Evaluation of Strain-Controlled Asphalt Binder Fatigue Testing in the Dynamic Shear Rheometer

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ABSTRACT

A laboratory study is being conducted to study the effectiveness of strain-controlled fatigue testing of asphalt binders in the Dynamic Shear Rheometer (DSR). The number of cycles until failure were recorded, with “failure” being defined as a 50% reduction in complex modulus (G^*). This criterion is based upon a previous study carried out by Dr. Monismith & Dr. Tsai (2005) for the Pacific Coast Conference on Asphalt Specifications. Nine binders were used to prepare asphalt concrete mixtures, which were in turn cut into rectangular beams and tested in strain-controlled bending to measure fatigue life. The current standard in the United States for binder includes measuring G^* and the phase angle (δ), then setting a maximum limit of the quantity $G^*sin\ \delta$ as a predictor to fatigue performance. The study carried out by Dr. Monismith showed that the fatigue performance of the asphalt concrete beams correlated poorly with the $G^*sin\ \delta$ value of the binder used in the mixture. The current study performed at the University of Wisconsin-Madison uses the same binders, along with mixture fatigue data from the previous study, in an attempt to evaluate the relevance of binder fatigue testing to mixture performance. The testing involves using Rolling Thin-Film Oven (RTFO)-aged binders to mimic the state of binder aging in the mixture beams. Samples are placed in the DSR using an 8-mm diameter by 2-mm thick geometry. Strain-controlled oscillations using two different sampling methods are run at 1% and 2% strain until failure; these strain levels were chosen to coincide with the strain levels used in the previous study (200µ and 400µ, respectively) (Masad et al 2001). Temperatures for testing are the same as the previous study at 10, 20, and 30C. Binder fatigue testing in the DSR has shown good correlation with the results of the mixture fatigue testing. However, sampling methods and the subsequent stress history of the materials have shown to have a significant effect on the fatigue behavior.

Keywords: binder, fatigue, DSR, healing, stress history.

1. INTRODUCTION

The current Superpave binder fatigue parameter has been shown to be insufficient as a predictor of pavement fatigue performance. Recent studies have shown that $G^*sin\ \delta$ values obtained from asphalt binders used in mixes correlates poorly to laboratory mixture fatigue testing (Monismith & Tsai 2005). Progress has been made during the last few years to introduce a more meaningful fatigue parameter for binders, but the extent to which a new test and the parameters derived from it will relate to mixture and pavement performance has yet to be determined. The lack of correlation between the binder $G^*sin\ \delta$ and field performance could be attributed to more than one factor. It is however believed that not using the actual conditions of stress and strain experienced by binders in typical mixtures and the reliance on small strain testing are among the most important responsible factors.

Recent studies have clearly shown that response of asphalt binders to repeated cyclic loading show damage accumulation behavior that cannot be predicted by the few initial cycles used to measure $G^*sin\ \delta$ (Bahia & Delgadillo 2005). Also, modeling of the strain distribution within the mix has shown that the binder can experience strain levels as high as 90 times those experienced by the mix (Masad et al 2001). By testing binders within the linear viscoelastic region, it is likely that the current specification is not addressing the actual behavior within the mix. These high strains may be indicating that fatigue failure of pavements is, in part, due to the non-linear behavior and subsequent stiffness reduction of binders within the mix. Various fatigue-testing protocols have been proposed in order to better model the fatigue behavior of binders. However, further investigation needs to be performed in order to relate to contribution of binder fatigue behavior to pavement performance.

The objective of the study performed by Monismith and Tsai in 2005 was to provide useful information about the contribution of asphalt binder properties to the fatigue performance of asphalt mixtures. Nine binders that are representative of those used along the Pacific coast of the United States were evaluated using the SuperPave testing protocol. Those same cements were used to prepare asphalt concrete mixtures of the same aggregate gradation, cement content, and air void content. Beam fatigue testing was performed on the mixtures using repeated flexural loading at a frequency of 10 Hz. Two strain levels were employed (200μ and 400μ), and the testing was performed in triplicate at three temperatures: 10, 20, and 30°C. Fatigue failure was defined as a 50% reduction in flexural stiffness of the beam specimens. Ultimately, it was found that the binder properties tested using the SuperPave protocol did not show indication of mixture fatigue performance.

