Evaluation of an Accelerated Procedure for Fatigue Characterization of Asphalt Binders

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ABSTRACT: *The ability of asphalt binders to resist fatigue damage is critical to the fatigue performance of asphalt pavements. Recently, there have been significant efforts to accurately measure and characterize binder fatigue properties in a way that is suitable for inclusion in binder specifications. This study takes a detailed look into a proposed "accelerated" binder test method that may be able to indicate traditional binder fatigue damage test performance in a much shorter time. A cyclic approach that relies on continually increasing applied load amplitudes to accelerate the growth of damage is investigated. This approach shows a potential to indicate fatigue performance via application of Viscoelastic Continuum Damage. A preliminary methodology is introduced to begin the development of this test procedure for use in binder fatigue specification.*

KEYWORDS: *asphalt, fatigue, polymer modification, viscoelastic continuum damage*

1. Introduction

The search for an improved binder fatigue test method is an on-going effort related to the improvement of asphalt specifications. The current specification practice of measuring $|G^*|\cdot\sin\delta$ does well to evaluate the effect of long-term aging on the material properties of asphalt, but it does not include actual evaluation of resistance to damage. Additionally, it does not account for the effect of pavement structure or traffic loading, as it is measured at only one load amplitude. During NCHRP Project 9-10, a test method was proposed that applies repeated cyclic loading to a binder specimen using the Dynamic Shear Rheometer (DSR), known as the time sweep (Bahia *et al.*, 2001). This methodology follows the definition of fatigue damage, and has been shown to achieve relevant fatigue performance criteria under the appropriate conditions (Anderson *et al.*, 2001; Martono *et al.*, 2007). Also, appropriate load amplitudes can be applied in order to account for the expected pavement strains based on pavement structure and traffic loading. However, the process can be time-consuming, and is thereby impractical for use as a specification-type test.

Recently, multiple test procedures have been under investigation for their abilities to act as a surrogate to the time sweep test. These "accelerated" procedures take significantly less time to perform, but work to unite these methods to time sweep performance via a fundamental link continues to be a challenge. One such test, the Binder Yield Energy Test (BYET), has shown promising correlations with accelerated pavement fatigue performance, but fundamental characterization of the nature of damage growth during this test is problematic for some modified asphalts (Johnson *et al.*, 2009). Recent work has suggested that an amplitude sweep procedure may hold promise for the indication of fatigue performance of asphalt binders (Martono and Bahia, 2008). The strain-controlled amplitude sweep, or linear amplitude sweep, is looked at in detail in this paper, and the results presented here show that there may be a benefit to employing the linear amplitude sweep in future specification.

2. Materials & Experimental Plan

Four binders (one unmodified and three polymer-modified) were selected for the initial portion of this study. It should be noted that the PG grades listed in

Table 1 include the effect of modification (where applicable), as each binder was sampled after being produced by various commercial suppliers. As such, the exact amount of each modifier is not known. All testing was performed after RTFO-aging in order to simulate the aging in lab-prepared mixtures, which will be used in future work to compare fatigue performance of binders and mixtures.

In order to determine the appropriate testing temperature, the concept of iso-stiffness testing was employed (Santagata *et al.*, 2009; Shenoy, 2002). However, the concept was slightly modified in order to incorporate both modulus and phase angle. Rather than selecting a temperature for each material that resulted in the same modulus, the research team used the parameter $|G^*|\cdot\sin\delta$ as the benchmark, using the temperature at which a value of 5,000 kPa (the current SuperPave specification limit) was achieved. This was determined from rheological master curves for both $|G^*|$ and phase angle (shown in Figure 1), which were generated using the models presented by Bahia et al. (2001) and measured from frequency sweep testing using 0.1% applied strain amplitude over a range of 0.1 – 30 Hz and temperatures from 7° - 28°C. The resulting testing temperatures used in this study are given in

Table 1.

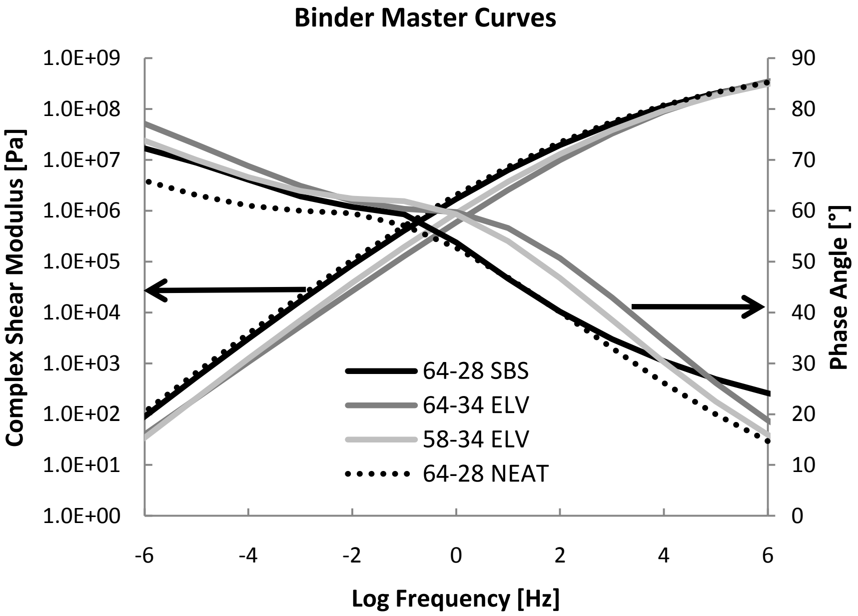

Figure 1. *Rheological master curves for the binders used in this study.*

Table 1. *Description of Binders*

Binder PG Grade	Modification Type	Testing Temperature [C°]
64 - 28	None	13.1
64 - 28	SBS	12.1
58 - 34	Elvaloy®	8.6
64 - 34	Elvaloy®	6.2

