Fatigue Evaluation Criteria for Aged Hot-Mix Asphalt Pavements

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ABSTRACT: An evaluation of aged flexible pavements was conducted to develop a method for improving the prediction of fatigue in aged hot-mix asphalt (HMA) surfaces. This is important for projecting airfield maintenance funding and predicting the performance of operating surfaces in a theater of operation. There has been little previous work done on predicting the remaining fatigue life of existing pavements. The goal of this project was to develop fatigue criteria to be used as part of field evaluations of flexible pavements. The current Department of Defense (DoD) fatigue criteria was developed solely from laboratory-aged HMA beam samples. This study involved both field and laboratory evaluations of aged HMA pavements from several military airfields. Field testing included visual inspections and estimating the in situ moduli of the HMA using seismic testing. Samples were extracted from each airfield and used to conduct laboratory testing, which included the determination of mixture and binder properties, indirect tensile strength tests, and beam fatigue tests. Field and laboratory test results were then used to develop improved fatigue performance predictions for aged HMA pavements. This study revealed that the effect of change in stiffness on fatigue is not well understood. For example, the remaining fatigue life increased with lower stiffness resulting from minimal oxidation. However, lower stiffness resulting from durability issues caused decreases in the remaining fatigue life.

KEY WORDS: Fatigue, asphalt, criteria, seismic, pavement

1 INTRODUCTION

1.1 Problem Statement

Military airfield pavement evaluation teams are tasked with providing accurate field assessments of load-carrying capacities for pavements so that major command engineers can support missions and optimize funds for pavement maintenance and rehabilitation. There is a need for predicting the performance of aged HMA when subjected to heavy wheel loads and high tire pressures of military aircraft. The ability of the Department of Defense (DoD) to select suitable operating surfaces in the theater of operation is limited by its current methods for evaluating HMA pavements. Future military missions may be severely impacted without the ability to accurately predict the performance of aged HMA pavements.

1.2 Objective and Scope

The purpose of this research was to address issues with evaluating and predicting the fatigue performance of aged HMA surfaces. To accomplish this goal, several aged HMA airfield surfaces were located and evaluated. The evaluation consisted of a visual inspection of the pavement surface, determination of the in situ HMA modulus, and the removal of slab-shaped samples to be used for producing laboratory test specimens. Laboratory testing included both physical characterization and mechanical tests, with emphasis on beam fatigue testing. The study was conducted in two phases: in Phase I the beam fatigue testing included one strain level (550 microstrain), and in Phase II fatigue testing included multiple strain levels (150, 350, and 550 microstrain). This paper focuses on the results from Phase II. Refer to Bell and Freeman (2007) for further information on the Phase I evaluation.

The data analysis portion of this investigation included a series of linear multiple regressions to identify significant independent variables for predicting laboratory fatigue performance, which was considered as representative for the remaining pavement fatigue life. The primary objective of this investigation was to develop fatigue life criteria to be used as part of field evaluations of aged HMA pavements.

2 BACKGROUND

2.1 Asphalt Fatigue Testing

Fatigue loading of HMA pavement layers can assume any mode of loading among an infinite spectrum of possible load patterns (Monismith and Deacon 1969). This spectrum is bounded, however, by two well-defined test conditions: controlled stress and controlled strain. Controlled stress loading is representative of the condition where the HMA-bound layers are relatively stiff compared to their support. This condition can often occur when the HMA-bound surface is 15.2 cm thick or more. Controlled strain loading is representative of the conditions where the HMA-bound layers are weak relative to their support. Such a condition often occurs when the surface HMA is 5.1 cm or less (Monismith and Deacon 1969).

If possible, beam fatigue testing conditions should be designed to address the specific pavement loading scenario. The most commonly referenced standardized procedure in the U.S. is published by the American Association of State Highway and Transportation Officials (AASHTO) as the Provisional Standard TP8-94 (AASHTO 2002). The procedure for this study was a controlled-strain test based on the provisional standard, at strain levels of 150, 350, and 550 microstrain, with a loading frequency of 5 to 10 Hz, and conducted at a temperature of 20°C. Controlled strain testing was used for this study because the AASHTO provisional standard existed and because HMA airfield pavements are typically constructed as thin HMA-bound layers over very stiff unbound pavement layers. This study focused on thin HMA airfield surface pavements.