The focus of this study is to determine the relevance of asphalt binder fatigue testing in the Dynamic Shear Rheometer using the mixture fatigue data from the study mentioned above. The reason to use DSR is that it has been widely used to measure the rheological properties of asphalt. The effectiveness of a new binder fatigue testing protocol in the prediction of mixture fatigue performance depends on the extent to which its properties can be accurately measured, and also on its contribution to mixture fatigue performance.

2. METHODS

2.1 Materials Selection

The asphalt binders used in this study were the same materials used in the study performed by Monismith & Tsai in 2005 for the Pacific Coast Conference on Asphalt Specifications. Nine representative cements were chosen, including six performance-graded materials rated from a PG 52-28 to a PG 76-16, one AC-20 polymer-modified material, one performance-based asphalt rated PBA-6A (also polymer modified), and one viscosity-graded material rated AR-4000. Cements in this study were aged using the Rolling Thin Film Oven Test (RTFOT) in order to simulate the state of aging in the mixtures tested from the previous study by Tsai et al. Table 1 includes a list of binders included and the PG grade of each binder.

Table 1. PG grades and types used in the study.

Name	PG Grade	Type
AB – 1	64 -22	Neat
AB – 2	64 -28	Modified
AB – 3	52 -28	Neat
AB – 4	64 -10	Neat
AB – 5	76 -16	Neat
AB – 6	70 -28	Modified
AB – 7	64 -28	Modified
AB – 8	64 -28	Neat
AB – 9	58 -16	Neat

2.2 Experimental Design

Due to the amount of time needed for traditional fatigue testing, all binders were tested at each combination of strain level and temperature before replicate testing is to occur, in order to complete a full set of data. In order to draw comparable conclusions to the results from the previous study, the testing temperatures were kept the same at 10, 20, and 30°C. The strain-controlled testing performed on the mixtures was performed at levels of 200μ and 400μ at 10 Hz; however, results from the study by Masad et al (2001) showed that strain levels experienced by the binder domain within a mixture can actually be up to 90 times that experienced by the mixture as a whole. Therefore, the 200μ and 400μ levels were multiplied by a factor of 50 in order to approximate the realistic strain levels experienced by asphalt binder in the mixture tests. Accordingly, strain levels of 1% and 2% were used at 10 Hz in the DSR tests.

2.3 Procedure

All tests were performed in a TA Instruments AR2000 Rheometer using an air-cooled environmental test chamber. A typical example of results and the definition of failure (50% G_0) is shown in Figure 1 below.