The objective of this study is to investigate the linear amplitude sweep procedure under the hypothesis that it can accurately indicate the fatigue performance of asphalt binders as measured by the time sweep. To test this, the following procedures were employed:

1. Time Sweep: Strain-controlled cyclic loading was applied at 5% applied strain up to 360,000 cycles at a frequency of 10 Hz. Two replicates were performed for each binder.

Linear Amplitude Sweep Test: All tests were run at 10 Hz frequency and temperatures listed in

2. Table 1, with an initial 100 cycles applied at 0.1% strain to determine undamaged linear viscoelastic properties. Each subsequent load step consisted of 100 cycles at a rate of increase of 1% applied strain per step for 20 steps, beginning at 1% and ending at 20% applied strain. A graphical example of this loading scheme is shown in Figure 2.

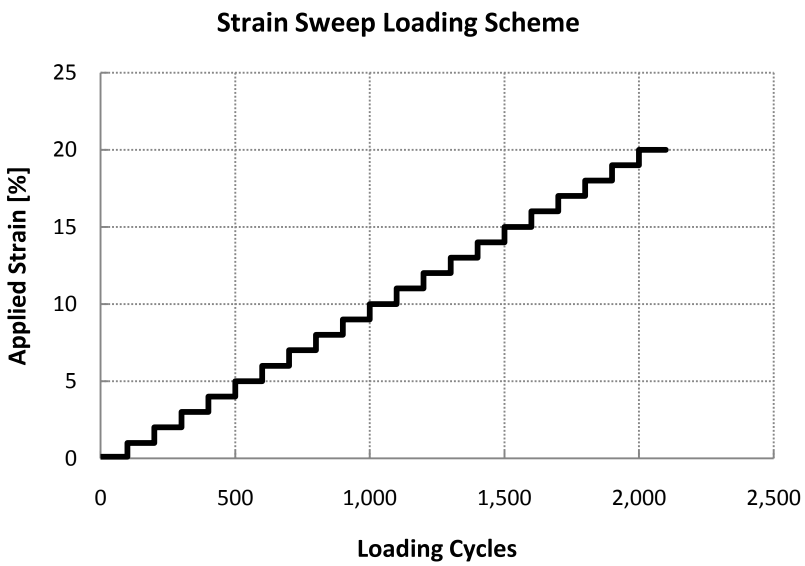

Figure 2. *Loading scheme for the linear amplitude sweep test employed in this study.*

All tests were performed with an Anton Paar Physica SmartPave dynamic shear rheometer (DSR) employing a peltier plate temperature control system and SuperPave 8-mm diameter by 2-mm thick specimen geometry.

3. Results & Data Analysis

3.1 Time Sweep Test Results

The choice of time sweep failure criterion for this portion of the study was N_{P20}, which is based on the dissipated energy ratio documented in previous work in the area of binder fatigue (Bahia *et al.*, 2001; Bonnetti *et al.*, 2002; Delgadillo and Bahia, 2005). This primarily serves as a starting point to begin ranking the relative performance of the materials. It became apparent upon review of the time sweep results that the SBS-modified binder has substantially higher fatigue damage resistance as compared to the other binders when measured in this fashion.

Table 2. *Binder Time Sweep Test Results*

Binder	N_{P20} - 5% strain (Replicate 1)	N_{P20} - 5% strain (Replicate 2)	N_{P20} - 5% strain (Average)
64 – 28 SBS	123,000	144,000	133,500
64 – 34 ELV	32,100	33,000	32,550
58 – 34 ELV	14,700	18,600	16,650
64 – 28 NEAT	24,600	25,500	25,050