While HMA beams in controlled-stress fatigue tests fail by fracture, defining the failure point for these beam tests is difficult. As a beam is damaged in controlled-strain tests, modulus and strength decrease with loading cycles resulting in the same imposed deflections producing progressively smaller stresses. With strain levels that are reasonable for pavements, the beams typically will not break during controlled-strain fatigue testing. As a consequence, arbitrary definitions for beam failure have been established. For example, failure is commonly defined as the number of repetitions required to reduce beam stiffness to 50% of its initial value (AASHTO 2002, Yoder and Witczak 1975). Other studies have explored beam failure definitions as beam stiffness reductions from 40 to 80% (Kingham and Kallas 1972).

To identify a loss in stiffness during a fatigue test, an ‘initial stiffness’ must be defined. Stiffness values can be erratic at the beginning of a fatigue test, so ‘initial stiffness’ is typically defined at a set number of strain repetitions. Initial stiffness is commonly defined as that found at strain repetitions between 50 and 200 (Abojaradeh et al. 2007). The AASHTO TP8-94 test procedure defines initial stiffness as that at the 50^{th} load cycle (AASHTO 2002).

2.2 Current Department of Defense Fatigue Criterion

The current DoD criterion for fatigue life of HMA surfaces provides a method for estimating allowable strain repetitions, *r* (Department of Defense 2001):

$$Log_{10}(r) = 2.68 - 5 \cdot Log_{10}(S_A) - 2.665 \cdot Log_{10}(E) \tag{1}$$

S_A = tensile strain at the bottom of HMA pavement
E = elastic modulus of HMA, psi

Equation 1 was derived from a graphical plot of allowable load repetitions, in terms of both stress and strain, which was proposed by Barker and Brabston (1975) for use by the U.S. Army Corps of Engineers. This criterion was derived from laboratory-produced beam samples. Equation 1 has empirical components, so the inputs must be entered in English units as shown (1 MPa = 145 psi).

3 EVALUATION PROCEDURES

3.1 Field Evaluations

The military pavements evaluated in this study ranged from 5 to 55 years old and were still operational. In cases where multiple samples were obtained from a single airfield, they were extracted from different features (e.g., apron, runway, or taxiway) representing different loading conditions on the airfield. The field evaluations included visual inspections of pavement surfaces and estimates of in situ HMA moduli. The visual inspections were summarized as pavement condition indices (PCI) (Department of Defense 2001). The in situ moduli of the HMA surfaces were estimated using a nondestructive portable seismic pavement analyzer (PSPA) via ultrasonic surface waves (Li and Nazarian 1995, Nazarian et al. 2005).

Given that the modulus of HMA pavements depends upon temperature, the HMA standardized in-place modulus was used in this study to normalize the estimates of modulus as provided by the PSPA. This was necessary because the PSPA tests in this study were performed at HMA surface temperatures ranging from 11.1 to 40.6^{o}C. The HMA standardized in-place modulus calculation standardizes measured moduli to a temperature of 25^{o}C and a loading frequency of 15 Hz (Li and Nazarian 1995, Nazarian et al. 2005).

Sampling from each pavement surface involved the removal of three 10.2-cm-diameter cores and the removal of a slab-shaped sample from the HMA surface material. Each slab sample, approximately 61 by 91.4 cm and at least 7.6 cm thick, was used for producing beams for beam fatigue testing. All HMA field samples were subjected to laboratory testing.

3.2 Laboratory Testing

In addition to testing the field-aged samples of HMA, this study included laboratory production and testing of slab-shaped samples constructed with a high-quality standard airfield mixture. The laboratory-prepared slabs were used to provide non-field-aged specimens for comparison to the field-aged specimens. The laboratory mixture was produced with AC-30 (ASTM D 3381-05) asphalt cement and well-graded crushed aggregates. The HMA mixtures were prepared in a portable pugmill mixer and compacted in a steel frame to produce slab dimensions of approximately 61 cm long by 61 cm wide by 7.6 cm thick. After the laboratory-produced slabs were removed from the frame, they were tested with the PSPA prior to coring and cutting for beams.

Laboratory testing included measurements of both physical and mechanical HMA properties. Physical property measurements included percent binder by mass (ASTM D 2172-05), kinematic viscosity of binders (ASTM 2170-07), binder penetration (ASTM D 5-06), dynamic shear rheometer (DSR) testing for binders (ASTM D 7175-07), gradation of extracted aggregates (ASTM C 136-06), air void content calculations based on measured bulk specific gravity (ASTM D 2726-08), and theoretical maximum specific gravity (ASTM D 2041-03). Mechanical property testing included indirect tensile strength (ITS) (ASTM D 6931-07) and beam fatigue under controlled strain (AASHTO 2002).