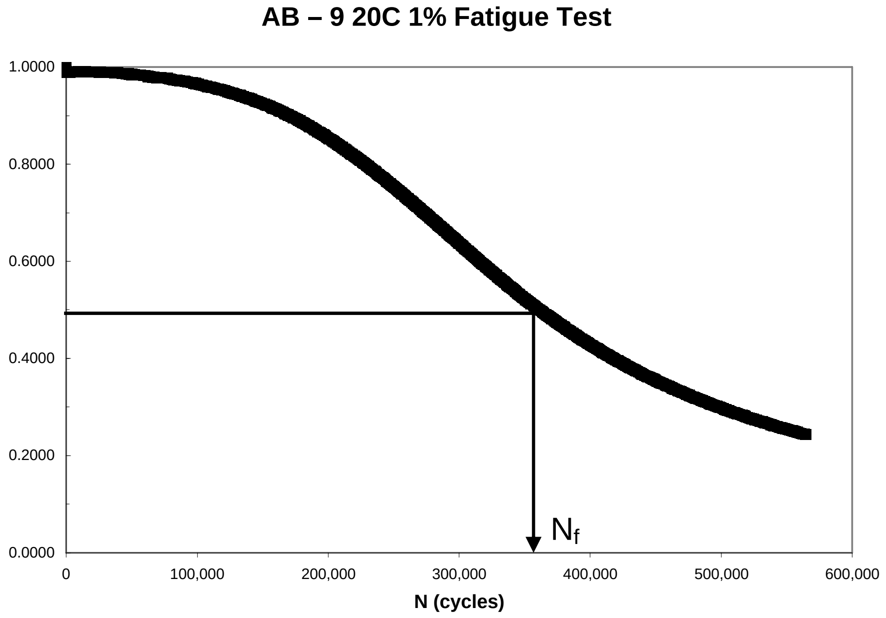

Figure 1. Typical Example of DSR binder Fatigue Test results and the determination of N_f (Number of cycles to failure)

For strain-controlled testing, the controller software includes three types of methods in order to control strain, as the machine is a controlled stress instrument. Two were employed for this study; the first is an iterative process known as "precision sampling" in which the instrument applies an initial "trial" torque, and then uses the resulting strain value to adjust the torque systematically until the designated strain is reached. Within this method, the operator has the option of either saving or disregarding the trial stresses as actual data points; both options were evaluated for this study. The second is a continuous method that is commonly thought of as "traditional" fatigue testing, in which the instrument continuously monitors and adjusts the torque necessary to apply the appropriate strain as the oscillations occur. The continuous method does not allow for any pause in the oscillations, so the rate of repeated cyclic loading is consistent throughout the entire duration of the test. However, since the instrument is stress-controlled, the precision of the strain levels achieved during testing are not as high as the precision sampling method. The need for the machine to adjust torque levels to reach the appropriate strain can be problematic at high frequencies if the machine isn't able to perform the calculations fast enough. The precision sampling method offers greater precision, but the oscillations are not continuous when the machine is adjusting the necessary torque level.

Samples were prepared by pouring hot liquid asphalt into silicone rubber molds approximately 8 mm in diameter by 2 mm in depth. Once cooled to room temperature, the cement disc was liquefied on the top and bottom surfaces with a heated metal spatula in order to provide good adhesion to the upper and lower plates of the DSR. Once in the machine, the specimen was trimmed and conditioned at the testing temperature for 20 minutes. Repeated cyclic loading was then performed until a 50% reduction in complex modulus *G** had occurred. This fatigue criterion was selected to match what was used in the previous mixture study.

3. RESULTS

One objective of the study performed by Dr. Monismith & Dr. Tsai was to explore the relationship between the SuperPave fatigue parameter $G^*\sin\delta$ and the fatigue performance of asphalt concrete mixtures. During the fatigue testing of the binder specimens for this study, the maximum value of $G^*\sin\delta$ was recorded and compared to mixture fatigue performance from the previous study. Figure 2 depicts the results which confirm the findings previously reported by Dr. Monismith and Dr. Tsai. The results clearly show that the binder fatigue parameter $G^*\sin\delta$ does not correlate with the fatigue performance of asphalt concrete mixtures.