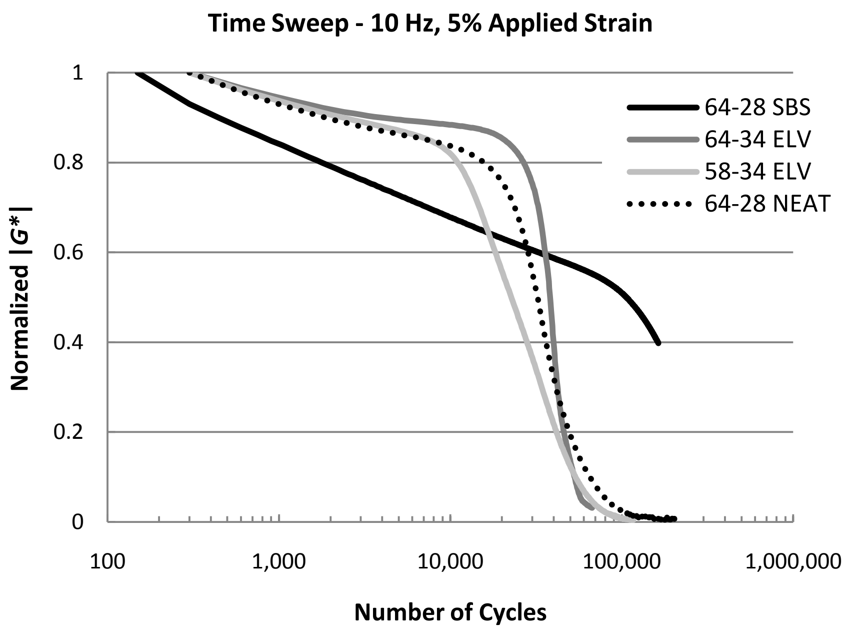

Figure 3. *Time sweep test results for the first replicate testing at 5.0% applied strain.*

3.2 Amplitude Sweep Test Results

The discovery of strain-hardening behavior in the BYET response (as shown in Johnson *et al.*, 2009) was not expected because, for the last several years, testing of binders in cyclic loading did not show such strain hardening behavior for modified asphalts (Bahia *et al.*, 2001; Martono *et al.*, 2007). In an effort to bridge the gap between the cyclic nature of fatigue damage and the monotonic nature of the BYET, investigation of the amplitude sweep test was begun as another consideration for an accelerated fatigue procedure. As shown in Figure 4, the test is comprised of a strain-controlled applied loading, and the resulting shear stress is plotted as the response. As shown in these results, there is no strain hardening behavior. The likely cause of this is related to the rate of loading in a cyclic test in comparison to the rate employed by the BYET. The linear amplitude sweep test operates at significantly higher strain rates due to the frequency of loading set at 10 Hz. At the highest applied strain amplitude (20%), the DSR loads the material from zero deformation to 20% strain in one direction, followed by 20% strain in the opposite direction in 0.1 seconds, far more rapid than the 1% per second employed by the BYET. Strain hardening behavior has been shown to occur at strain levels greater than 1,000% using the BYET; however, the criticality of characterizing binder material properties to such high strain levels needs to further investigation as to whether it is applicable to actual failure strains experienced in the binder phase of an asphalt pavement.

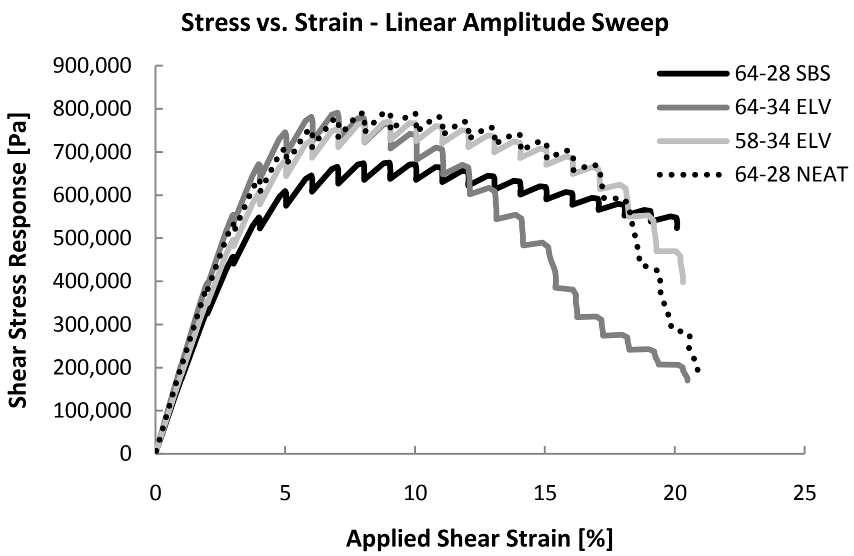

Figure 4. *Linear amplitude sweep test results for the first replicate testing.*

One benefit to the linear amplitude sweep is the ability to analyze the results using continuum damage mechanics. Following work done on fatigue characterization of sand-asphalt mastics (Kim *et al.*, 2006), the data was analyzed by evaluating the change in dissipated energy versus reduction in dissipated energy.

The quantification of damage is derived from the equation for dissipated energy under strain-controlled conditions:

$$W = \pi \cdot \gamma_0^2 \cdot |G^*| \sin \delta \tag{1}$$

Damage intensity (D) can then be calculated using the following equation:

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

where I_D is the initial damaged value of $|G^*|\sin\delta$, and the value of α is taken as $1 + 1/m$, where m is the slope of the log $E(t)$ / log (t) relaxation curve for the given material generated from converting frequency sweep data to relaxation modulus using the approximate inter-conversions given by Schapery and Park (Schapery and Park, 1999), as employed previously by Johnson et al. (Johnson *et al.*, 2009).

