University Transportation Research Center - Region 2

Final Report

Characterization of Fatigue Properties of Binders and Mastics at Intermediate Temperatures using Dynamic Shear Rheometer

Performing Organization: Rowan University

October 2013

Sponsor:
University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

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16. Abstract

The paper compares the fatigue life of neat and modified PAV-aged binders and mastics and determines the influence of dust on fatigue life using the Linear Amplitude Sweep (LAS) method. It will also compare these results with results from the DER and 50% Drop Methods as reported in previous research. The binders used were PG 58-28, PG 64-22, PG 70-22, PG 76-28 and PG 82-22. The dust content for the mastic binder was 0%, 5%, and 15% dust to binder by mass. Using the fatigue life of the binder with 0% dust as a baseline, a range of temperature (based on the difference between high and low performance grade) of 86 may make the binder susceptible to fatigue however increasing the range to 92-104 may produce an increase in fatigue life for small amounts of dust (5%). Although the PG 82-22 experienced a decrease in fatigue life with the addition of a small amount of dust, the change was very small prospectively (dropping only 0.7%) suggesting that this binder also experiences a slight increase in fatigue life with the addition of 5% dust. It was determined that two types of failure (mode I and mode II) were occurring in the LAS tests and that the results from the DER and 50% Drop tests may have been either of these failure types. This made it difficult to compare the two procedures based on the results. Further studies must be performed to determine what causes the two different failure types (mode I and mode II). Overall, the binders with higher range in PG grade appear to be less sensitive to addition of dust and binder should be appropriately selected if sensitivity to dust is to be minimized.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The objective of this research was to compare different fatigue testing methods and to observe the effects of strain amplitude and dust content on modified and unmodified binders. Research began with an extensive literature review and binder testing was conducted using the Dissipated Energy Ratio (DER) and 50% Drop in Modulus (DM) Methods. Later in the project, a version of the Linear Amplitude Sweep (LAS) Method was used to test the samples. Five different binders were tested at three different percentages of dust. Binders tested were PG 58-28, 64-22, 70-22 (neat samples), 76-28, and 82-22 (modified samples). This percentage was a measure of the dust-to-binder ratio by mass. The amounts used were 0%, 5%, and 15%. Due to equipment malfunction and the length of the tests, only PG 64-22, 70-22, and 82-22 were tested using the DER and DM Methods. This study observed two types of failure, failure type 1 is a plate adhesion failure (shear) and failure type 2 (tension). Based on the DER and 50% Drop Methods, small amounts of dust decreases the cycles to failure of neat samples but possibly increases the cycles to failure with larger amounts. Also, adding a small amount of dust to modified samples can increase the cycles to failure by approximately 345%. Based on the LAS Method, the addition of dust to the binder decreases the fatigue life of binders with smaller temperature ranges between high and low temperature PG grade (86ºC). Binders that have a large temperature range experience an increase in fatigue life with a small addition of mastic but decrease with the addition of larger amounts. Further studies must be performed to determine what causes the different failure types. Additionally, the true grade of the binders should be measured in order to appropriately compare the fatigue testing methods.

BACKGROUND

Mastic binder is the addition of dust with binder. Dust consists of particles which pass the No. 200 sieve and, due to their size, combine with the binder in such a way that they can be considered part of the effective binder. For this reason, it is important to study mastics in addition to pure binder to determine the effects of dust.

In the SuperPAVE binder specification, AASHTO M320, the value G*sin(δ) was determined to be the measure of fatigue.(1) This value is determined by testing binders at an intermediate temperature using a Dynamic Shear Rheometer (DSR). This specification however, is not an accurate measure of fatigue life. In a study by Johnson et al., the fatigue life of asphalt mixes was compared to the fatigue life of the binders as defined by G*sin(δ). His results show that alternate methods seem to be more accurate based on field studies.(2) Several studies have been dedicated to better define a criterion that can satisfactorily explain a fatigue failure.

Three methods of determining fatigue life were selected for analysis in this study: the 50% Drop in G*, the Dissipated Energy Ratio (DER), and the Linear Amplitude Sweep (LAS) methods. Each method was used to determine the fatigue life of modified and unmodified binders and mastics. Most studies to date were performed on RTFO-aged binders (neat, polymer, and chemically modified). There is a lack of fatigue testing done on mastics and long term-aged binders and mastics. It is these results that the study here has analyzed.

OBJECTIVES

The objectives of this paper are:

1) Analyze the effect of different dust to binder ratios with different types of binders on the fatigue life.
2) Compare the fatigue lives of long term-aged neat and polymer-modified binders with and without dusts obtained from the 50% Drop, DER, and LAS methods.

INTRODUCTION

Using the data from a strain controlled DSR test, the 50% Drop and DER methods were used to calculate fatigue. The dissipated energy ratio, which is the value of the cumulative dissipated energy over the dissipated energy at a particular cycle *n.* The 50% drop in G* value and the dissipated energy ratio from the sweep-test have been used to determine the number of cycles to failure. The ways in which failure is described are:

1. the number of cycles it takes to cause the initial G* value to drop 50%, and
2. the number of cycles it takes before the dissipated energy ratio (DER) diverges from a linear trend.(2,3,4,5)

Though neither method has been defined as the most accurate measure of the fatigue life of binders, both have proven to be more accurate than traditional methods.(2) More recently, a new method has been developed called the Linear Amplitude Sweep Method, which defines failure as the point at which the initial G*sin(δ) has dropped 35%.(9)

The 50% Drop in Modulus Method

This method requires the simple calculation which involves the initial G* value (G_i^*) and the G* value at the *n*th cycle (G_n^*), as shown in Equation 1:

$$\% \, drop = \frac{(G_i^* - G_n^*)}{G_i^*} * 100 \qquad [1]$$

When the percent drop has reached 50%, the sample is considered to have failed (see Figure A1).

The Dissipated Energy Ratio Method

This method calculates the amount of energy dissipated per cycle. The cumulative dissipated energy ($W_{\sum n}$) over the dissipated energy at each cycle (W_i) is called the dissipated energy ratio (DER). The dissipated energy at a given cycle is as shown in Equation 2:(3)

$$W_i = \pi * \varepsilon_i * \sin(\delta_i) * \sigma_i \qquad [2]$$

Cumulative energy and DER are calculated using Equations 3 and 4, respectively.

$$W_{\sum n} = \sum_{i=1}^{n} W_i \qquad [3]$$

$$Dissipated\ Energy\ Ratio = \frac{W_{\sum n}}{W_i} \qquad [4]$$

This value, when plotted against the number of cycles produces a graph which moves linearly upward, then undergoes a nonlinear region which moves into a second linear region, more steep than the first, as shown in Figure 1.

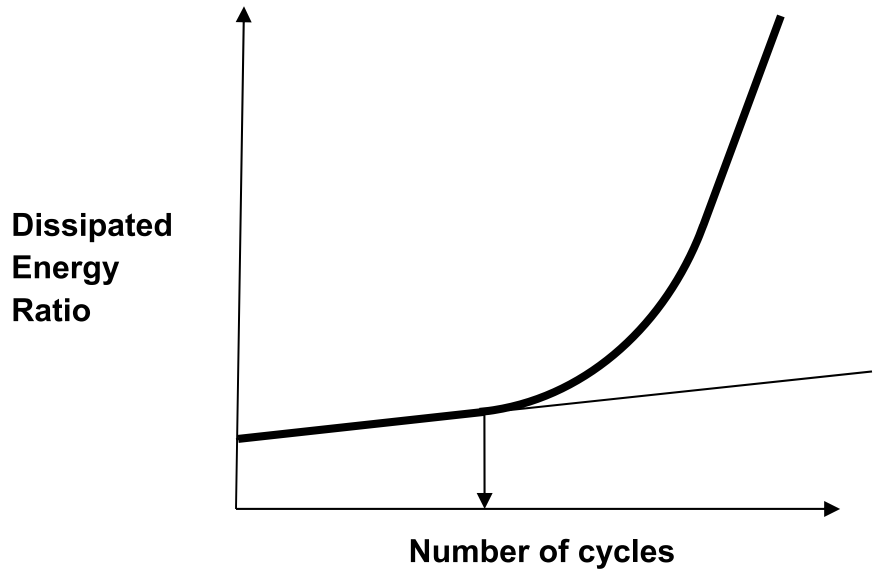

Figure 1. Schematic of Dissipated Energy Ratio Versus Number of Cycles

The first linear region is the initial stage where the stiffness (G*) of the binder begins to drop. The nonlinear region is called the crack propagation stage. Here, the binder has, by definition, failed and macrocracking is forming within the sample.