Beam fatigue testing was performed under controlled strain conditions using a pneumatic beam fatigue apparatus. All tests were performed on beams with dimensions of 6.4 cm wide, 5.1 cm in height, and 38.1 cm long. Tests were conducted over a span of 30.5 cm, with four-point loading, at a single temperature of 20°C. Loading was applied at a frequency of 10 Hz with a haversine waveform. The controlled strain levels during testing included 150, 350, and 550 microstrain. These strain levels were identified as bounding the common strain levels for typical airfield pavement structures under C-17, C-130, and F-15 aircraft loads as determined by linear elastic analyses. Fatigue testing was generally terminated at 24 hours, which allowed for the application of 850,000 load cycles. During analyses, linear extrapolation of beam stiffness versus Log_{10} cycles, specifically beams tested at 150 microstrain, was needed for some test results so that they could be included in the comparisons and analyses of beam performance.

4 RESULTS

4.1 Defining Failure for Beam Fatigue Tests

Given that the beams in this study were mostly aged field samples rather than laboratory-produced beams, the definition of beam failure required careful consideration. While beam failure in this study was defined in the traditional manner of percent loss in beam stiffness, the values assigned to initial beam stiffness and to stiffness at failure were investigated to ensure that they met the needs of this study.

The definition of initial stiffness could not assume a predefined number of preconditioning repetitions because the changes in stiffness over the first several hundred load cycles were variable between HMA pavements from different sampling sites. Therefore, in this study, initial stiffness was defined as the earliest stiffness value where the changes in stiffness (linear scale) with Log_{10} cycles assumed a smooth curve. With this definition, cycles at initial stiffness ranged from 15 to 240 for aged HMA samples and from 40 to 270 for unaged laboratory-mixed samples.

To assign an appropriate percentage loss in stiffness as failure in the beam fatigue tests, the authors tested the unaged beams at strain levels of 350 and 550 microstrain. Concurrently, expectations for repetitions to beam failure could be defined by applying these strain levels and the HMA standardized in-place modulus values for the unaged HMA specimens to the current DoD HMA fatigue criterion (Equation 1). For these beam tests, the DoD-predicted cycles to failure occurred at beam stiffness levels equal to approximately 70% of the initial beam stiffness values. Therefore, failure for fatigue testing of aged HMA samples in this study was similarly assigned as the number of cycles at which beam stiffness is equal to 70% of the initial stiffness.

4.2 Summary of Beam Fatigue Results

Given that fatigue results are typically positively skewed, the Log_{10} values offer improved symmetry to data. *Log Ratio* values, defined in Equation 2, provided a convenient method of comparing measured and predicted cycles to failure. *Measured Cycles* are determined from the beam fatigue tests, and *Predicted Cycles* are determined from the original DoD fatigue criterion (Equation 1).

$$Log\ Ratio = \frac{Measured\ Cycles}{Predicted\ Cycles} \tag{2}$$

The advantage of using *Log Ratio* is that fatigue data may range over several orders of magnitude. The use of logarithms kept the data within limits that were easy to plot and compare. While using *Log Ratio*, several rules of thumb for the calculated quantities were applied. For example, if *Log Ratio* equals -2, this meant that the predicted cycles to failure exceeded the measured cycles to failure by a factor of 100; therefore, the fatigue life was highly unconservative. If *Log Ratio* equals +1, this meant that the measured cycles to failure exceeded the predicted cycles to failure by a factor of 10; therefore, the fatigue life prediction was conservative.

4.3 Applicability of the DoD Fatigue Criterion to Aged Hot-Mix Asphalt

The *Log Ratio* values were then used to determine whether a new criterion was needed when evaluating the potential future performance of aged HMA. The deciding factor was whether the original DoD fatigue criterion predicted cycles to fatigue failure with sufficient accuracy. A comparison of predicted and measured fatigue performance for the aged samples is shown in Figure 1. In this figure, the deviation from the line of equality tends to be more on the unconservative side, and there are several cases in which the deviation exceeds two log cycles. Based on these findings, the authors confirmed the need for a new criterion for predicting fatigue life of aged HMA as it is evaluated in the field.