As can be seen in Figure 5, the plots of normalized $|G^*|\sin\delta$ (used as an indication of material integrity) versus damage intensity show the well-established trend of decreasing material integrity as damage intensity increases. However, as the curves intersect at many points, the relative ranking of these materials changes depending on which level of damage is selected as the benchmark (the higher the material integrity for a given level of damage, the better a material's resistance to damage accumulation). Indeed, there is no denying that non-linear behavior may be responsible for a portion of the initial decrease in $|G^*|\sin\delta$. However, for the purposes of this paper, any change in $|G^*|\sin\delta$ will be attributed to damage, with future efforts focused on the accurate characterization of non-linearity for use in VECD analysis of linear amplitude sweep data.

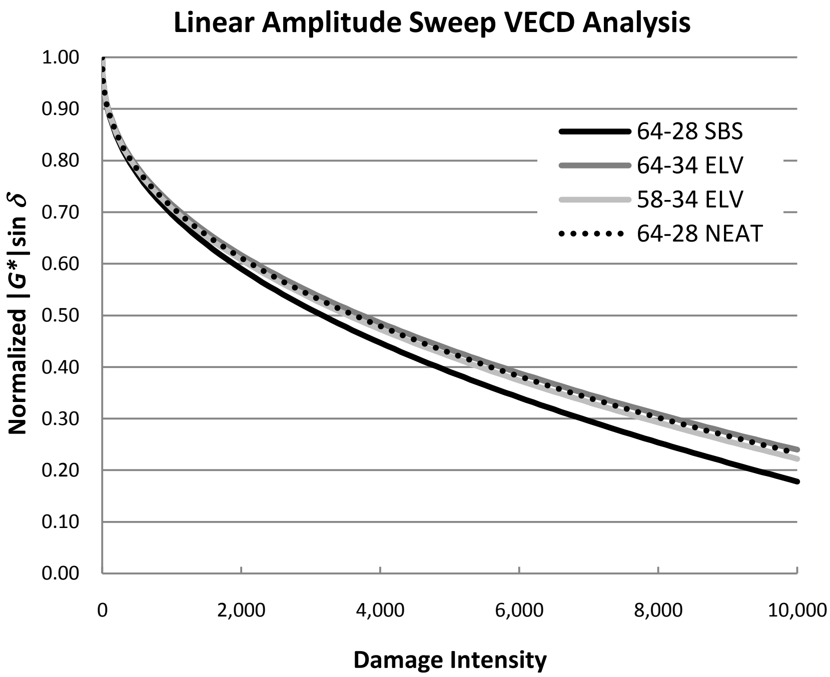

Figure 5. *Plot of normalized |G*| sinδ versus damage from linear amplitude sweep testing.*

In theory, this plot is characteristic of a material's damage resistance capabilities. One possible application of this would be to specify a minimum amount of damage accumulation for given level of material integrity. In order to compare the material integrity at varying levels of damage between the materials, a simple power law following that used by Kim et al. (Kim *et al.*, 2006) was used in the form of

$$|G*|\sin\delta = \mathrm{C}_0 - \mathrm{C}_1(D)^{\mathrm{C}_2} \qquad [3]$$

The values of the fitting parameters C_0, C_1, and C_2, along with the calculated α values and R^2 of the fit for Equation 3 to experimental data, are shown in Table 3.

Table 3. *Average values of Linear Amplitude Sweep VECD fit coefficients*

Binder	C_0	C_1	C_2	R^2	α
64-SBS	12.49	0.192	0.432	99.18%	2.42
64-ELV	14.97	0.225	0.426	99.17%	2.39
58-ELV	14.50	0.225	0.425	99.40%	2.39
64-NEAT	14.62	0.230	0.422	99.41%	2.45

3.3 Comparison of Test Methods

One of the main objectives of this research is to develop a test method and subsequent analysis framework that can be used to efficiently evaluate the fatigue performance of asphalt binders. Currently, the time sweep procedure is the most commonly accepted test procedure for comparison to mixture and pavement fatigue performance, as its methodology is the very definition of fatigue evaluation. However, the accelerated method shown here has been compared to the time sweep in an attempt to find a more efficient procedure that can still provide adequate indication of time sweep performance.

For the comparison of the linear amplitude sweep results to those from the time sweep, it should first be noted that applying the same VECD analysis methodology as was used for the linear amplitude sweep to the time sweep data does not produce characteristic curves that overlap with their linear amplitude sweep counterparts. The two different test procedures appear to be producing damage in differing ways, as shown in Figure 6. Moving forward, making the direct comparison between time sweep and linear amplitude sweep test results using the VECD framework will most likely require one to account for the effect of the substantially higher strain levels employed by the linear amplitude sweep, which may be inducing a non-linear behavior that is not necessarily due to damage.