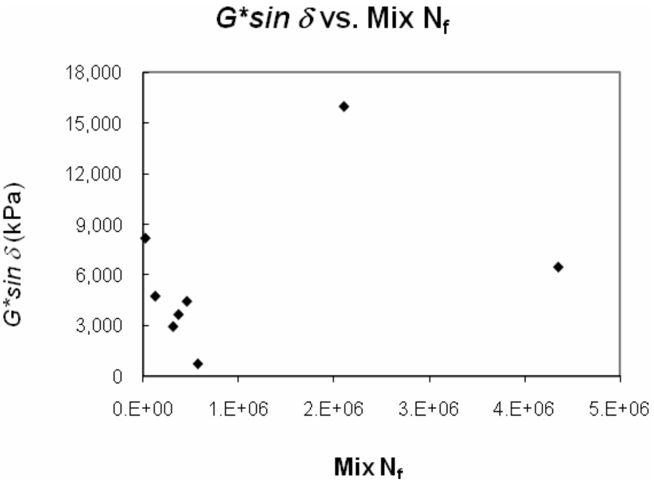

Figure 2. Plot of $G^*\sin\delta$ values against mixture fatigue life

3.1 First Trial Testing Using Precision Sampling Method

The first trial of using the DSR was conducted using the precision sampling method (without saving trial stresses) at 20°C. Not all samples tested achieved a 50% stiffness reduction by the testing limit of 48 hours, so only the samples that did so are included in the figures. The method is considered a good approach as the strain is kept as close to the target strain as possible. As seen in Figure 3, the trial has yielded results showing a significant correlation between binder fatigue and mixture fatigue. With exception of one binder, the correlation is above 90 %.

It should be noted however that during the periods of time when the instrument is adjusting the torque levels needed for target strain, the material is experiencing some form of rest periods. It is unknown at this time exactly when they are occurring or for how long, but the manufacturer of the instrument has confirmed that there are indeed periods of time when the machine is not oscillating at the specified frequency so that torque adjustments can be made. Due to this fact, the number of cycles during the test could not be calculated simply by multiplying testing time by oscillating frequency, so testing time until failure was used for comparison analysis.

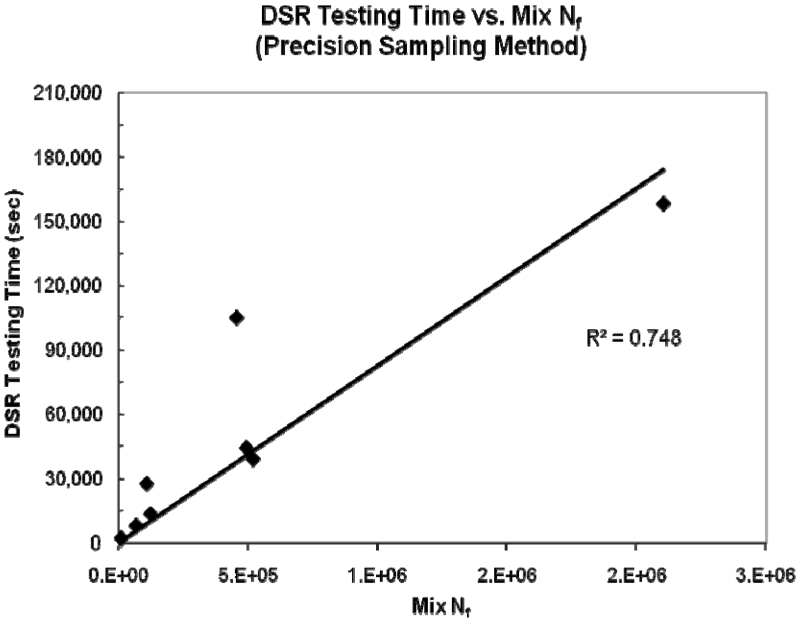

Figure 3. Plot of DSR testing time until failure against mixture cycles until failure for the precision sampling method.

Table 2. Test combinations shown in Fig. 3.

Binder	Strain Level
AB - 1	1%
AB - 1	2%
AB - 3	2%
AB - 4	1%
AB - 4	2%
AB - 5	2%
AB - 8	2%
AB - 9	2%

Since it is known that rest periods could allow healing and that healing could have a significant effect on fatigue life it was necessary to explore the effect of conducting DSR testing using another setting.

3.2 Second Trial Testing Using Continuous Oscillation Method

In the second trial the continuous oscillation method was used in which the oscillation does not stop and the adjustment of stress to keep strain constant is done while the oscillation continues. This could lead to higher strains in most cases as the adjustment requires time while stress is kept same.

