Excellent	Good	Very Poor	Excellent
Both Modes	Good	Excellent	Good	Very Poor	Excellent

Using the Pronk method (Pronk, 1997), the energy ratio was plotted *versus* the number of repetitions for each specimen as shown in Figure 3. The energy ratio values at failure were plotted *versus* the number of cycles at failure for all specimens on the log-log scale as shown in Figure 4. Excellent fit was obtained for the two modes of loading separately as well as the two modes combined. However, the determination of the number of load cycles to failure was not straightforward.

The energy ratio as defined by the Rowe and Bouldin Method (Rowe and Bouldin, 2000) was plotted *versus* the number of repetitions for each specimen as shown in Figure 5. The energy ratio values at failure were plotted *versus* the number of cycles at failure for all specimens on the log-log scale as shown in Figure 6. A good rating was obtained for the two loading modes separately and combined as shown in Table 2. As discussed earlier, the main advantage of this method is that the number of cycles to failure can be easily defined as the peak of the energy ratio curve for both controlled stress and strain modes as shown in Figure 5.

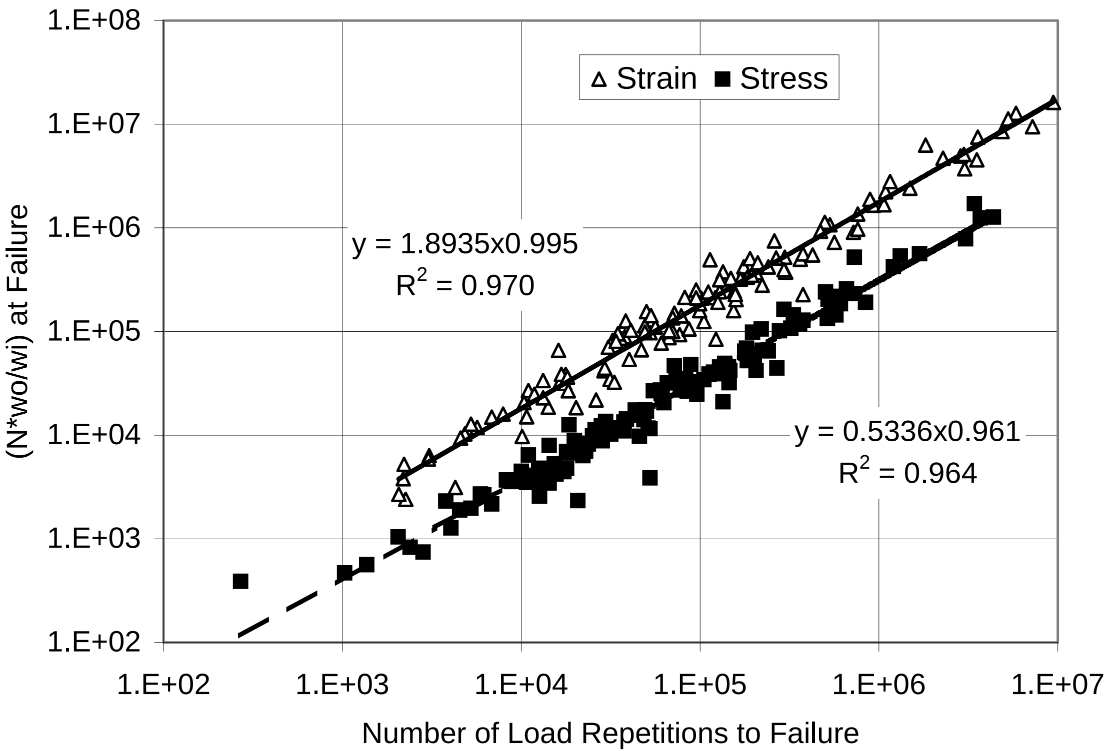

Figure 2: Energy Ratio (n*w_o/w_i) *versus* Load Cycles at Failure Using Pronk and Hopman Method for All Mixes for Controlled Stress and Controlled Strain

By applying the Ghuzlan and Carpenter method (Ghuzlan and Carpenter, 2001) to the results of the six mixes tested in this study, the data were largely scattered in such a way that the number of cycles to failure could not easily be defined as shown in Figure 7. The method produced very distinct fatigue criteria for the stress and strain control cases as shown in Figure 8. It was very difficult to combine both modes of loading in one line. A fair rating was obtained for the strain control mode loading and a good rating for the stress control was obtained. The rating for the combined modes was very poor as shown in Table 2.