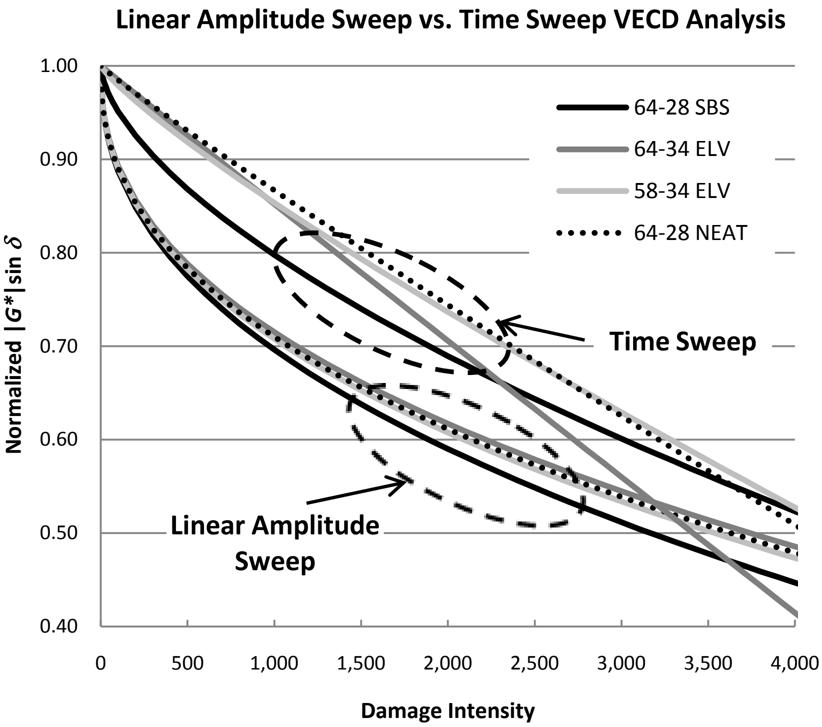

Figure 6. *Comparison of VECD analysis from linear amplitude sweep & time sweep data.*

However, in an effort to investigate any possible relationship between linear amplitude sweep and time sweep damage accumulation characteristics, a prediction of fatigue life was calculated using the derivation shown by Kim et al. (Kim *et al.*, 2006):

$$N_f = \frac{f\left(D_f\right)^k}{k\left(\pi \frac{I_D}{|G^*|} C_1 C_2\right)^\alpha} |G^*|^{-\alpha} (\gamma_{max})^{-2\alpha}$$

[4]

Where $k = 1 + (1 - C_2)\alpha$;

f = loading frequency, Hz;

$|G^*|$ = undamaged complex shear modulus;

D_f = damage accumulation at failure.

First, the time sweep data at 5.0% applied strain was analyzed in the same fashion as the linear amplitude sweep data in order to obtain the appropriate curve fit coefficients, given in Table 4. It should be noted that the equations used to characterize the damage accumulation differs from work previously employed to apply VECD concepts to binder time sweep test data (Wen and Bahia, 2009). Most current applications of VECD analysis employ the strain energy density function for uniaxial monotonic testing (Daniel and Kim, 2002; Kim and Little, 1990; Lee and Kim, 1998), given by Equation 5:

$$W = \frac{1}{2}E\varepsilon^2 \qquad [5]$$

Where E = modulus of the material;

ε = strain.

The area underneath a monotonic stress-strain curve can be thought of as the energy consumed by the material during testing. However, the equation for the energy variable W in Equation 1 is the dissipated energy during cyclic loading, which is proposed due to the cyclic nature of the test procedures being analyzed in this work.

Table 4. *Values of Time Sweep VECD fit coefficients*

Binder	C_0	C_1	C_2	R^2	α
64-SBS	9.11	2.58E-02	0.618	99.70%	2.42
64-ELV	11.83	1.85E-03	0.992	99.79%	2.39
58-ELV	10.95	4.72E-03	0.844	99.65%	2.39
64-NEAT	10.99	2.22E-03	0.940	99.70%	2.45

Equation 4 was then used to predict the fatigue life at two applied strain levels, 3% and 5%, using the VECD coefficients from linear amplitude sweep and time sweep analyses in order to compare the fatigue life of these materials as predicted from separate test methods. Additionally, Equation 4 was simplified in the manner shown by Kim et al. (Kim *et al.*, 2006):

$$N_f = A(\gamma_{max})^B, \quad [6]$$

Where

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

$$B = -2\alpha. \quad [8]$$

The selection of the level of damage accumulation to use in the fatigue life prediction model must be done in a consistent manner for each material. One can select a single value for all materials, but it was found in this particular study that the level of damage at a consistent level of reduction in $|G^*|\sin\delta$ gave the best relationship. Therefore, the damage intensity corresponding to a 35% reduction in $|G^*|\sin\delta$ for each characteristic VECD curve was used for input into the fatigue model parameter D_f. A summary of model parameters and results are given in Tables 5 and 6.

Table 5. *Time Sweep VECD model inputs and results.*

Binder	A	B	3% N_f	5% N_f
64-SBS	8.624E+07	-4.832	426,834	36,165
64-ELV	3.626E+07	-4.776	190,826	16,637
58-ELV	2.821E+07	-4.778	148,129	12,902
64-NEAT	4.873E+07	-4.902	223,330	18,258

Table 6. *Linear Amplitude Sweep VECD model inputs and results.*

Binder	A	B	3% N_f	5% N_f
64-SBS	6.810E+06	-4.832	33,705	2,856
64-ELV	4.588E+06	-4.776	24,146	2,105
58-ELV	4.271E+06	-4.778	22,428	1,953
64-NEAT	5.491E+06	-4.902	25,163	2,057

Although the values for estimated fatigue life for each material differ between the test methods used to derive them, one can see a strong correlation between the test procedures when the values are plotted against one another. While not a 1:1 relationship, the amplitude sweep appears to have the ability to indicate fatigue life as measured with the time sweep test, as shown in Figure 7 and Figure 8 below.