Linear Amplitude Sweep Method

Due to repeatability and efficiency issues concerning most fatigue criterion techniques, Kin el al. developed the Linear Amplitude Sweep Method (LAS).[8] This test defines failure as a point which can be calculated once the initial G*sin(δ) has dropped 35%.[9] This testing method is based on the same principles as the Dissipated Energy Ratio and 50% Drop in complex modulus methods and is established as a more accurate measure of the fatigue life of binders.

This method is conducted by applying increasing strain amplitude. Several calculations are done to determine the number of cycles to failure N_f. First, damage accumulation (D(t)) is calculated based on the initial undamaged value of G* (MPa) from the 1% applied strain interval (I_D). At a given applied data point (γ_0), the dynamic shear modulus (G^*), the phase angle (δ), a value calculated from the slope of the cycles versus the storage modulus (α), and time (t) in seconds, where *i* is the i^{th} cycle, as shown in Equation 5 is calculated:[9]

$$D(t) \cong \sum_{i=1}^{N} [\pi * I_D * \gamma_0^2 * (|G^*| * \sin\delta_{i-1} - |G^*| * \sin\delta_i]^{\frac{\alpha}{1+\alpha}} * (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \qquad [5]$$

Then, the damage at failure (corresponding to a 35% drop in modulus) is calculated using the average value of $|G^*| \sin\delta$, which is the variable C_0, and coefficients derived through linearization of the power law (C_1 and C_2), as shown in Equation 6:

$$D_f = 0.35\left(\frac{C_0}{C_1}\right)^{\frac{1}{C_2}} \quad [6]$$

The damage to failure is used to define variable *A* and *B*, which will allow for the equation for the cycles to failure to be calculated. For *A,* the equation uses the loading frequency (*f*) of 10 Hz and a value calculated using C_2, α, and *k*. All other variables are previously defined and the *A* and *B* values are calculated using Equations 7 and 8:

$$A = \frac{f*(D_f)^k}{k*(\pi*I_D*C_1*C_2)^\alpha} \quad [7]$$

$$B = 2*\alpha \quad [8]$$

Finally, N_f is calculated using Equation 9:

$$N_f = A*(\gamma_{max})^{-B} \quad [9]$$

An example of the output table, the generated graph of Shear versus Strain, and the Constant “C” versus Damage Intensity can be seen in the Appendix as Table A1, Figure A2 and A3 respectively.

Studies to date have not looked in-depth at the fatigue lives of long term-aged binders and mastics. Especially, the interaction of the polymer modified binders and the dust is not well understood. Additionally, the influence of factors, such as initial stiffness and strain amplitude, on mastics with polymer modified binders has not been sufficiently studied.

SUMMARY OF THE LITERATURE REVIEW

Strain Amplitude

In the DSR testing procedure, the strain amplitude is a measure of the amount of deformation the binder endures. This can be related to the intensity of the traffic loads, especially for thin overlays. As the strain amplitude increases, the fatigue life of the binder decreases due to increased deformation. This deformation weakens the binder and eventually it will break down, or crack over several loading cycles. Masad et. al. found that the strain within the binder comprises about 90 times the average throughout the hot mix asphalt sample. In light of these results, a study of the effects of strain amplitude should be performed on neat polymer modified binders and mastics.(6)

Instability Flow

Instability flow is a type of failure which can occur during sweep tests in the DSR. It is a condition in which the binder begins to flow, causing the surface area of the sample in the DSR to decrease. This type of failure is not true fatigue failure and is avoided by making the binder sufficiently stiff at the beginning of testing. Anderson et al recommended testing at temperatures so that the initial G* value at least 15 MPa.(3) Because the LAS tests are performed at the intermediate temperature of the binder, instability flow is only a concern for the 50% Drop and DER methods.

Stiffness of Binder in Fatigue Testing

When using the testing procedure for the 50% Drop and DER methods, a specific initial modulus (G*) value must be attained in order to achieve true fatigue failure. To attain the proper stiffness, the temperature of the binder must be adjusted and will be low in comparison to Superpave fatigue tests.(3) This was confirmed in a study by Planche et. al., noting that under repeated shear, the initial complex modulus can significantly affect the behavior of the binder.(5) Anderson et. al. determined initial modulus ranges for neat, SB crosslinked, EVA modified, and chemically modified binders to be 28-55, 15-45, 13-45, and 22-45 MPa respectively.(3) A minimum of 15 MPa is recommended.

Impact of Steric Hardening and Temperature

An asphalt binder which has been heated to a fluid consistency stiffens at ambient temperatures (around 20°C). This reversible phenomenon is called steric hardening and can occur during fatigue testing. Evidence of steric hardening can be observed by an increase in modulus during the beginning of the test.(3,5) Steric hardening can most simply be described as thixotropy (molecular structuring) which can be reversed by working the material mechanically or by applying heat. Increased levels of steric hardening occur in samples which are cooled slowly and can affect the stiffness of the binder.(15) The effect of steric hardening on test results, though it can be accounted for, depends heavily on binder composition. At low strains and temperatures, steric hardening can make results for the binder appear incorrect as the initial modulus will actually increase before it decreases to display a typical fatigue life curve.(5) This phenomenon is small enough not to sway the results, but it is important to mention in order to explain initial binder stiffening.

In Anderson's study, temperature was found to have a linear effect on fatigue life (as temperature increased, fatigue life increased).(3) This was confirmed by Shen and Bonnetti.(4,7) This is due to the fluidity of the binder, which affects the healing rate and propagation of cracks.

Healing

A rest period between loadings will allow the binder to recover and close some of the micro-cracks, this process is called healing.(7) Tests conducted by Planche et. al show that binders partially recover given a certain amount of rest during fatigue testing.(5) The greater the rest periods, the higher is the fatigue life, thus, rest periods significantly affect the fatigue life. These periods have less affect near and beyond the point of failure because after the binder has failed, changes occur rapidly and the microcracking becomes macrocracking.(5) Rest periods have greater affect on polymer-modified binders, which heal faster than neat binders. This is because cohesive bonds within polymer modified binders are more readily reestablished when given time between loading cycles. It is the same property that allows these binders to be more resistant to rutting as well as fatigue damage. Additionally, at low temperatures the healing rate of binders is less pronounced. This is due to the increased stiffness of the binder, a more fluid state being more conducive to healing.(2,5,7)

Impact of Modified Binders

The fact that polymer modified binders experience longer fatigue lives than neat binders has been proven in past studies.(5,7) In a study by Bonnetti et al. in which the impact of modified binders on fatigue life was analyzed, it was determined that these binders have improved fatigue life, especially SB cross-linked samples.(4) This is confirmed by Anderson et al. and Planche et al.(3,5) Planche in particular comments on the impressive fatigue life of cross-linked elastomer modified binders.(5)

SUMMARY OF THE WORK PREFORMED

All the binders and mastics were short term aged in RTFO and long term aged in pressure aging vessel.(11,12) The dust was a dust sample (passing the No 200 sieve) and had a specific gravity of around 2.0. To create the mastic binder, the binder and dust were heated to 250°C and mixed for 15 minutes based on a procedure recommended by Chen at al.(13) This step was executed before RTFO and PAV aging. Temperature was maintained constant throughout the mixing process.(14) Table 1 below shows the materials tested with the 50% Drop and DER testing methods. PG 82-22 is modified with SBS and SBR polymers.

