THE FATIGUE PERFORMANCE OF ASPHALT MIXTURES IN THE FOUR POINT BENDING BEAM FATIGUE TEST IN ACCORDANCE WITH AASHTO AND ASTM ANALYSIS METHODS

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ABSTRACT

A series of mixtures have been analyzed in the bending beam fatigue test. These mixes have been analyzed in accordance with both ASSHTO (based on the SHRP research program) and ASTM (published in 2009) specifications for fatigue analysis. The materials evaluated included conventional HMA materials, SMA and highly modified materials used for bridge deck water-proofing. The AASHTO method bases the life on a "50% stiffness loss criteria," whereas the ASTM bases life on an adaption of the dissipated energy concept. The fatigue lives from the two methods are critically examined with the varrious different mixtures considered. Recommendations are made for alternate data capture routines based upon stiffness reduction during the fatigue test and damage evolution rather than the more normal method of recoding the stiffness based on cycle number. This enables the life of a specimen to be more accurately assessed than that done currently using data collection which is based upon a logarithmic procedure. Additional refinements and recommendations to the ASTM test method are presented.

Keywords: Fatigue, bending beam, stiffness reduction

1. INTRODUCTION

The use of fatigue tests for analysis of asphalt mixes has been in existence since the late 1950's (Pell, 1961). Several different loading arrangements exist and those commonly used today include two, three and four point bending tests and those conducted in direct tension-compression mode. The current methods for conducting bending beam fatigue tests in the USA were refined and adopted in specifications in the early 1990s following work conducted as part of the Strategic Highway Research Program (Tayebali et al., 1994; Deacon et al., 1994). In the work conducted at this time the use of computers for controlling sophisticated test was relatively new. For example in work conducted at Nottingham (Rowe, 1996), use was made of Hewlett Packard HP85A Personal Computer for controlling push-pull testing while bending beam fatigue tests were conducted using personal computers with Intel 286 chips. Some testing and analysis was conducted using the 386 chips at this time. The reliance on these older computers and associated software resulted in a need for efficient programming and limitation of data file size. With the rapid advance over the past two decades the limitations that existed have simply vanished. Previously, programmers kept file sizes limited and notes in the AASHTO 321 (2007) specification indicate that this may be an issue. The data presented in this specification is collected on a semi-log basis in order to control/limit the amount of data being collected. When using regression analysis in the determination of test parameters the amount and frequency of data can affect the analysis parameters and consequently the results of a test significantly. The ASTM D7460 (2008) version of the fatigue specification uses a different determination of the failure point which was based upon dissipated energy considerations. The parameter "nE*" peaks at the location in a test where the dissipated energy per cycle starts to change significantly. This signifies the point where damage merges to form micro-cracks which then propagate more rapidly through the beam. This peak occurs in both controlled stress and strain tests. However, in the controlled strain test the peak at this point can be followed by a secondary increase in this parameter when the test is continued to very low stiffness values. Since the ASTM method relies less on curve fitting the variability that results from inclusion or exclusion of data is lower but the data collected scheme will result in some deviations. The parameters that can affect the result in this method are also discussed.

2. BENDING BEAM FATUGUE TESTING

In the USA the two standards applied to bending use a beam subjected to bending action with a continuous 10 hertz haversine or sinusoidal loading, ASTM D7460 and AASHTO T321. Typically the test is conducted at a temperature between 15 and 25^{o}C. While this paper presents data from this type of testing it should be noted that the same type of analysis can be applied to the trapezoidal fatigue test conducted in Europe or other cyclic loading fatigue test configurations.

During the bending beam fatigue test a cyclic load is applied to a specimen and the evolution of damage is monitored. For the work presented herein analysis had been conducted in IPC fatigue machines (see Figure 1) at either the Asphalt Institute (Lexington, Kentucky) or in the Rutgers Asphalt Pavement Laboratory (RAPL) located within the Center for Advanced Infrastructure Testing (CAIT) at Rutgers University (New Jersey). The data from these tests is stored in as ASCII format comma separated variable (CSV) file. This makes subsequent analysis of the data by other software programs and or spreadsheet routines relatively easy.

In this paper we have presented data from several studies. Conventional asphalt mixes include those used in New Jersey and Kentucky made in accordance with state specifications. These include a PG64-22 and PG76-22 binders (the latter is typically a modified binder). We have also included SMA mixtures made with modified binders and specialized bridge deck wearing course (BDWC) mixes that are intended for water-proofing applications. We have provided aggregate size information in the various figures. All the analysis information of fatigue data presented in this paper has been collected by the two laboratories during the last 4-years.