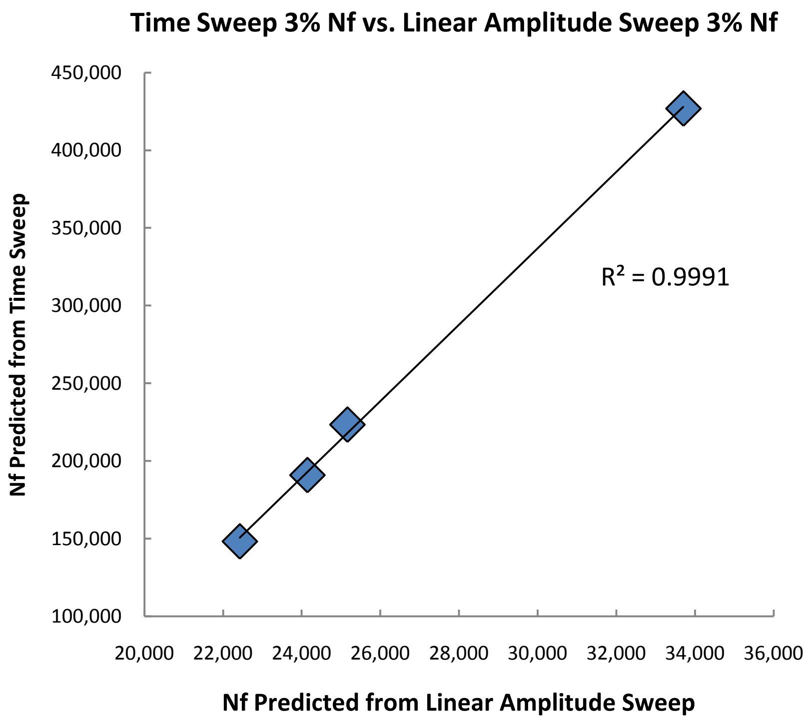

Figure 7. *Plot of predicted N_f at 3% applied strain from times sweep and linear amplitude sweep VECD analyses.*

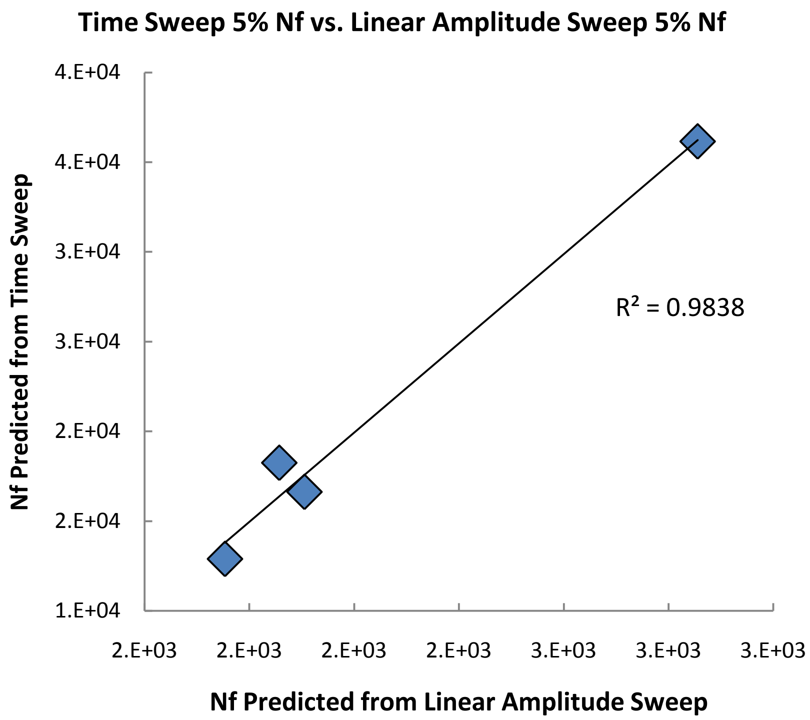

Figure 8. *Plot of predicted N_f at 5% applied strain from times sweep and linear amplitude sweep VECD analyses.*

The correlations shown in Figure 7 and Figure 8 are very encouraging, and thus further investigation of the relationships between the accelerated linear amplitude sweep analysis and the time sweep was pursued. The time sweep binder data measured at 5% strain was characterized by VECD analysis and used to estimate the constant "*A*" (Equation 7) in the commonly used fatigue law shown in Equation 6. The linear amplitude sweep data was used to estimate the same constant using VECD analysis. The values of the "*A*" constant from the two tests were compared as shown in Figure 12.

$$N_f = A(\gamma_{max})^B, \qquad [6]$$

Figure 9 shows that there is a good possibility that the parameters for the fatigue law given in Equation 6 may be successfully indicated from the linear amplitude sweep test in the place of a time sweep test using a simple linear relationship.