Table 1 - Materials Tested (50% Drop and DER Methods)

	Neat binder (PG 64-22)	**Neat Binder (PG 70-22)**	**Modified binder (PG 82-22)**
No dust	X	X	X
Dust (5% by mass of binder)	X	X	X
Dust (15% by mass of binder)	X	-	-

Testing Protocol (50% Drop and DER)

Testing temperature:	Temperature to achieve an initial G* value of approximately 15MPa
Plate size:	8-mm
Gap:	2-mm
Frequency:	10 Hz
Strain amplitude:	0.5% and 1.5%
Number of cycles:	560,000 (minimum)

The number of cycles was selected based on a study conducted by Anderson et al. At 560,000 cycles (approx 16 hours) the binder, modified or neat, is most likely to have failed.[3] Table 2 below shows the materials tested with the LAS testing method.

Table 2 - Materials Tested (LAS Method)

	Neat Binder (PG 58-28)	Neat Binder (PG 64-22)	Neat Binder (PG 70-22)	Modified Binder (PG 76-28)	Modified Binder (PG 82-22)
No dust	X	X	X	X	X
Dust (5% by mass of binder)	X	X	X	X	X
Dust (15% by mass of binder)	X	X	X	X	X

Testing Protocol (LAS)

The testing temperature is the same as that of the intermediate testing temperature where PAV DSR is tested. The test begins with a frequency sweep which is a conditioning step to prepare the binder for the strain sweep. The test is run until failure.

Plate size: 8-mm

Gap: 2-mm

Frequency Sweep: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30 Hz, at a strain of 0.1%

Strain Sweep: 0.1%, 1.0%, 2.0%, 3.0%, 4.0%, 5.0%, 6.0%, 7.0%, 8.0%, 9.0%, 10%, 11%, 12%, 13%, 14%, 15%, 16%, 17%, 18%, 19%, 20%, 21%, 22%, 23%, 24%, 25%, 26%, 26%, 27%, 28%, 29%, and 30% at a frequency of 10 Hz

Failure Types

Two types of failure were identified throughout the tests, shown in Figure 2. Failure type 1 occurred for almost all DER and 50% Drop tests. The LAS tests produced both failure types. Failure type 1 exhibited more of a shearing kind of failure, on the other hand failure type 2 indicated distinct tension or mixed mode crack in the binder.

Figure 2. Failure type 1 (top) and failure type 2 (bottom)

The number of cycles to failure was determined by identifying the point where the DER versus cycle becomes non-linear and where the percent drop in modulus reached 50% for the DER and 50% Drop methods respectively.[10] The results from the previous publication were assumed to be the same failure type and due to the length of the test, repeatability was not thoroughly explored. With the LAS test, it was determined that there were two distinct failure types and that failure type 2 produced more repeatable results. Failure type 1 exhibited a smooth surface of failure, possibly due to the binder not adhering to both DSR testing plates. Failure type 2 displayed a rough surface with binder remaining on both DSR plate. Examples of these failure types are displayed in Figure 2 above. With the LAS test, the graph of G* versus time was plotted for each test. This revealed the difference between failure type 1 and 2. Figure 3 shows the G*-value against time during the LAS test. Note that there is an initial drop off, which is expected, when it transitions from frequency to strain sweep (from blue to red). However, there is also a clear "drop-off" point during the strain sweep testing phase, which indicates a failure in plate adhesion, indicating failure type 1.

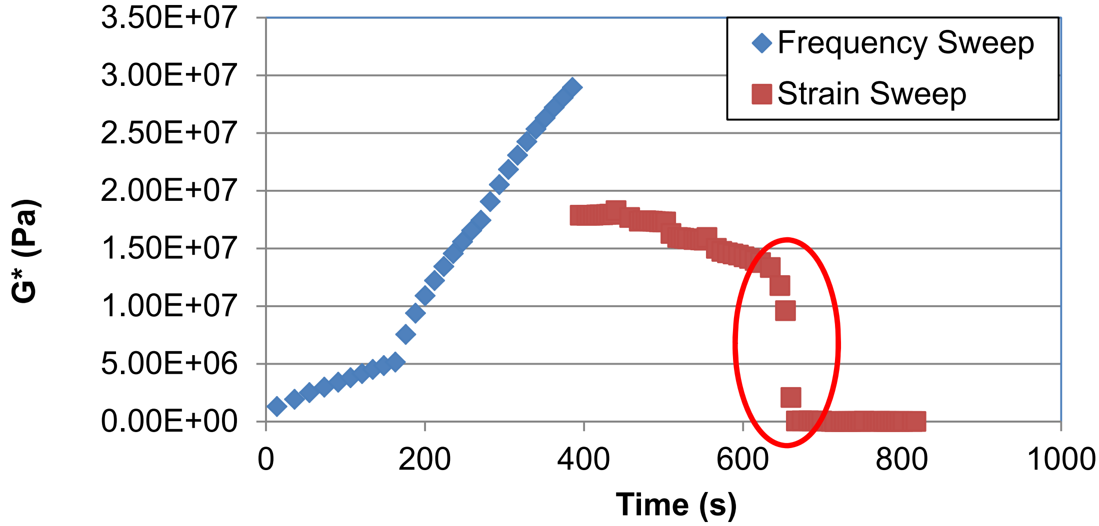

Figure 3. G* versus time for a PG 58-28 (failure type 1)

Figure 4 shows a typical G*-value versus time graph for failure type 2. As depicted, there is a gradual sloping drop in G* until it reaches near zero. After this point, the DSR displays the spiking values which signify complete failure.

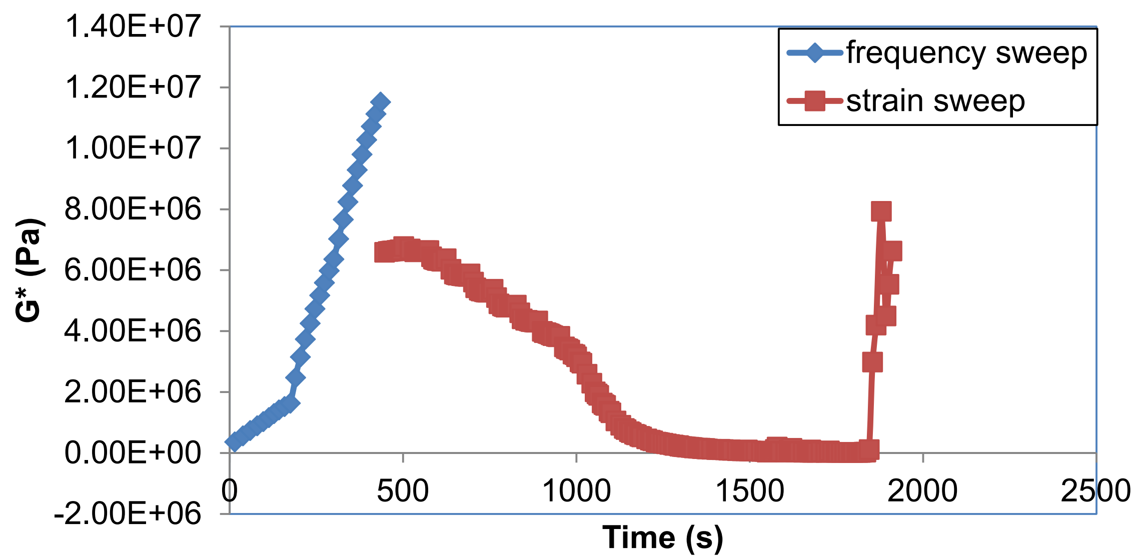

Figure 4. G* versus time for a PG 58-28 (failure type 2)