Fatigue test data is often plotted on log stiffness vs. log loading cycles by evidenced by many early researchers in this field (Pell et al., 1961; Pell and Cooper, 1974, Cooper, 1976). However, it should be noted that the stiffness reduction that occurs can also be plotted on linear graphs. Often linear plots enable a more clear assessment of the quality of curve fits to the data sets. Rowe and Bouldin (2000) have previously demonstrated that the change in stiffness during a bending beam fatigue test is best represented by graphs with linear scales.

During the research conducted during the SHRP program this practice was adopted by Tayebali et al. (1992, 1994). The analysis if data was then used to estimate the location where the stiffness had dropped by 50% using an exponential equation to the data as follows:

$$S = Ae^{bN}$$

where:

- e = natural logarithm to the base e,
- A = constant, and
- b = constant
- N = number of loading cycles

Whereas the wording in the AASHTO T321 standard excludes the data beyond the point where the estimate of the initial stiffness has dropped below 50%, this data is often included in analysis by various researchers, extending the analysis. We have referenced the analysis performed strictly in conformance with the AASHTO method by a (S) whereas the analysis including additional data is indicated by a (R). An example of a data set collected and analyzed to both schemes is shown in Figure 2 using both linear and log axis. The regression parameter (r^2) is high in both versions of the analysis (0.95 and 0.98). However, this statistic is often misleading and although the high number is obtained the relationship may be non-descriptive. By simple inspection it can be seen that the exponential fit appears to fit the data when log scales are used but clearly is non descriptive when the data is inspected to linear basis.

The ASTM standard contains definition of failure which is based upon determining the peak location from a curve of normalized modulus versus cycles to failure, as shown in Figure 3.