As shown in Figure 4, the continuous oscillation method did not yield strong correlation of the binder fatigue life (defined as cycles to 50 % G^*) to the mixture fatigue results (also defined as 50% reduction in mixture stiffness). Testing was run at 20°C as well as 30°C due to the shorter duration of the test method in an effort to gather more data points. As can be seen in the figure below, the data begins to diverge as it moves farther from the origin. There could be several reasons for the lack of correlation such as edge effects in the DSR, change in loading mode (shear in the DSR versus bending in the mixture fatigue), or the lack of good estimate of actual strain in binder domains in the mixture. Whether the differences are due to the condition of edge fracture as described by Anderson et al. (2001), or if it is due to fundamental differences in fatigue properties when the binder is introduced to a mixture is unclear at this time. Due to the wide range of strains experienced by the asphalt binder domain within a mixture, it is also possible that the non-linear behavior is a critical factor.

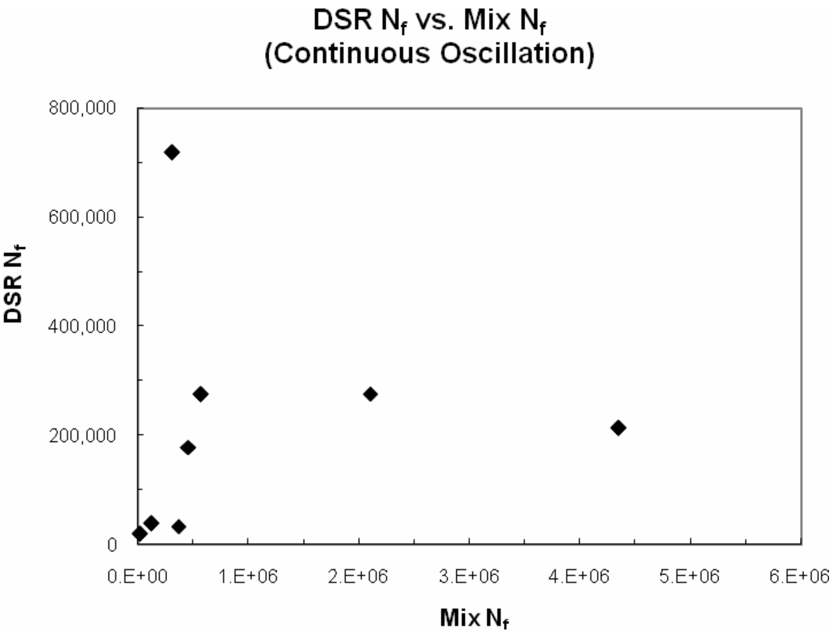

Figure 4. Plot of DSR cycles until failure against mixture cycles until failure for the continuous oscillation method.

Table 3. Test combinations shown in Fig. 4.

Binder	Temperature (°C)	Strain Level
AB – 1	20	1%
AB – 1	30	1%
AB – 1	30	2%
AB – 3	20	2%
AB – 3	30	2%
AB – 4	30	2%
AB – 7	20	2%
AB – 8	20	2%

4. COMPARISON OF DIFFERENT STRESS HISTORIES IN THE DSR

To compare the fatigue response due to the different stress histories, selected binders were tested in the DSR using different protocols. Figure 5 below depicts the results. By plotting the value of G^* during the binder fatigue test versus the DSR testing time, it becomes evident that the stress history of the sample plays an important role in its fatigue performance. For the material shown in the figure below (labeled “Asphalt Cement – 2”), the fatigue life while using the continuous oscillation method was far less than that of the precision sampling method. Based on preliminary results, fatigue life also appears to depend on whether or not the trial stresses are saved as data points.