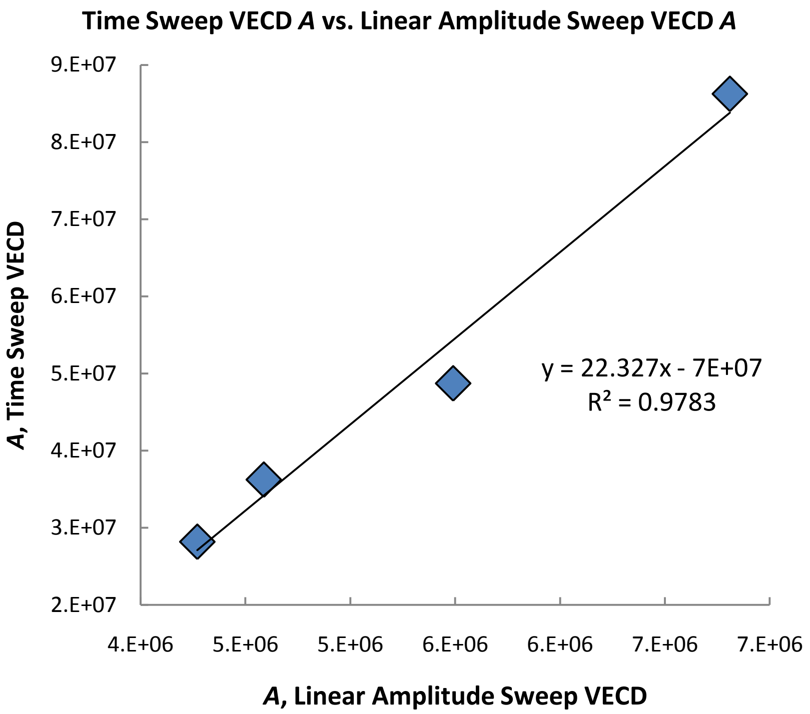

Figure 9. *Plot of the fatigue law parameter "A" derived from VECD analysis of time sweep versus linear amplitude sweep tests.*

3.4 Verification with Additional Binders

In order to begin verifying the relationship between linear amplitude sweep and time sweep results, three additional binders (RTFO-aged) were evaluated using these test methods. The materials were selected from the Turner-Fairbank Highway Research Center's (TFHRC) Accelerated Pavement Testing program to evaluated the fatigue performance of modified binders (Kutay *et al.*, 2008). The control PG70-22 binder (B6272), a crumb rubber modified binder (B6286), and an ethylene terpolymer modified binder (B6289) were tested using the same linear amplitude sweep procedure and 5% applied strain time sweep. The testing temperature was set at 19°C to match with the accelerated pavement testing program that these materials were initially used for. Results of the linear amplitude sweep and time sweep analyses are given in Table 7.

Table 7. *Linear Amplitude Sweep VECD model inputs and results for TFHRC binders.*

Binder	A	B	3% N_f	5% N_f
B6272	8.043E+06	-4.788	41,800	3,623
B6286	1.071E+08	-5.162	369,195	26,433
B6289	4.278E+08	-5.363	1,181,039	76,276

The results were then added to those shown in Figure 9, now shown in Figure 10. As can be seen, the correlation holds and appears to be valid as long as the linear amplitude sweep and time sweep testing temperatures are the same.

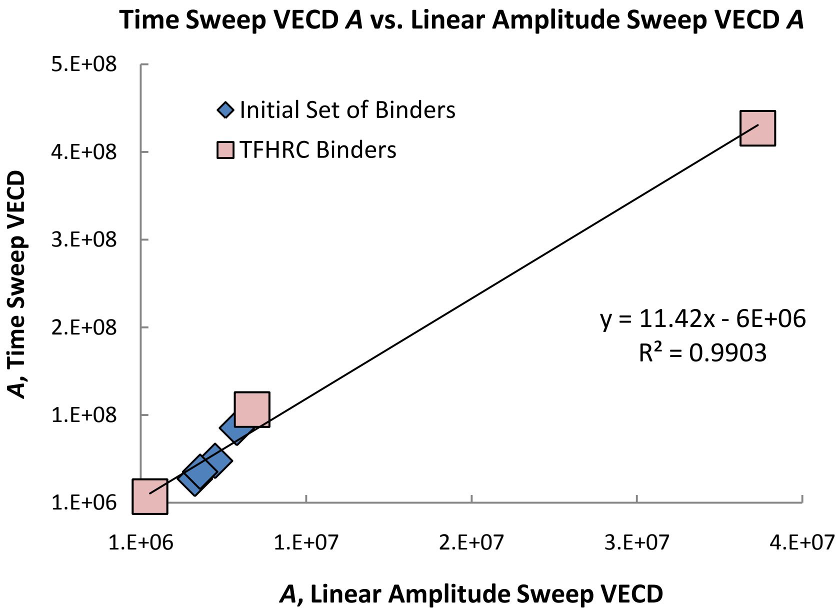

Figure 10. *Plot of VECD "A" with both sets of binders included.*

4 Preliminary Validation Efforts with Field Performance

Upon the discovery of the afore mentioned relationship between linear amplitude sweep and time sweep test results, further steps are now being taken to validate these findings with historical pavement performance data. The United States Long Term Pavement Performance (LTPP) program monitors a select number of highways, recording the extent of the pavement distresses among many other factors. Raw materials for each of these pavements were sampled and stored during their construction, and a limited amount of asphalt binder has been made available to test new evaluation methods, such as the linear amplitude sweep, against measured field performance data.