Figure 1: IPC fatigue device

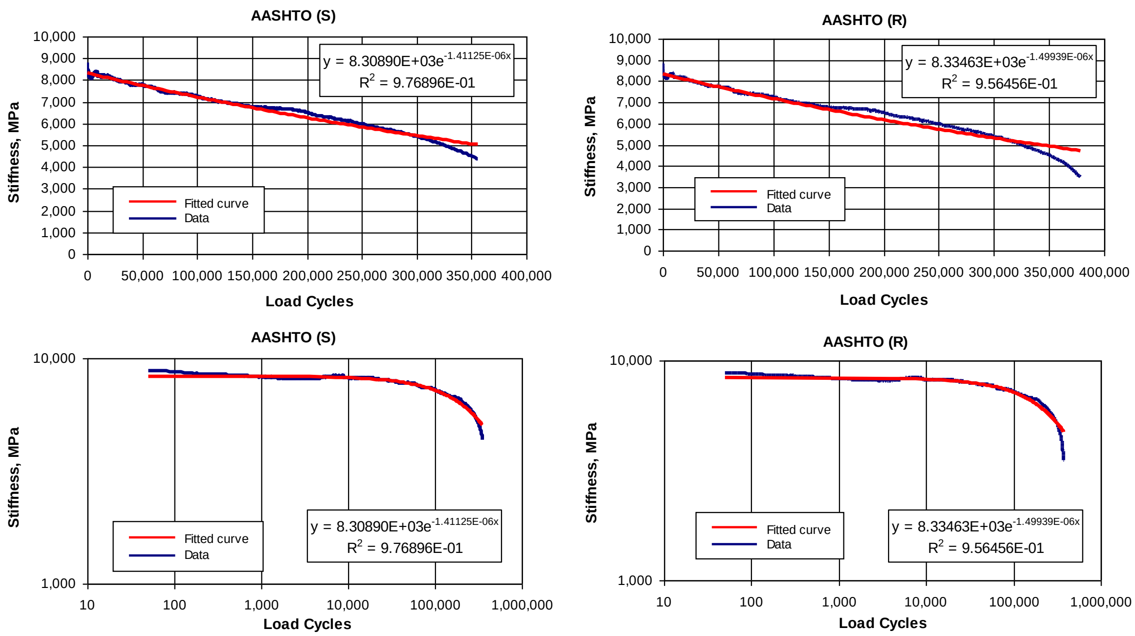

Figure 2: Representations of fatigue curves on linear and log scales with AASHTO

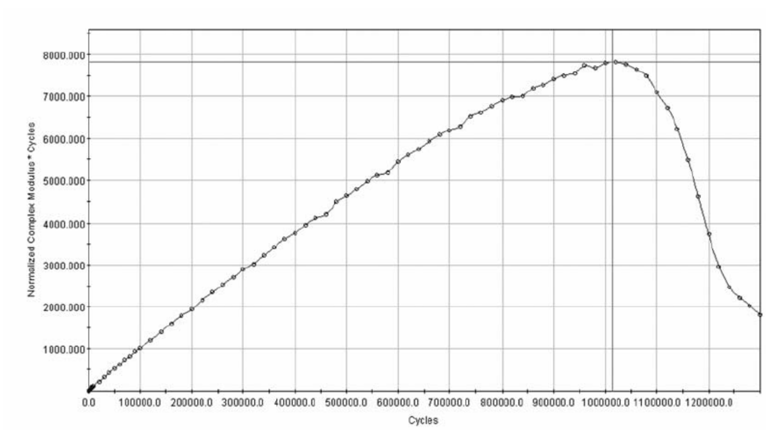

Figure 3: Normalized complex modulus × cycles plotted against cycles

During SHRP data was typically stored for analysis from data in the 4-point bending beam test using a semi-log basis. This data format was used in the development of the AASHTO T321 standard and is typical of that presented in various reports and papers published from that research, Tayebali et al. (1992, 1994). However, one key aspect of any parameter analysis such as determination of the constants *A* and *b* in the AASHTO equation using regression methods is the number and spacing of data points that are used in the analysis.

In the orginal specification the number of data points was collected on a semi-log basis whereas in the newer test devices data is collected on an equal spacing within each decade of testing. In order to assess the difference introduced by the new data collection scheme versus that used in the orginal test development data was analyzed from several test results using a semi-log consideration and all the collected data. We have referenced the two data collection schemes as IPC (the equipment used in the testing) and SHRP (to reflect the orginal limitations of data collection that was used to develop the AASHTO test method) for convenience.

The result of using more data in the fatigue analysis per the current IPC data collection scheme increases the average fatigue life by approximately 24 to 26% depending upon the amount of data included in the analysis as demonstrated by the data shown in Figure 4. The inclusion of data beyond the 50%

stiffness reduction has the potential to change the data analysis more significantly. In the data set analyzed below the biggest variation when more data is included in the analysis occurs with the soft highly modified materials. The analysis of conventional materials using the limited log based data (SHRP) often produced the same result.

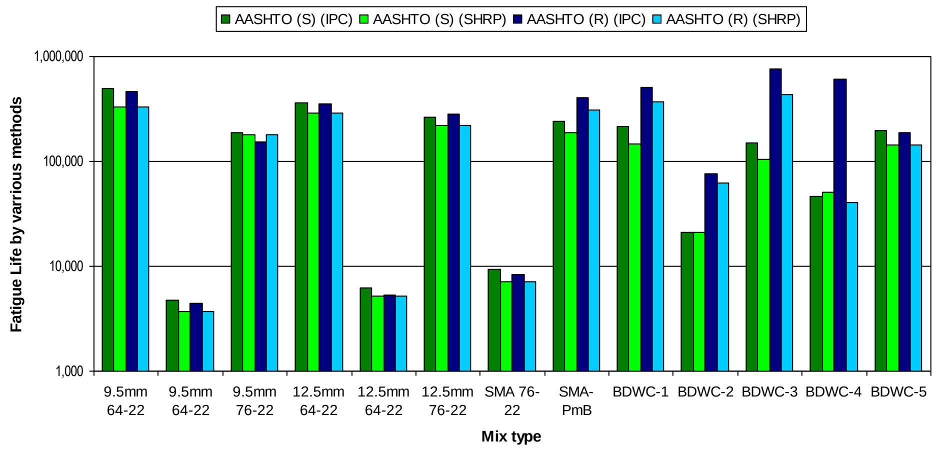

Figure 4: Fatigue life from analysis method AASHTO 321 using different data inclusion/exclusion schemes

The variation obtained with an AASHTO analysis scheme can be further studied by investigating the change in life with varying percentages of terminal stiffness included in the analysis. The data in Figure 5 demonstrates that significant differences can exist with modified materials whereas the changes that occur with conventional materials are significantly reduced. However, it should be noted that the variations in excess of 40% obtained with conventional mixes is not a desirable basis to form a specification.