Impact of Dust on Fatigue Life According to the DER and 50% Drop Methods

A recent study by Peebles et al. adding a small amount of dust (5% by mass) to neat binder shortened the fatigue life based on DER and 50% drop in modulus method. However, adding a same small amount of dust to a modified binder lengthened the fatigue life. The study concluded that the impact of addition of dust to the binders on fatigue life is dependent on whether the binder is modified or not.(10)

Table 3 – Test Results (50% Drop and DER Methods)

Strain (%)	Binder	Initial G* (MPa)	Initial G*sin(δ) (MPa)	Cycles to failure: DER (cycles, N)	Cycles to failure: 50% Decrease in G* (cycles, N)	Diff. (%)
1.5	64-22 M0%	21.90	14.11	124,499	144,092	13.6%
1.5	64-22 M5%	18.72	12.21	18,802	19,500	3.58%
1.5	64-22 M15%	17.9	12.3	179,048	259,007	30.9%
1.5	70-22 M0%	19.68	13.12	10,608	10,876	2.46%
1.5	70-22 M5%	24.01	14.95	5,378	6,264	14.14%
1.5	82-22 M0%	15.85	11.05	241,293	252,106	4.29%
1.5	82-22 M5%	20.26	13.48	1,074,896	1,143,808	6.00%
0.5	64-22	23.44	14.94	not reached	not reached	-
0.5	82-22	17.69	11.93	not reached	not reached	-

Fatigue Binder Criterion

It should be noted that the "point of estimated failure" is an approximation. Due to the randomness of the plot of slope, the method utilized to determine the end of the linear region is based on the R^2-value of the segment of the data which was an approximate line. The R^2-value had a minimum requirement of 0.97. The point at which the R^2-value reached this value was taken to be the transitioning point. An example of the graphs before and after the removal of the outliers can be found in the Appendix, Figures A4 and A5. The quantitative error incorporated with this designation is difficult to determine, however it should be considered that the results with respect to the DER method are not exact.(10)

Strain Amplitude

The neat binder was tested with strain amplitudes of 0.5% and 1.5%. At the lower amplitude, the point of failure was not reached based on the criteria, the DER method and the 50% drop in modulus method. As shown in Figure 5, a strain amplitude of 1.5% caused the neat binder to fail around 130,000 cycles. The same binder tested at 0.5% strain amplitude shows little deviation from the linear trend though it ran for 10 times the number of cycles. Though the values cannot be compared quantitatively, it is apparent that the lower the strain amplitude, the greater the cycles to failure.(10)

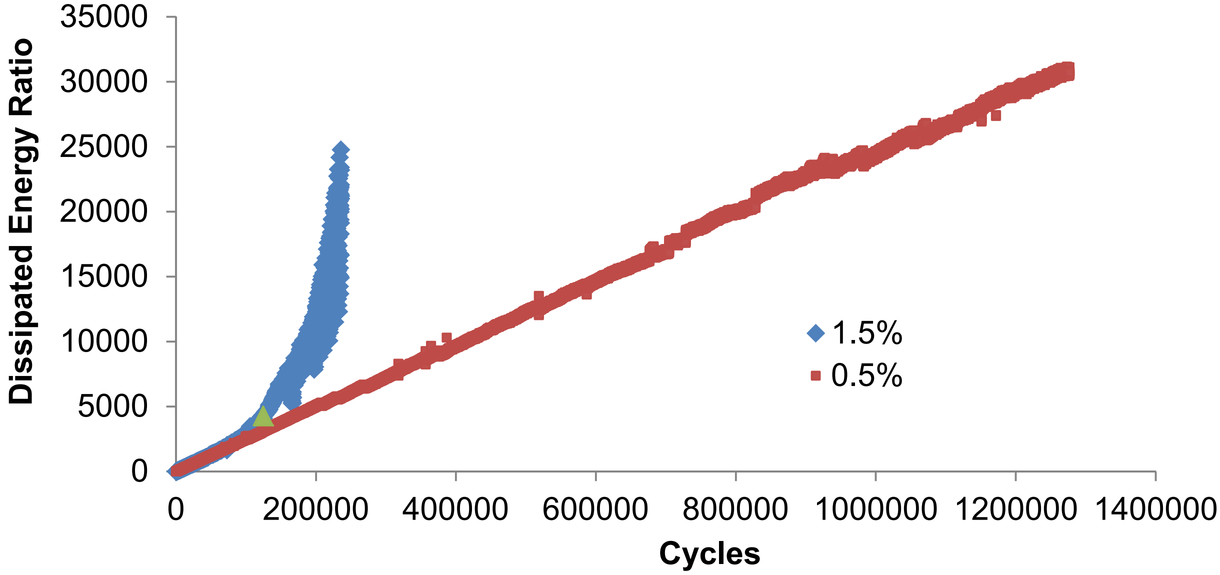

Figure 5. Comparison of strain amplitude (PG 64-22 sample)

The Impact of Dust on the Fatigue Life (DER and 50% Drop Methods)

Figure 6 shows a comparison between the PG 64-22 samples with 0%, 5%, and 15% dust. The black dots represent the points of failure. This graphically displays what was reported in Table 3: a small addition of dust will decrease the cycles to failure and a larger addition of dust will increase it.(10)

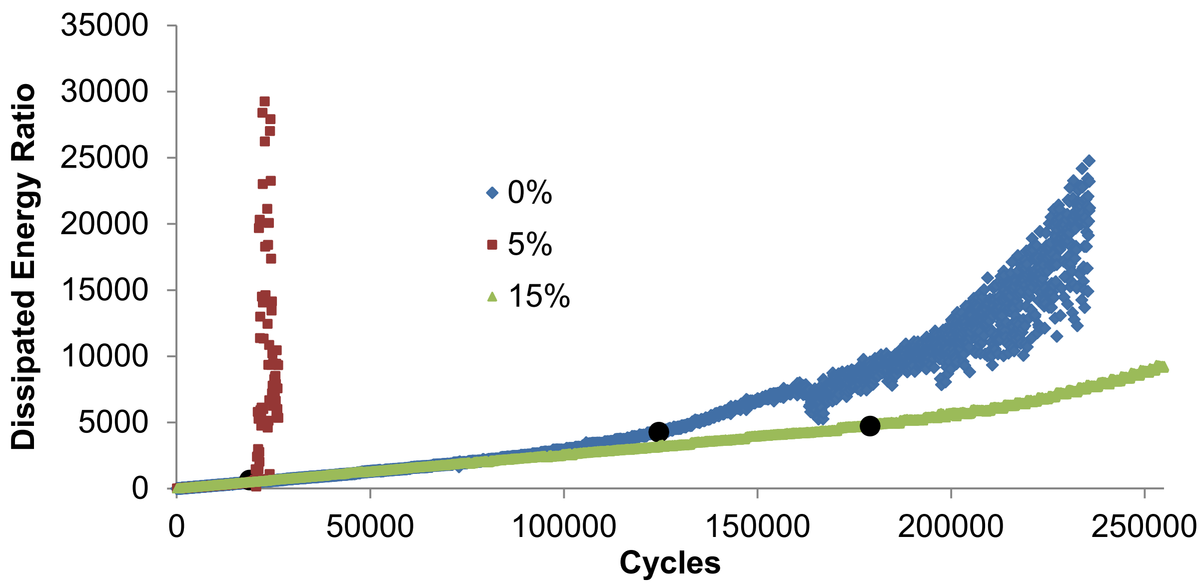

Figure 6. PG 64-22: no dust versus mastic

To analyze this phenomenon in depth, the cycles to failure were considered with respect to the initial G* values. As displayed in Figure 7, the G* values do not correlate with the cycles to failure. The initial stiffness values are fairly close in number so they cannot account for the drop and then increase in cycles to failure as the dust content increases.