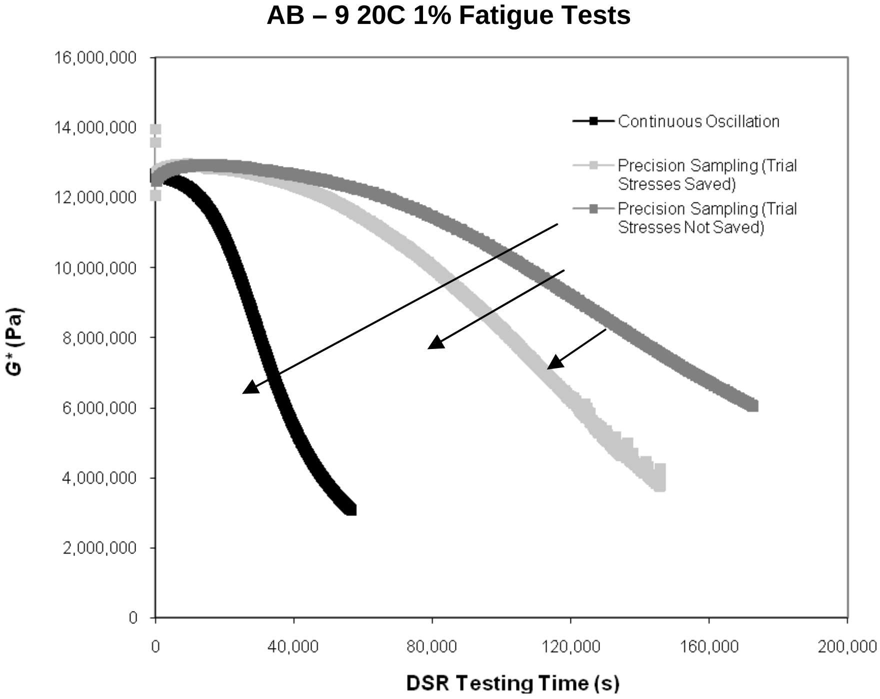

Figure 5. Plot of binder stiffness against testing time for different types of fatigue tests

The above results agree with information regarding rest periods and healing reported in the literature. It has been shown that rest periods have a significant effect on the fatigue behavior of asphalt mixtures (Kim & Lee 1998, Little et al 2002). Dr. Little’s study involved use of repeated cyclic shear loading of sand and binder mixtures in a device similar to the DSR, and found that by applying ten 2-minute rest periods over the duration of a single fatigue test, fatigue life increased on an average of 70%. The results from the precision sampling method are showing that these periods of inconsistent oscillation are increasing the fatigue life of the samples, and are doing so with good correlation to mixture fatigue results.

The performance discrepancy from two different stress controlling methods, continuous vs. iterative, in the DSR fatigue tests indicates that the effect of loading history on the fatigue behavior of binder is very significant. The Iterative method consists of loads at target strain level, loads during adjustment to reach target strain level, and possibly some rest periods. However, this is not the case for the continuous method. The different loading histories between the two methods complicate the characterization of fatigue behavior. The loading history has to be quantified in the future fatigue tests, even for the same tests by the same device, but with different method to control the applied loads by the device.

5. CONCLUSIONS AND RECOMMENDATIONS

As this study is a work in progress, further testing at all combinations of temperatures and strain levels will be performed for all conditions used in the mixture fatigue study in order to provide additional information on the varying levels of fatigue life of binders tested in the DSR. However, the preliminary findings raise three main issues about this topic:

1. It is clear that the current asphalt binder fatigue parameter ($G^*\sin\,\delta$) does not correlate with mixture fatigue results.
2. Using the DSR to measure binder fatigue is a plausible method. However, careful control of the DSR equipment used to test binders' fatigue performance is critical to the value of the data output. As seen in this study, three different fatigue test data sampling methods can yield significantly varying results. Knowledge of these methods and the variables affected by their differences are essential to making the proper inferences about the data collected.
3. Continuous oscillation or "traditional" fatigue testing of binders does not show a clear relation to mixture fatigue performance. The work done to replace the current SuperPave fatigue parameter needs to be expanded to evaluate whether fatigue properties of binders can be effectively measured using existing equipment, and then correctly applied to mixture and pavement performance.
4. The stress history on the binder has a significant effect on the fatigue performance of the binder. It is speculated that the main effect is due to rest periods that are not well controlled in the existing software of certain DSR devices. The healing properties of binders need to be evaluated alongside those of mixtures in order to obtain a greater understanding of the fatigue performance of asphalt pavements.

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