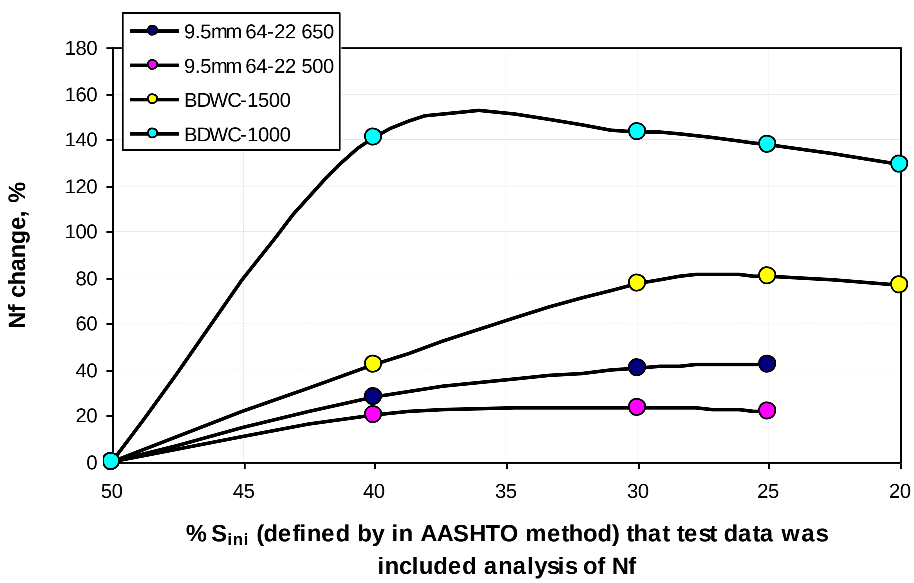

Figure 5: Effect on fatigue life by varying the amount of data included in the analysis

The adoption of functional form must be carefully assessed to determine if it is consistent with the observed data. Additional analysis of data collected during the SHRP project was presented by Rowe (1993) and Rowe and Bouldin (2000). This analysis led to the conclusion that the functional form adopted in the AASHTO T321 test method did not adequately describe the stiffness reduction that occurs in a fatigue test. Further work conducted by Ghuzlan, and Carpenter (2000) considered the use of a dissipated energy ratio and its rate of change during a test. Other methods used to define failure in a fatigue have included the peak in phase lag between the stress and strain response. However, these latter methods have problems in consistently defining the failure point and currently have not been adopted in any nationally recognized procedure. It is interesting to note that these additional procedures all tend to define the same location which occurs as a crack is initiated in a specimen but the peak in the dissipated energy ratio appears to best method to define the where micro-cracks have propagated and coalesced to form a macro-cracks (Ajideh et al., 2010). The principle advantage of the ASTM method which is based upon the peak in the dissipated strain energy concept is that failure is defined by a simple and reproducible parameter. The definition of the peak with data collection using the IPC method is very reproducible and historically two main methods have been used to determine this. Rowe (1993, 1996) used a 6-order polynomial fit to the data to a location just beyond the peak. The simple differential of the parameters of this curve fit allows for some smoothing of the data and possibly a better definition of failure than that using the specified maximum point as defined in the ASTM method. The normalized modulus is effectively the stiffness ratio of the modulus at any cycle to that measured initially and this ratio could be notated as $n\hat{E}^*$ ($\hat{E}^*$ = complex modulus ratio) when the stiffness is a complex extensional modulus or $n.S_R$ (S_R= bending stiffness ratio) when a bending stiffness is considered. It should be noted that in a controlled displacement (strain) fatigue test that a secondary increase in the normalized modulus × cycles parameter can occur. This data should be removed from the analysis since is represents data collected while the specimen is in a failed condition. A typical set of data showing this effect is shown in Figure 6 where the specimen has been continued to 14% of the stiffness obtained at 50-cycles. For this specimen the peak in $n\hat{E}^*$ occurred at 49% stiffness reduction. Figure 7 shows the effect of including or excluding the tail from the polynomial analysis. While this method is not currently within the ASTM method the fitting of a curve function does help to remove any spikes in the data analysis and produce more consistent analysis. The differences obtained between the different analysis methods used (spline, polynomial or simple maximum) are very small. In the example shown in Figure 6 and Figure 7 a difference of 72 cycles exists from the minimum to maximum value, which represents 2% of the mean value. The variation in this method is further illustrated in the analysis of results presented earlier in Figure 4. We have shown the polynomial smoothing method compared to the strict ASTM definition (max) in Figure 8 which compares the results from the ASTM analysis to that obtained from the AASHTO method (IPC data collection scheme using extended data sets) which is most commonly implemented in the USA. The data shows reasonable agreement with the range of deviation of the ASTM analysis being between 0.3 and 4.4%. The difference between the AASHTO (R) and the ASTM method gives a life difference that is between -17 to +43% of the life as determined by AASHTO (R).