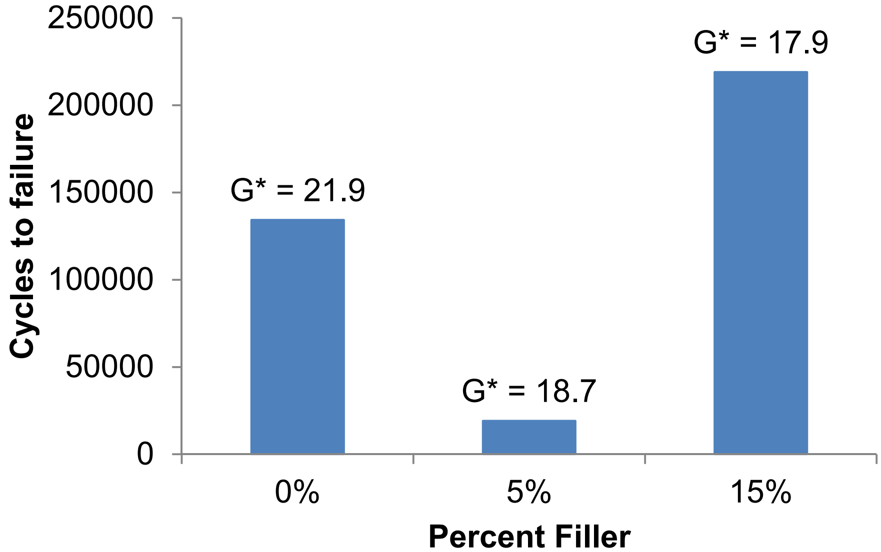

Figure 7. PG 64-22: no dust versus mastic

Figure 8 shows a comparison between the PG70-22 and the PG70-22 with 5% dust. As with the PG 64-22, a small amount of dust decreases the cycles to failure. It would seem that the mastics for neat binders fail much earlier for low mastic percentages (5% dust), reducing the fatigue life by almost 85%. However, increasing the mastic percentage to 15% may increase the fatigue life (as can be seen from the PG64-22 binder with 15% dust).[10]

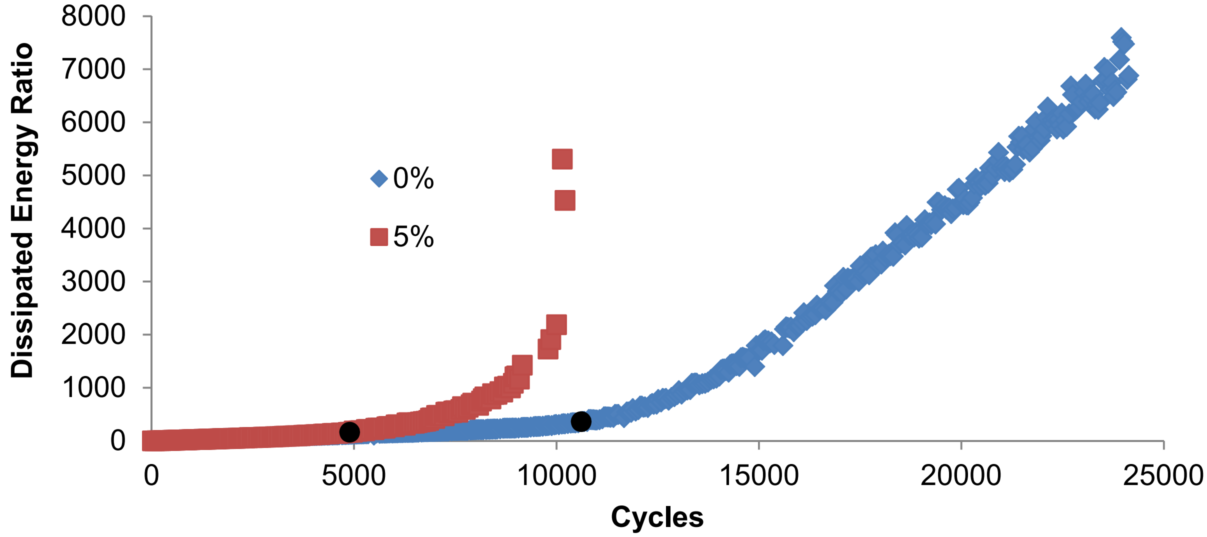

Figure 8. PG70-22: no dust versus mastic

Figure 8 shows the failure in modified binder PG 82-22 with no dust occurred after fewer cycles than the mastic which lasted almost 345% longer. The mastic for the polymer modified binder had notably increased cycles to failure than that of the polymer modified binder. This suggests that the dust reacts differently depending on the modification of the binder.(10)

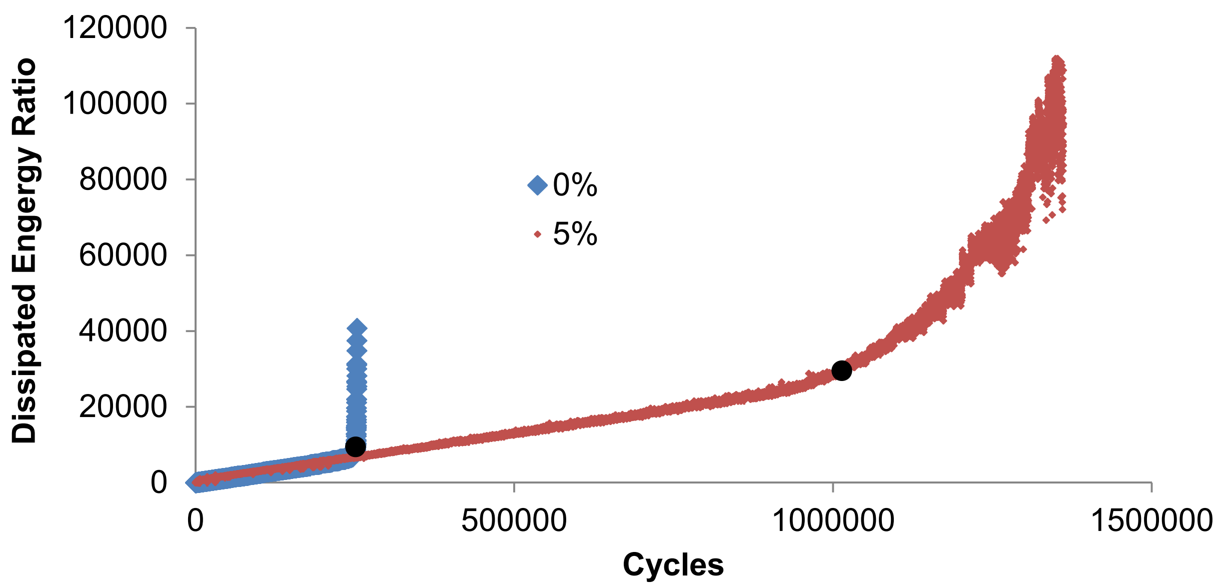

Figure 9. PG 82-22: no dust versus mastic

The reason for the difference between reactions from neat and polymer-modified binders can only be speculated since the polymers and thus the chemical reactions (should they be the cause of the phenomenon) used for modification are unknown. It is assumed that some form of reaction occurs within the polymer modified binder during mastic mixing which strengthens the sample with respect to fatigue life.

The Impact of Dust on the Fatigue Life (LAS Method)

Figure 10 shows the number of cycles to failure at a strain of 2.5% for PG 58-28. As shown, using the LAS method, adding 5% by mass dust to binder decreases the fatigue life. Adding 15% dust by mass can increase it from the sample with 5% but remains less than the 0% dust sample. Error bars are shown and represent 95% confidence intervals.