New Fatigue Failure Criterion

By applying Abojaradeh method (Abojaradeh et al., 2007), a new rational fatigue failure criterion was developed based on the Rowe and Bouldin failure definition (Rowe and Bouldin, 2000). By normalizing Rowe and Bouldin energy ratio *(N_i*S_i)* by dividing it by the initial stiffness (S_o), a new energy stiffness ratio is developed as follows:

$$\textit{Energy Stiffness Ratio} = \frac{N_i * S_i}{S_o} \qquad (6)$$

where N_i is the cycle number, S_i is the stiffness at cycle i and S_o is the initial stiffness taken at cycle number 50. By plotting the energy stiffness ratio value (N_i*S_i/S_o) *versus* the load cycles, a peak value can be obtained as shown in the example in Figure 9. The reason that the energy stiffness ratio increases before it reaches its peak is that the value of N_i continuously

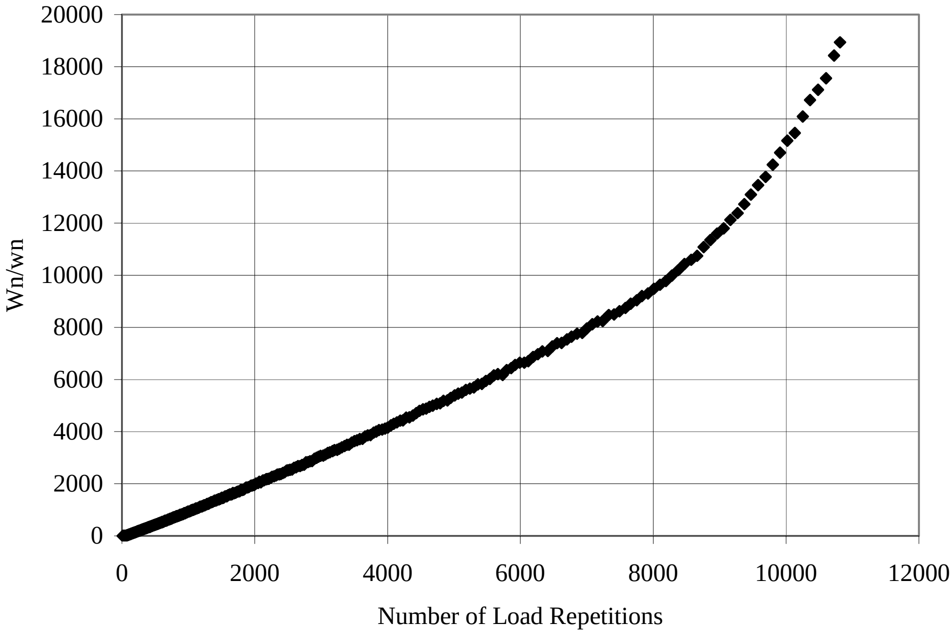

Figure 3: Example of Energy Ratio (W_n/w_n) *versus* Number of Load Repetitions Using Pronk Method (Salt River Base Aggregate, Chevron 76-16 Binder, Strain Control Test, 70°F)