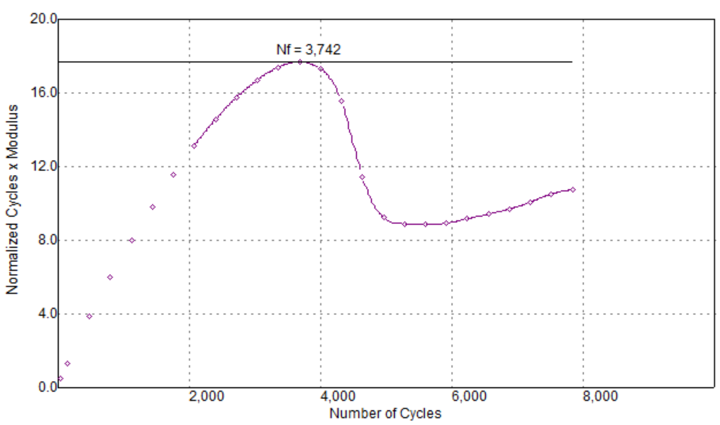

Figure 6: Data from fatigue test analyzed using ASTM method with Cubic spline fit through data in region of test termination

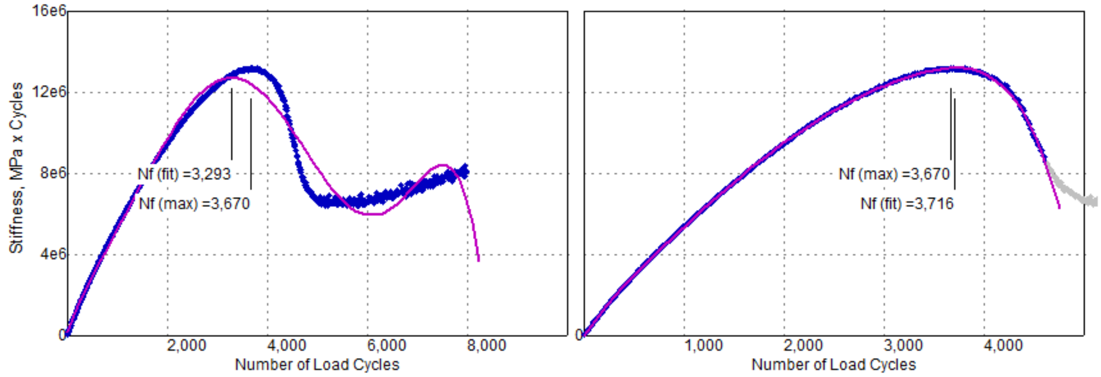

Figure 7: Effect of data trimming on 6-order polynomial smoothing to ASTM analysis