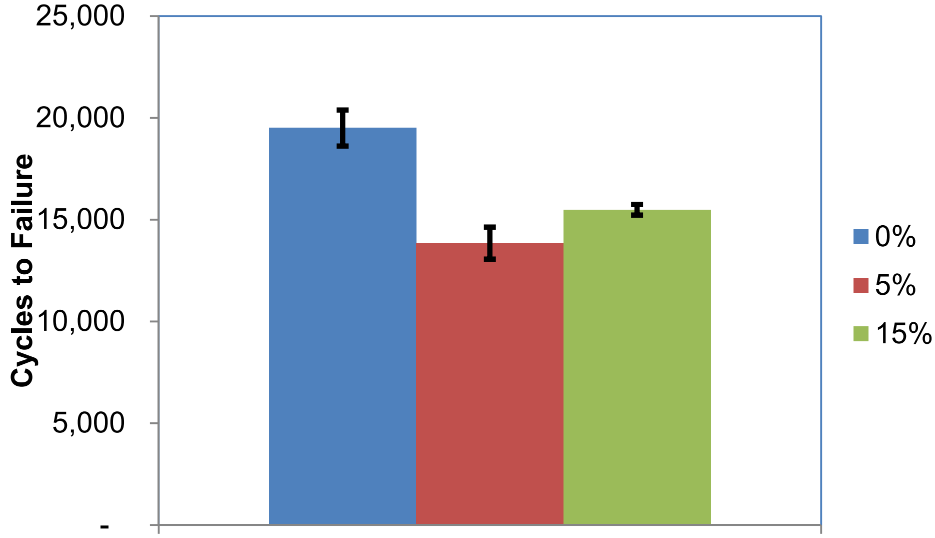

Figure 10. Number of cycles to failure based on LAS method (PG 58-28)

Figure 11 shows the results for PG 64-22. The fatigue life decreases with the addition of 5% dust as with the PG 58-28, however it continues to decrease with the addition of 15% dust by mass.

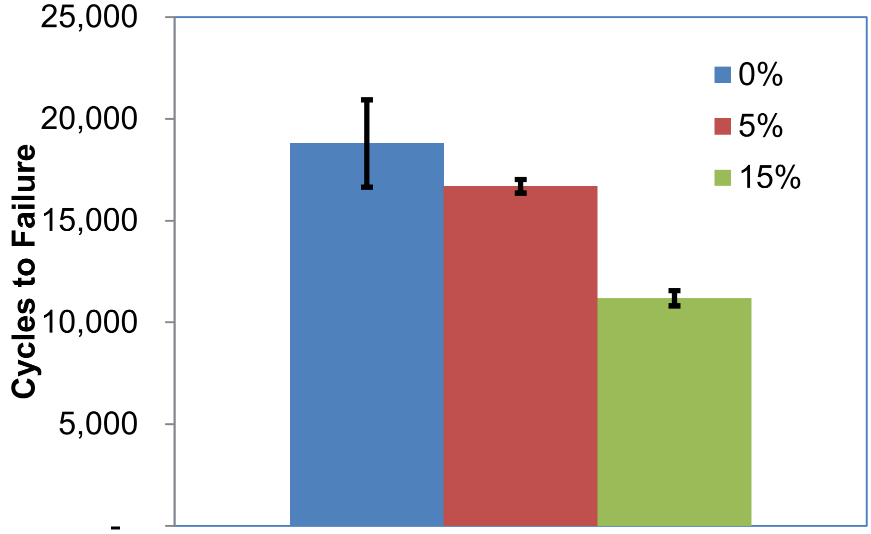

Figure 11. Number of cycles to failure based on LAS method (PG 64-22)

Figure 12 displays the results from the PG 70-22 samples. In this case, adding 5% dust slightly increased the fatigue life but adding additional dust (15%), the fatigue life drops below both measurements from the previous samples (0% and 5%).

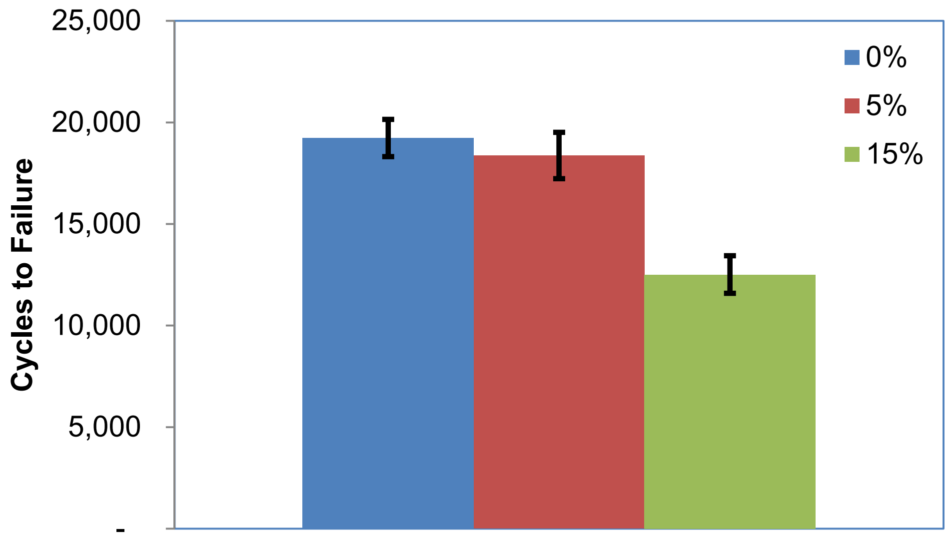

Figure 12. Number of cycles to failure based on LAS method (PG 70-22)

Figure 13 shows the results from the PG 76-28 samples. Here, as with the PG 70-22, the fatigue life increases and then decreases with the 5% and 15% dust, respectively. However, the drop in fatigue life from the sample with 5% dust and the sample with 15% dust is not as significant as that of the PG 70-22 mastics.

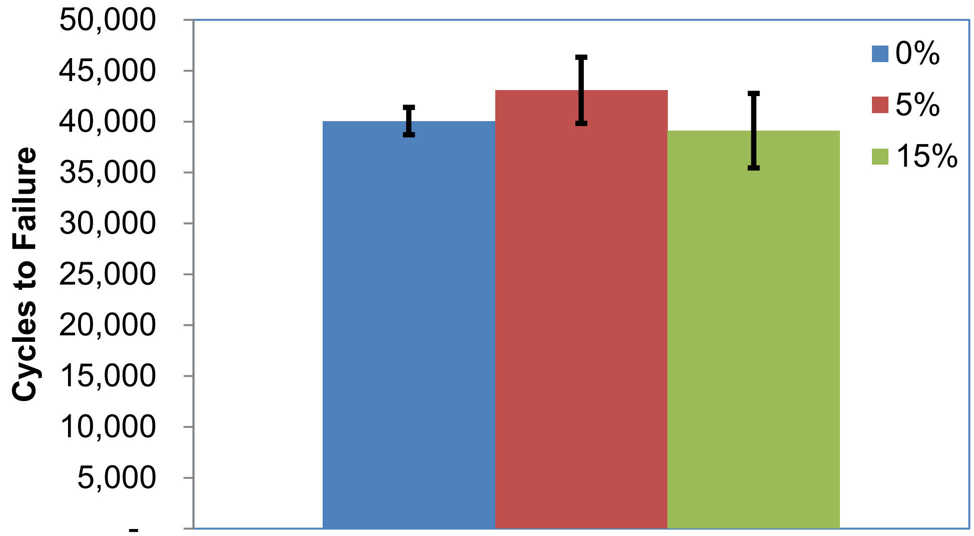

Figure 13. Number of cycles to failure based on LAS method (PG 76-28)

Figure 14 shows the results for PG 82-22, modified for higher temperatures. The trend was consistent with that of PG 70-22 where increasing the dust content lowers the fatigue life. The more dust, the less cycles to failure.