5 DEVELOPMENT OF A FATIGUE CRITERION FOR AGED HOT-MIX ASPHALT

This study was conducted in two phases. For brevity, only the most critical Phase I conclusions are summarized so that the reasoning behind Phase II testing can be established.

5.1 Phase I

Phase I beam fatigue testing included one strain level (550 microstrain) and one testing temperature (20°C). The most important conclusions from the Phase I study follow.

1. The standardized PSPA-measured modulus, ITS peak strength, and DSR parameters proved useful for predicting the laboratory fatigue life of aged HMA specimens.
2. The following independent variables were found ineffective for predicting the laboratory fatigue life of aged HMA: asphalt binder content, HMA air void content, aggregate gradation, binder viscosity, and binder penetration.

3. While laboratory fatigue life decreased with increasing strains as expected, fatigue life increased with increasing modulus values. The latter finding surprised the authors because this effect of modulus on fatigue life was contrary to the original DoD criterion (Equation 1). The authors believe that the contradictory effect of modulus was caused by the different sources of changing moduli, as explained in the following paragraph.

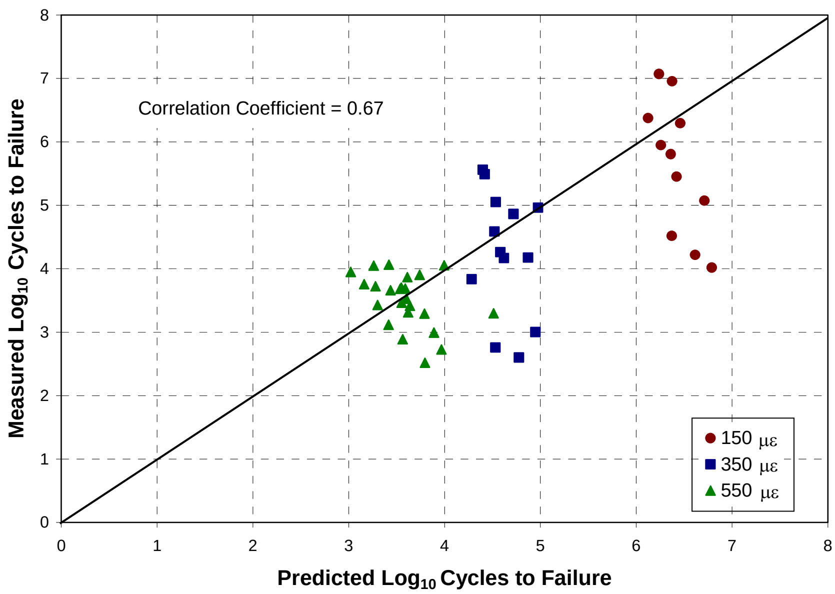

Figure 1: Measured versus predicted fatigue failure for aged field samples using original DoD fatigue criterion (Equation 1).

During the development of the original DoD criterion, the high-modulus, laboratory-compacted HMA samples showed shorter fatigue lives because the higher-modulus HMA mixtures were created primarily by mixture changes and by lowering the testing temperature. In the case of testing aged field HMA samples, however, two concurrent processes deserve consideration. One process is the aging of binders, which increases moduli and decreases fatigue life (i.e., low modulus is advantageous). The second process is HMA degradation as caused by loading and environmental influences. Degradation causes decreases in both moduli and fatigue life (i.e., high modulus is advantageous). The authors propose that the modulus values measured by both the PSPA (standardized to 25°C and 15 Hz) and ITS tests provided indications of material integrity. The low-modulus, field-aged samples had been damaged during service and therefore tended to degrade quickly under fatigue cycling; the high-modulus, field-aged samples tended to be better able to withstand repeated strains.

5.2 Phase II

Phase II fatigue testing included multiple strain levels: 150, 350, and 550 microstrain. Laboratory testing for Phase II included DSR and ITS testing, as well as beam fatigue testing under controlled strain. Field testing included the estimation of the HMA standardized in-place modulus via the PSPA measurements. Also, pavement age and PCI were included in the Phase II analysis because this information would always be available to a pavement evaluation team.