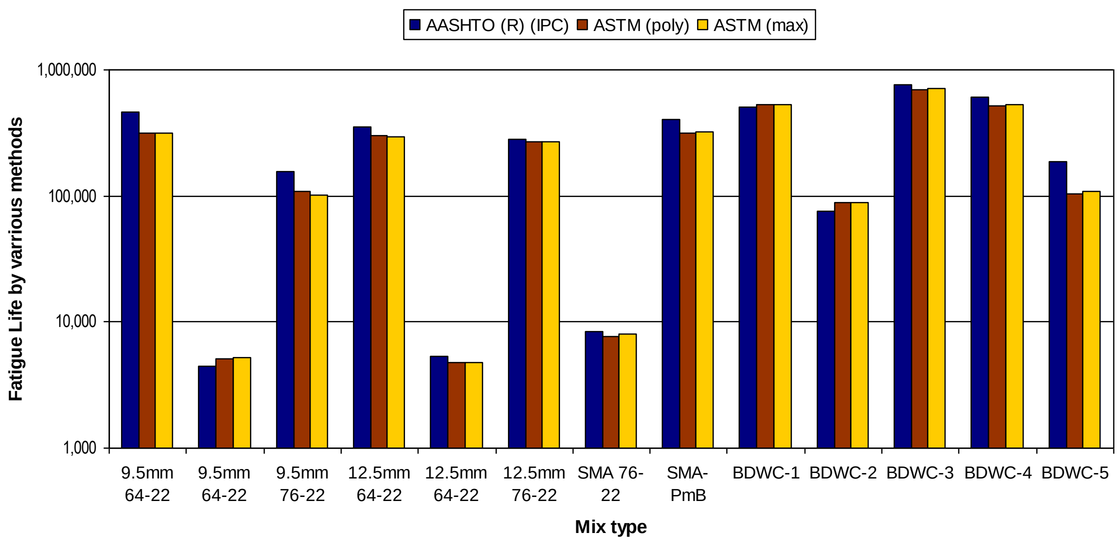

Figure 8: Analysis of fatigue data using the ASTM method compared against method AASHTO (R)

3. DISCUSSION

The results from fatigue tests are used in several contexts in specifications and assessment of performance. In some cases a specifying agency requires a given level of performance at a specified strain level. This has recently become a common practice with the use of some highly modified materials such as BDWCs which have performance requirements in several states (for example New York, New Jersey, etc.). In addition, with the recent introduction of the Mechanistic-Empirical Pavement Design Guide (MEPDG) several states have been assessing material performance to produce relationships between strain level and fatigue life. The AASHTO standard does not contain any information on precision and bias whereas the ASTM quotes the within-lab repeatability on two specimens as two results should not differ by 0.787 when the logs of the number of cycles to failure is considered. The use of log averaging is important for the expression fatigue data since the results are typically considered to be log normally distributed. When power law relationships are established for use in the MEPDG the results are effectively treated in the same manner.

The analysis of the data did not demonstrate that any significant difference exists regarding the within-lab repeatability on two specimens as this was further tested by evaluating an additional ten mixes. The principle improvement by using the peak in nÊ* is that the analysis is not sensitive to the amount of data included in the regression analysis including; 1) the initial value of stiffness or cycles, 2) the definition of an arbitrary failure stiffness, and 3) the type of smoothing used to define the peak that occurs. These aspects should greatly improve the repeatability between laboratories and remove the practice of customized analysis by laboratories.

The choice of the nÊ* (or nS_R or NM (as in the ASTM method)) is a simple parameter that is consistent with other damage/failure definitions. The variation in stiffness, phase angle, dissipated energy per cycle and nÊ* is shown in Figure 9 for the same result as shown in Figures 6 and 7. It can be clearly observed that the peak in the ratio of nÊ* is consistent with the deviation of stiffness reduction and energy dissipated per cycle deviate from a linear fit (as shown by the red dashed lines in the figure). It is interesting to note that the deviation from this line is the also the location identified by the change in dissipated energy ratio (DER) as proposed by Ghuzlan, and Carpenter (2000). However, the definition of this point from the method proposed by them is difficult due to inherent scatter/noise in the data. The change in the phase angle has a minor peak before this occurs but the most significant change in phase angle occurs after the specimen has significant cracking. In the later stages of the test when the specimen has a significant fatigue crack the shape of the curve from the load cell and displacement transducer becomes very irregular and can no longer be considered sinusoidal (Rowe, 1996). In this data set that location occurs at approximately 4,700 cycles. If the peak in phase angle is considered before this location the result obtained would be approximately 2,600 cycles. The most significant problem in using the phase angle peak or shape to define the failure is the clear definition of failure. The peak is not always defined and if curve fitting to sin curve is used then some criterion is needed to define the failure point. Conceptually, the error calculation procedures as used for dynamic modulus testing as specified in AASHTO T62 could provide a basis for this type of analysis. However, this type of method is really unnecessary since the calculation of nÊ* is very easy and different procedures for data smoothing result in very little error in the result calculated.