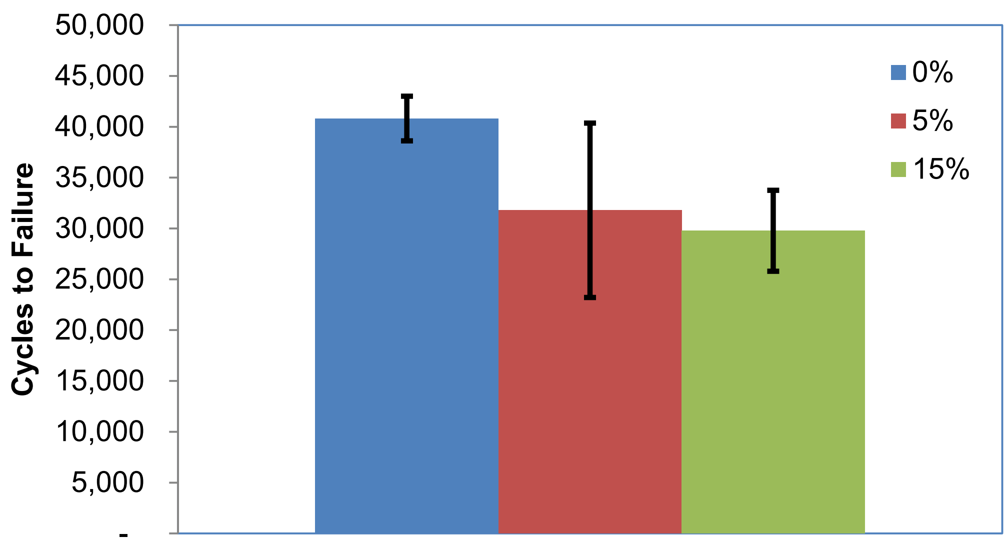

Figure 14. Number of cycles to failure based on LAS method (PG 82-22)

Impact of Binder Grade and Dust Content on Fatigue Life

Table 4 shows a comparison of the decrease or increase in fatigue life in relation to the binder and the amount of dust added. "Increase" and "decrease" are in reference to the base sample (0% dust by mass).

Table 4 - Drop in Fatigue Life Based on Performance Grade and Amount of Dust

Binder	Range of temperature between high and low PG grade	5% dust	15% dust
PG 58-28	86	decrease	decrease
PG 64-22	86	decrease	decrease
PG 70-22	92	decrease	decrease
PG 76-28	104	increase	decrease
PG 82-22	104	decrease	decrease

This summary reveals that the range of temperature between high and low PG grades may have an effect on the fatigue life when dust is added. A range of 86 may make the binder susceptible to fatigue however increasing the range to 92-104 may produce an increase for small amounts of binder. Although the PG 70-22 and 82-22 experienced a decrease in fatigue life with the addition of a small amount of dust, the change was very small prospectively (dropping only 1.4% and 0.7% respectively) suggesting that replicates may reveal that these binders on average may experience a slight increase in fatigue life with the addition of 5% dust.

Comparison of Fatigue Life Between LAS Method and DER and 50% Drop Method

The reason for reporting only cases of failure type 2 for the LAS test was because failure type 2 is more repeatable and may more accurately represent fatigue failure. Failure type 1 resulted in cycles to failure values which seemed random and inconsistent. Though the failure types were not identified during the DER and 50% Drop tests, based on the physical evidence (see Figure 2), most of the tests performed using that procedure were failure type 1. Because pictures weren't taken of every test it is difficult to identify which results from the DER and 50% Drop tests were failure type 2. For this reason, these methods cannot be accurately compared to the LAS test.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions are:

1. Based on the DER and 50% Drop Methods, small amounts of dust will decrease the cycles to failure of neat samples but possibly increase the cycles to failure with larger amounts.
2. Based on the DER and 50% Drop Methods, adding a small amount of dust to modified samples can increase the cycles to failure by approximately 345%.

3. Based on the LAS Method, the addition of dust to the binder decreases the fatigue life of binders at the temperature range between high and low PG grade of 86 degrees. However, as the difference between the high and low PG grade increases, the decrease in fatigue life is much lower and even increases at lower percentages of dust.

RECOMMENDATIONS

Further studies must be performed to determine what causes the two different failure types (mode I and mode II). Overall, the binders with higher range in PG grade appear to be less sensitive to addition of dust and binder should be appropriately selected if sensitivity to dust is to be minimized.

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APPENDIX: Raw Data

Example Data PG 64-22:

LAS Method

Table A1 – Data table for PG 64-22 analysis

Sample:		**Damage level:**	35%
Model:	$\lvert G^*\rvert \sin d = C_0 - C_1(D)^\wedge C_2$		
C_0	C_1	C_2	***Summed Error***
1.000	0.047	0.518	0.674
α	$\lvert G^*\rvert \sin\delta_{initial}$	D_f	***k***
1.696	6.957	47	1.817
A	***B***	Applied Strain [%]	N_f
4.693E+05	-3.392	2.5	**20,976**
		5.0	**1,999**