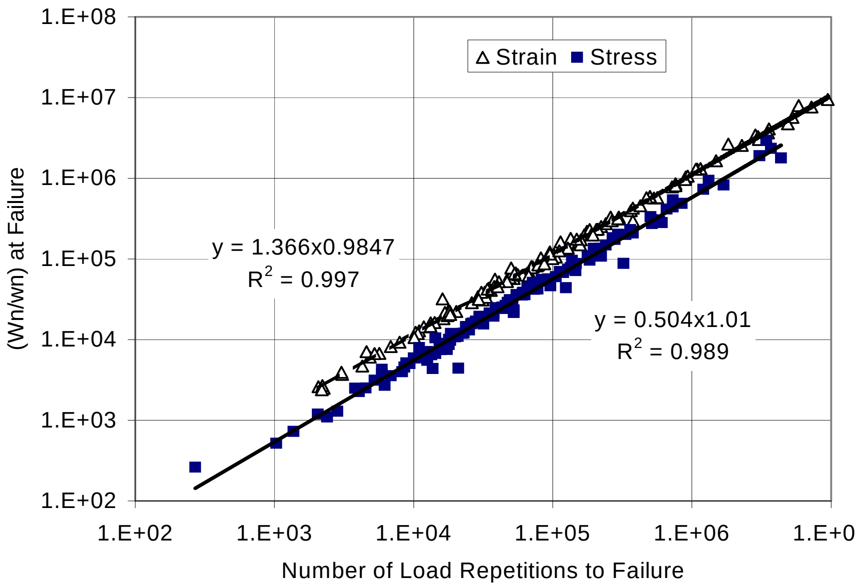

Figure 4: Energy Ratio (W_n/w_n) *versus* Load Cycles at Failure Using Pronk Method for All Mixes for Controlled Stress and Controlled Strain

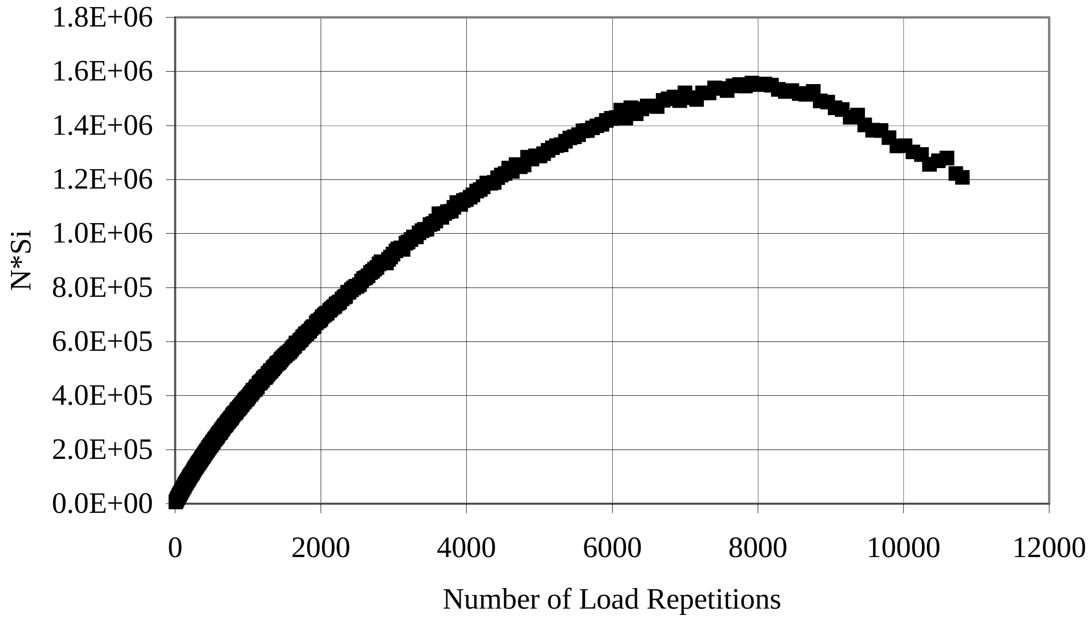

Figure 5: Example of Energy Ratio ($N*S_i$) *versus* Number of Load Repetitions Using Rowe and Bouldin Method (Salt River Base Aggregate, Chevron 76-16 Binder, Strain Control Test, 70^oF)

increases during the test, whereas the S_o value is constant. The value of S_i during this time might be slightly decreasing. After reaching its peak, the energy stiffness ratio decreases suddenly because of the sudden decrease in the stiffness of the material even with the increase of the N_i value. Thus, failure is defined as the number of load repetitions at the peak value of the curve for either constant strain or constant stress mode, as shown in Figure 9. The (N_i*S_i/S_o) value at failure, when plotted *versus* the corresponding number of cycles at failure for all specimens on a log-log scale, results in a straight line relationship with high coefficients of determination as shown in Figure 10. The results also show that there is little to no significant difference between separate curves for constant stress and constant strain. Figure 11 shows the fatigue failure plot for the two modes of loading combined. Excellent fit was obtained for the two modes of loading separately as well as the two modes combined as shown in Table 2. Also, the determination of the number of load cycles to failure was straightforward.