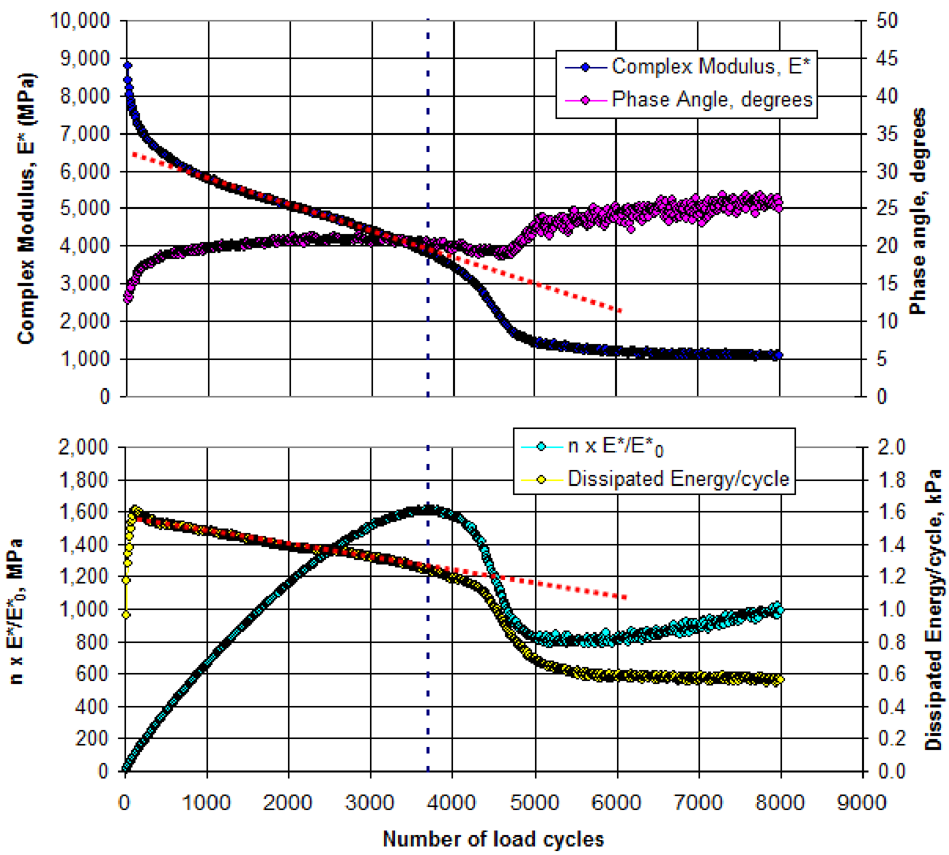

Figure 9: Variation in complex stiffness modulus, phase angle, dissipated energy per cycle and nÊ*

The collection of fatigue test data during the test can be curtailed by tracking the nÊ* parameter and terminating the test at the maximum value in this parameter has decreased by 10%. This is an easy parameter to track in data acquisition and would ensure that a crack exists in the specimen at point of termination. The results that have been analyzed in this paper suggest that the stiffness at which the test would be terminated for a fatigue test would be lower for a less stiff, highly modified material. In addition, since the fatigue damage process is linear within a test, the data collection could easily be implemented on a stiffness reduction basis rather that as a function of the cycles number. This would provide more equally spaced data throughout the test. Previously, data has been collected on a 5% stiffness reduction basis (Rowe, 1996) and this has proved adequate for defining the peak of the nÊ* parameter. This data could be collected on any arbitrary stiffness reduction, for example a 1% stiffness trigger to data collection would provide approximately 50 to 80 data points for a specimen.

3. SUMMARY

This paper presents an analysis of fatigue data using two methods originally developed as part of the SHRP work. One of these methods forms the analysis procedure contained within the AASHTO method while the other is used in the ASTM method. The AASHTO method currently requires a regression analysis to a functional form that is non-descriptive of the data within the method. Different research laboratories and different analysis methods can obtain significantly different results depending upon the data collection scheme used for the testing and the subsequent data selection for analysis. In order to avoid these ambiguities it is recommended that the AASHTO method is changed to define failure as the peak in nÊ* (or equivalent parameter for bending stiffness). Additional concluding comments can be made as follows:

- The newer data collection schemes increase the calculated fatigue life by approximately 25% over those used to originally develop the specification.
- Differences in fatigue life calculated by the AASHTO method are more sensitive to the data included for highly modified products.
- Different methods of smoothing the nÊ* data in the ASTM format have minimal effect on the calculated fatigue life.
- Trimming of data which is representative of cracked beams is recommended to improve analysis.
- Consideration of the nÊ* parameter could be used for the test termination.
- The data collection scheme could be improved by storing data on a stiffness reduction basis.

Some additional work could be conducted to look at the errors produced in fitting sinusoidal curve to the data sets. This could provide some useful guidance on data trimming and/or test termination. Analysis of sine curves could follow the same scheme as currently being used for dynamic modulus testing in AAHTO TP62.

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