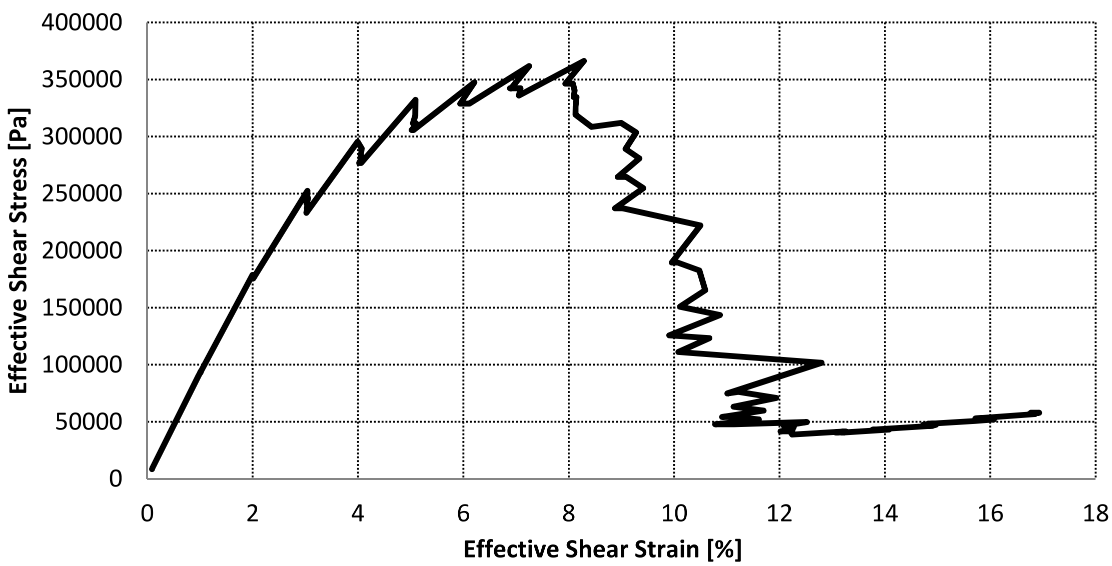

Figure A1. Amplitude sweep data

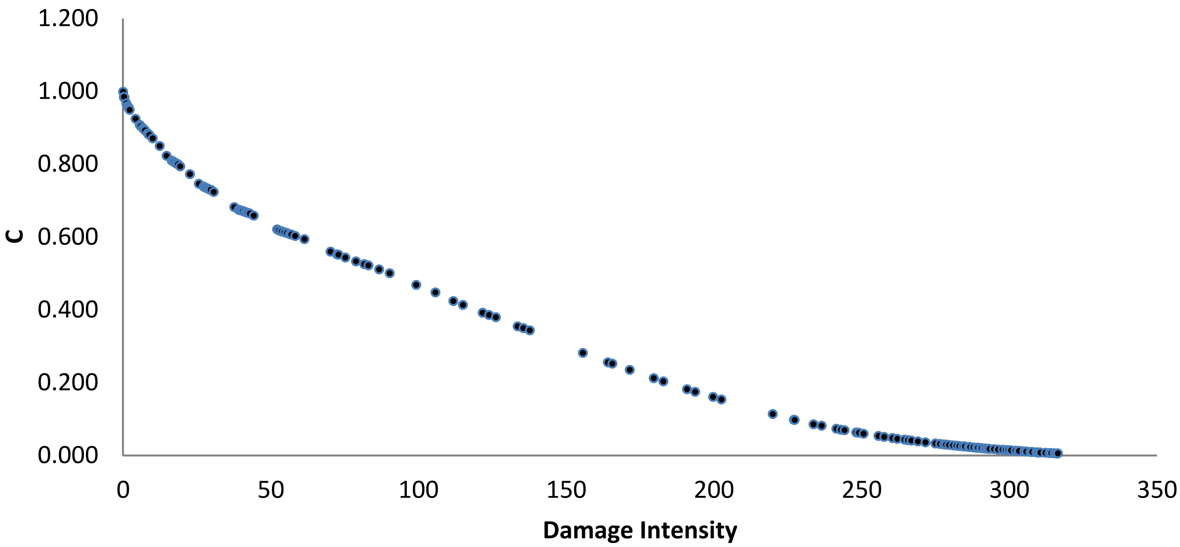

Figure A2. Damage curve from amplitude sweep

50% Drop in Modulus Method:

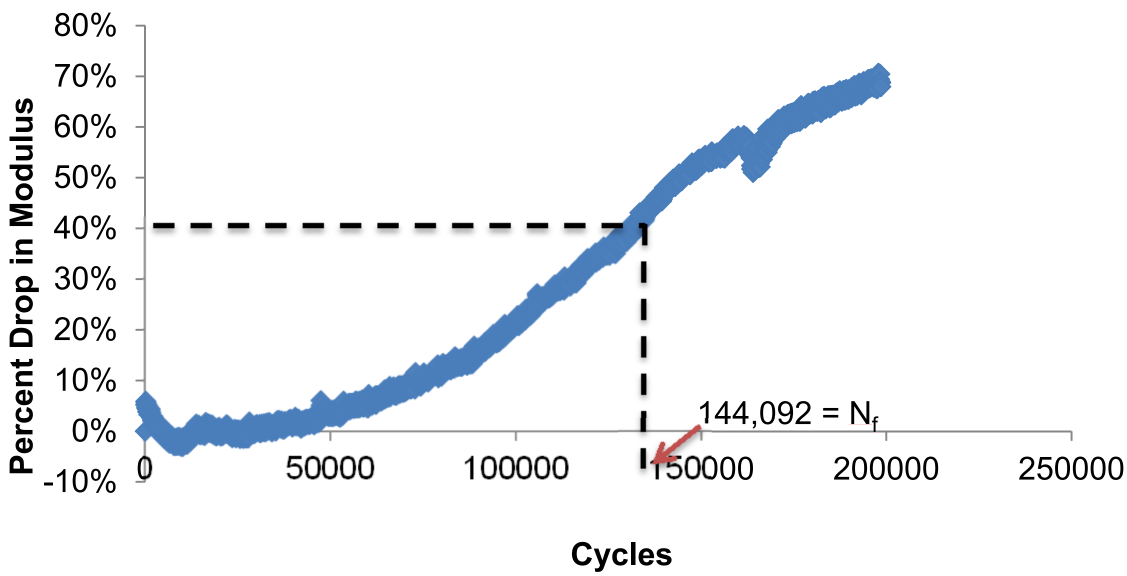

Figure A3. Drop in modulus versus cycles

DER Method

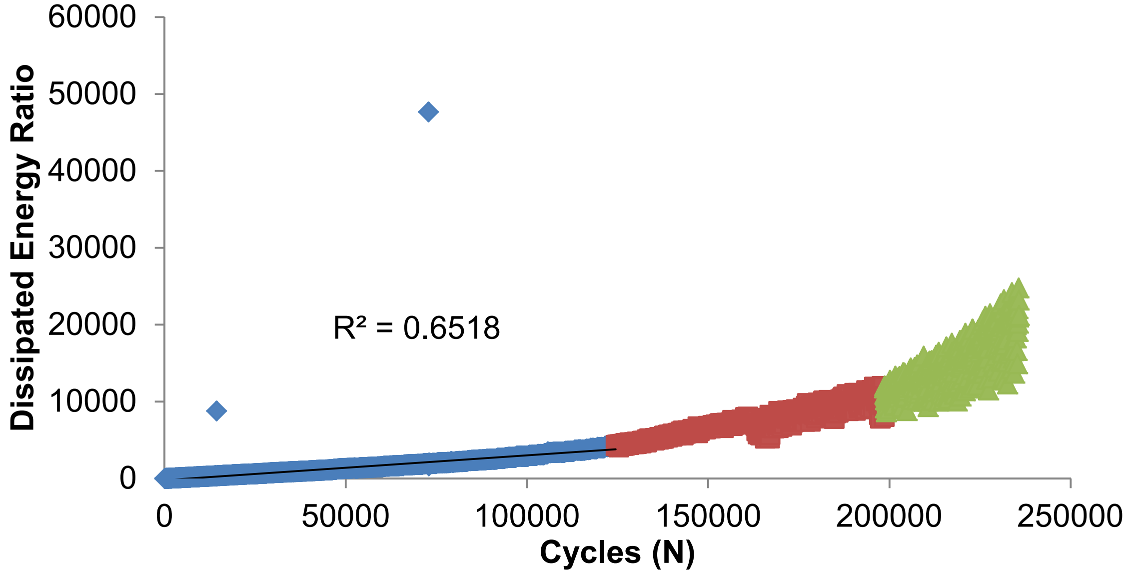

Figure A4. PG 64-22 before removal of outliers

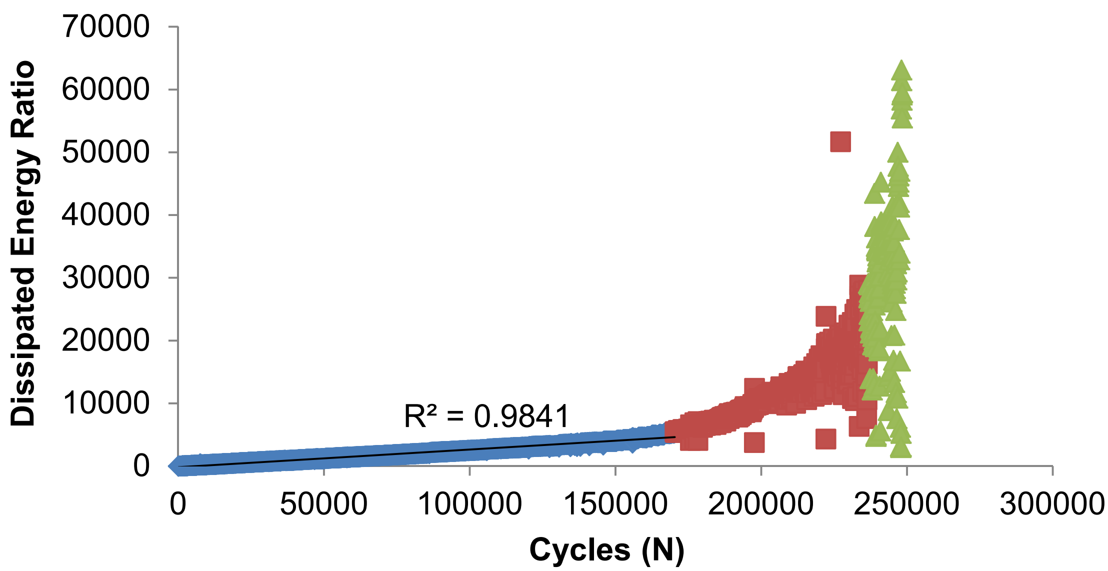

Figure A5. PG 64-22 after removal of outliers

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