The regression equation developed in Figure 11 is:

$$y= 0.4816\, x^{0.9911}. \qquad (7)$$

Since the expression (N_i*S_i/S_o) at failure is (N_f*S_f/S_o), Equation 7 is actually:

$$\frac{N_f S_f}{S_o} = 0.4816(N_f)^{0.9911}.$$

Since the power of 0.991 is very close to 1.0, Equation 7 may be approximated by:

$$\frac{S_f}{S_0} = 0.4816. \qquad (8)$$

Equation 8 shows that the stiffness at failure is very close to 0.5. This conclusion is very significant, since it provides an independent proof that failure occurs when the stiffness of the beam is reduced to 50 percent of its initial value.

It is concluded that the energy stiffness ratio at failure as defined in this paper represents a basic material property at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading. This concept was validated for the six asphalt mixes used in this study.

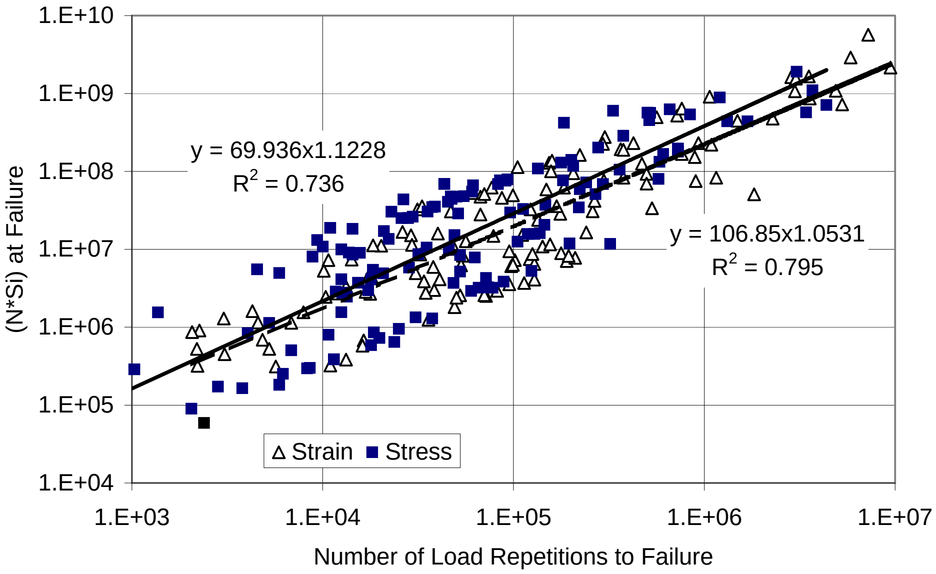

Figure 6: Energy Ratio (N*S$_i$) *versus* Load Cycles at Failure Using Rowe and Bouldin Method for All Mixes for Controlled Stress and Controlled Strain