The significance with which independent variables were able to predict Log_{10} cycles to failure were analyzed by forward stepwise multivariate linear regressions. Strain level was also included as an independent variable. In the forward stepwise approach, independent variables were added individually, starting with the variable that contributed most significantly to the ability of the regression equation to predict the dependent variable. In this process, any of the independent variables having a nonsignificant contribution to predicting the dependent variable were excluded from the regression. The significance of an independent variable's contribution was judged by its P-value, which is the probability of being incorrect if the independent variable is identified as making a significant contribution to the regression. Independent variables with P-values less than 0.05 (5%) were considered to be worthy of being including in the regression model.

The Phase II analysis warranted the following conclusions.

1. Among the independent variables studied, strain level during fatigue testing was the best predictor of Log_{10} cycles to failure. The second most effective independent variable was standardized PSPA-measured modulus. Again, fatigue life generally increased with increasing moduli.
2. ITS peak stress provided a good substitute for standardized PSPA-measured modulus as a predictor of Log_{10} cycles to failure. Fatigue life generally increased with increasing ITS peak stress. This substitution was made possible by a positive correlation between ITS peak stress and PSPA-measured modulus ($R^2 = 0.55$; adjusted $R^2 = 0.53$).

5.3 Defining the New Criteria in Equation Form

New fatigue criteria for aged HMA were developed for two types of available evaluation data.

1. HMA standardized in-place modulus (15 Hz and 25°C), as estimated with a PSPA.
2. ITS peak stress at 25^{o}C, as estimated by testing 10.2-cm-diameter cores.

The use of an HMA standardized in-place modulus would be preferable because the test is fast, and it does not require samples to be transported to a laboratory. Although linear regressions (multivariate) were used to find significant predictive independent variables, both linear and nonlinear equations were considered for this new criterion. The most promising equation found in this study for predicting fatigue life from strain and in-place PSPA modulus is shown in Equation 3. The units for the terms are the same as for Equation 1.

$$Log_{10}(r) = 7.94 - [\frac{\ln(S_A \cdot 10^{-6})}{2.61}]^2 + \frac{E}{438{,}000} \quad (3)$$

r = allowable strain repetitions for field-aged HMA
S_A = tensile strain of HMA
E = HMA standardized in-place modulus, psi

A scatter plot comparing predicted and measured Log_{10} cycles to failure is shown in Figure 2. This plot shows substantial improved predictions as compared with Figure 1, which is a similar presentation for the original DoD criterion when applied to aged HMA. The new criterion is shown in the form of aged HMA pavement fatigue evaluation curves in Figure 3.

A similar nonlinear equation (Equation 4) was identified for the case of predicting fatigue life using *ITS peak stress* data, in terms of psi (1MPa = 145 psi), along with strain data.

$$Log_{10}(r) = 8.36 - \left[\frac{\ln(S_A \cdot 10^{-6})}{2.62}\right] + \frac{ITS\ Peak\ Stress}{264} \quad (4)$$

A similar scatter plot was produced for this equation (not included in this paper for brevity), and it showed that the predictive equation using strain and *ITS peak stress* provided accuracy commensurate with the predictive equation using strain and HMA standardized in-place modulus measured with the PSPA (correlation coefficient = 0.77).

Generally, a shift factor is applied to correlations relating laboratory tests to field tests. A shift factor was not used for Equations 3 and 4 because the work required to develop the shift factor was beyond the scope of this paper.

The new fatigue criteria, as described in this paper, addressed the performance of field-aged HMA only at room temperature (20 to 25°C). This limitation in applicable temperatures is a consequence of keeping the field sampling and laboratory testing to a reasonable volume of work. The Phase II report for this study (Bell et al. 2008) provides details of a process for extending these criteria to other pavement temperatures, as well as demonstrations of its use.

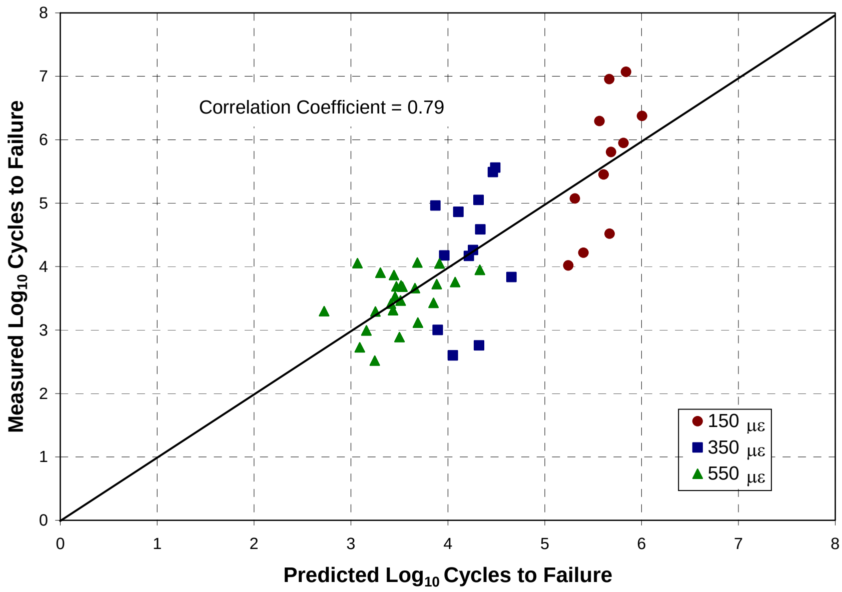

Figure 2: Measured versus predicted fatigue failure for aged field samples using Equation 3.

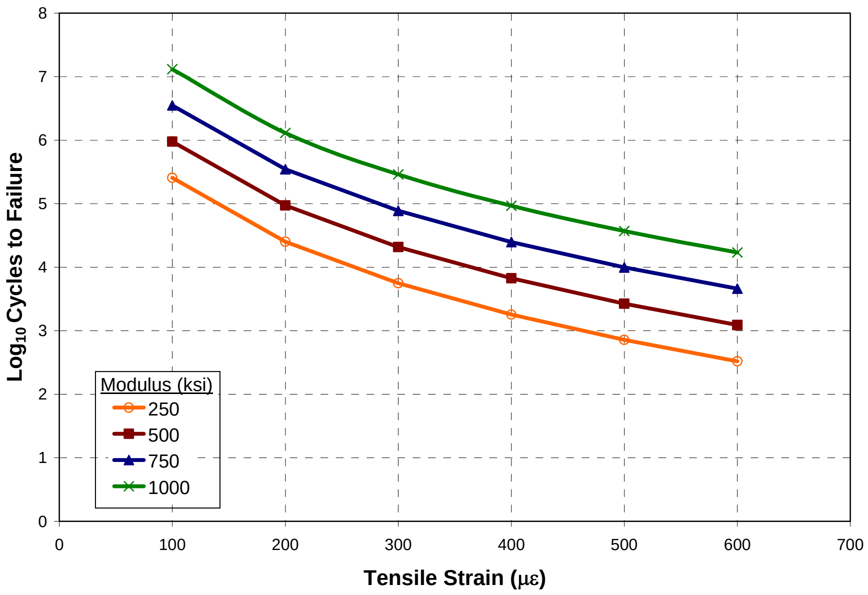

Figure 3: Fatigue evaluation curves for aged HMA based on Equation 3.

6 CONCLUSIONS

This paper provides an overview of a study conducted to develop a method for evaluating the remaining fatigue life of HMA pavement surfaces. Conclusions from this investigation are as follows:

1. The current DoD criterion, which was developed using laboratory-prepared specimens, has difficulty predicting fatigue failure for aged HMA samples obtained from the field. Results from this study concluded the criterion can be highly unconservative in its predictions. That is, the current DoD criterion may predict more passes to failure than a pavement can handle.
2. The current DoD fatigue criterion predicts decreases in fatigue life with increases in the stiffness of HMA. The results from the study on field-aged HMA, however, showed increases in cycles to failure with increases in mixture stiffness. The contradicting results are likely caused by the different sources of changing moduli.
3. The authors propose that the field modulus values measured in this study by the PSPA, and converted to a standard modulus at 25°C and 15 Hz, provide an indication of material integrity. The low-modulus, field-aged samples tended to degrade quickly under fatigue cycling, and the high-modulus, field-aged samples tended to be able to withstand repeated strains better.
4. This paper presents two methods for predicting the remaining fatigue life for field-aged HMA airfield surfaces. These predictive equations (Equations 3 and 4) are shown to be improved methods as compared to the current DoD criterion (Equation 1). The independent variables required for predicting remaining fatigue cycles include strain level and either HMA standardized in-place PSPA modulus or ITS peak stress.
5. There was very little correlation between the stiffness of the HMA mixture as measured by the PSPA (standardized to 25°C and 15 Hz) and mixture stiffness as measured at the beginning of beam fatigue testing. This finding emphasizes the difficulties associated with quantifying elastic modulus values for HMA.

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