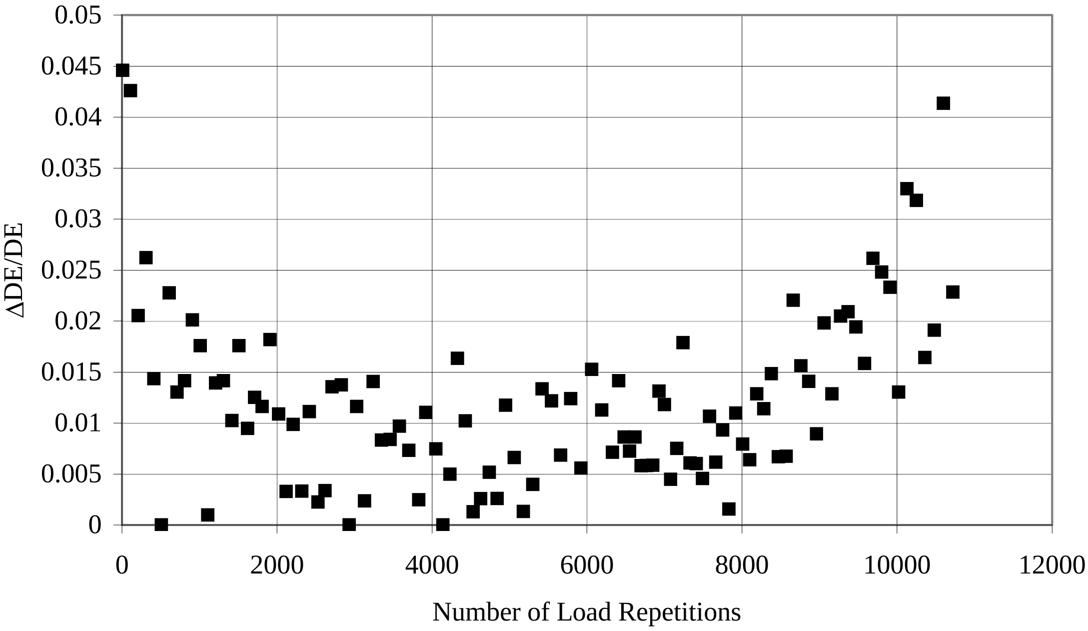

Figure 7: Example of Energy Ratio (ΔDE/DE) *versus* Number of Load Repetitions Using Ghuzlan and Carpenter Method (Salt River Base Aggregate, Chevron 76-16 Binder, Strain Control Test, 70^{o}F)

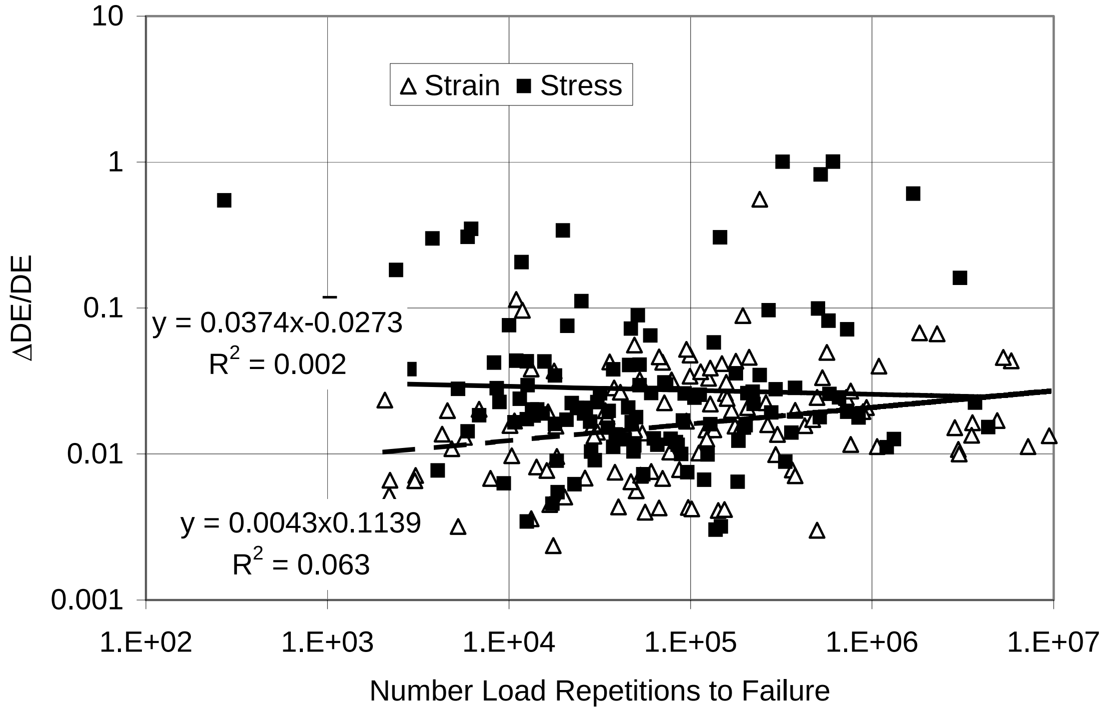

Figure 8: Energy Ratio (ΔDE/DE) *versus* Load Cycles at Failure Using Ghuzlan and Carpenter Method for All Mixes for Controlled Stress and Controlled Strain

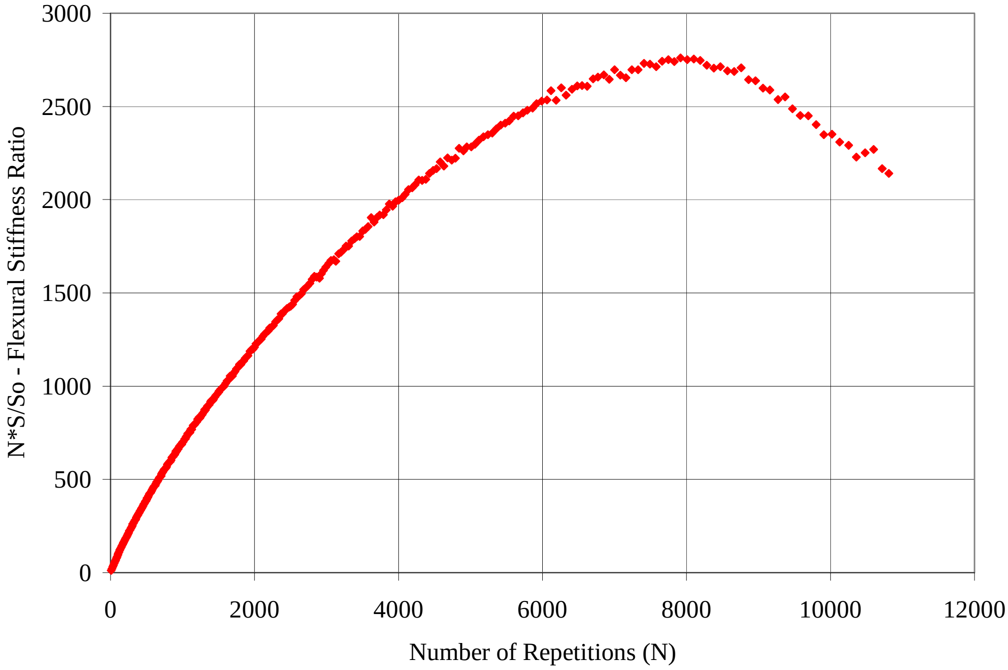

Figure 9: Example of Energy Ratio ($N*S_n/S_o$) *versus* Number of Load Repetitions Using the New Method (Salt River Base Aggregate, Chevron 76-16 Binder, Strain Control Test, 70^oF)

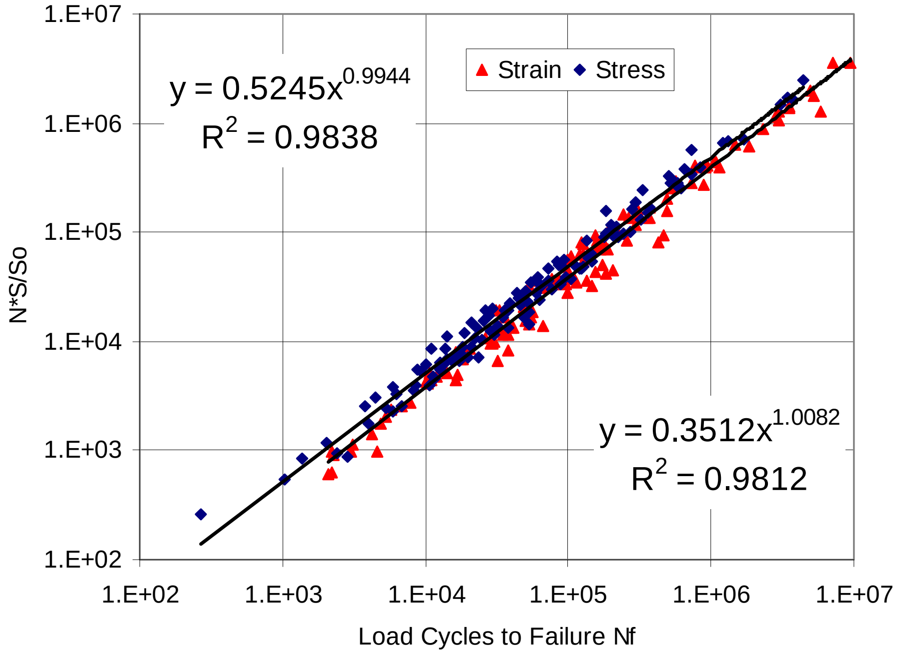

Figure 10: Energy Ratio ($N*S_n/S_o$) *versus* Load Cycles at Failure Using the New Method for All Mixes for Controlled Stress and Controlled Strain

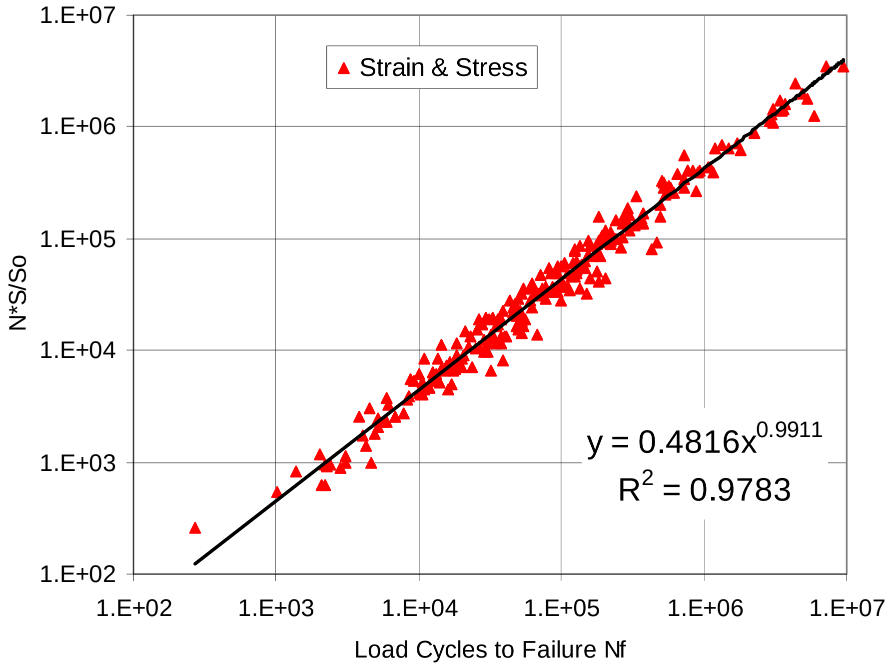

Figure 11: Energy Ratio ($N*S_n/S_o$) *versus* Load Cycles at Failure Using the New Method for All Mixes for the Controlled Stress and Controlled Combined

Summary of New Fatigue Failure Criterion

A new rational fatigue failure criterion was developed in this study based on the concept of energy dissipation. A new definition of the energy stiffness ratio is developed in this study as (N_i*S_i /S_o). By plotting the value of the new energy stiffness ratio (N_i*S_i /S_o) *versus* the load cycles, a peak value can be obtained. Failure is then defined as the number of load repetitions at the peak value of that curve for both controlled stress and controlled strain modes as shown in the example in Figure 9. By plotting the new energy ratio (N_i*S_i/S_o) value at failure and the corresponding number of cycles at failure for all specimens on the log-log scale, a straight line with a much higher coefficient of determination R^2 results as shown in Figure 10. Excellent ratings were obtained for both strain and stress control modes. The results also show that there is no significant difference between the two curves for controlled stress and controlled strain. It was noted that the curves from constant strain testing and constant stress testing have almost the same trend. Figure 11 shows the fatigue failure plot for the two modes of loading combined. Again, an excellent rating of fit was obtained with an R^2 value of 0.9911 as an average for all mixes used in the study. It is concluded that the energy stiffness ratio at failure as defined in this new method represents a basic material behavior at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading. This concept was validated for six different asphalt mixes including the asphalt rubber mix (ARM).

CONCLUSIONS

A new flexure fatigue failure criterion was developed in this study to provide the potential for unifying the phenomenological description with a more rational energy-based description. A new definition of the energy stiffness ratio was developed as (N_i*S_i /S_o), where *i* is the cycle number, S_i is the stiffness at cycle i and S_o is the initial stiffness. Excellent fit was obtained for the two modes of loading separately as well as the two modes combined. Also, the determination of the number of load cycles to failure was straightforward.

The new energy stiffness ratio model provided an independent proof that failure occurs when the stiffness of the beam is reduced to 50 percent of the initial stiffness. This model represents a basic material property at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading.

The following conclusions are drawn from this study:

1. A single failure criterion depending on dissipated energy was presented for fatigue characterization that is independent on the mode of loading.
2. The method shows a well-defined failure condition during the test, strengthening the arbitrary 50 percent reduction in the specimen stiffness.
3. The developed fatigue failure criterion is preferred over other energy-based criteria because of its rationality and accuracy of fit of data.
4. Although the new failure criterion developed in this study has not been calibrated in the field, it has the potential to closely simulate field performance to be used for pavement design.

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