Seven binders have initially been tested, but the research team hopes to expand this number to approximately 30 binders to refine testing limits. Information regarding the seven binders, along with the measured VECD fatigue model parameters, is given in Table 8. Testing was performed at the SuperPave intermediate temperature for each binder in an attempt to account for the local climate conditions for each highway section. Various climate types were also included, listed as Dry-No Freeze (DN), Wet-No Freeze (WN), and Wet-Freeze

(WF). The measure fatigue distress is listed as the total cracked area of the pavement in square meters.

Table 8. *Information and results for LTPP binder evaluation using the linear amplitude sweep*

Binder	Testing Temp [°C]	Climate Type	Cracked Area [m^2]	*A*	*B*
PG76-10 (04-B901)	37	DN	328	3.978E+06	-3.804
PG76-28 (34-0961)	28	WF	178.8	5.483E+06	-4.296
PG76-22 (37-0962)	31	WN	0.01*	1.180E+08	-4.592
PG58-34 (09-0961)	16	WN	2.1	1.436E+07	-4.679
PG64-22 (34-0901)	25	WN	49.5	7.936E+06	-4.265
PG52-40 (89-A902)	10	WF	6.7	7.278E+06	-4.495
PG64-22 (35-0902)	25	DN	32	9.880E+06	-4.338

*Measured distress is zero, but is listed as 0.01 for inclusion on logarithmic plot.

The VECD fatigue model parameter *A* was plotted against the amount of measured fatigue cracking for each section, as shown in Figure 11, and it can be seen that there appears to be a good correlation using a power law relationship. An increase in the linear amplitude sweep *A* parameter generally indicates an increase in fatigue resistance. As can be seen in Figure 11, the relationship is intuitive since fatigue cracking decreases as the *A* parameter increases. As more test results become available, this data can be useful in determining appropriate specification limits for the results determined from linear amplitude sweep testing.

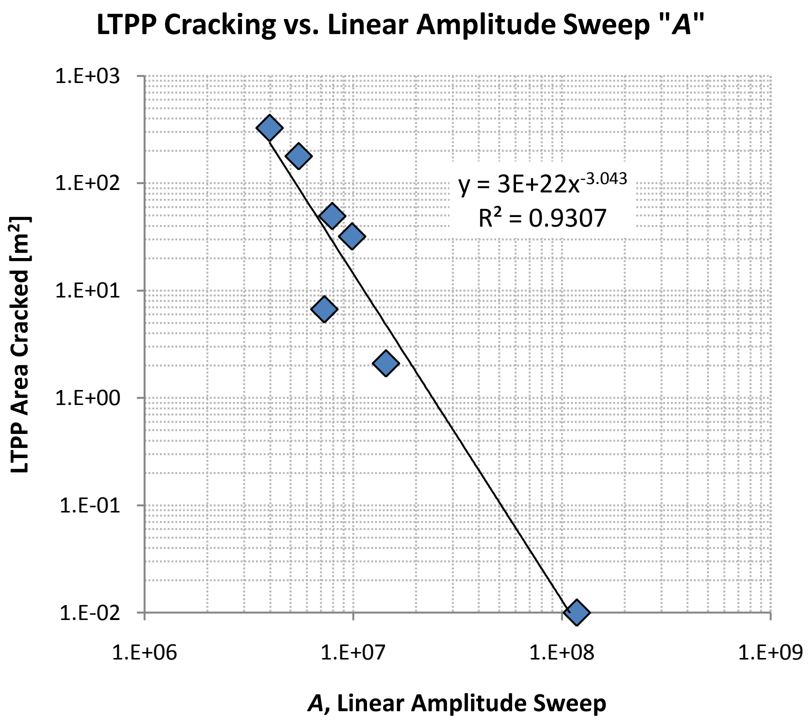

Figure 11. *Fatigue cracking from LTPP measurements compared to the linear amplitude sweep VECD A parameter.*

5 Proposed Accelerated Fatigue Testing Procedure

Based on the preliminary findings from the VECD analysis of linear amplitude sweep data, the application of the linear amplitude sweep as an accelerated fatigue test is believed to be promising. The procedure to apply the analysis is as follows:

1. Determine the value of the factor α: If the rheological master curve for the material in question is available, a value for α can be derived using Schapery & Park's inter-conversions, as was used for this study. However, many modern DSR's have the capability to measure relaxation modulus directly, which may be a valid alternative.
2. Perform the amplitude sweep as described at the binder's continuous intermediate temperature grade for the testing temperature. If the information about the true grade intermediate temperature (at which

$|G^*|\cdot\sin\delta$ = 5,000 kPa) is not available, the SuperPave intermediate temperature is sufficient.

3. Calculate the damage intensity, D, using Equation 2. Then the VECD model parameters C_0, C_1, and C_2 can be determined by fitting Equation 3. The damage intensity at failure, D_f, can be calculated using Equation 3 by setting the value of $|G^*|\sin\delta$ to be reduced by 35% from its undamaged value and solving for D.

4. Fatigue law parameters A and B can be calculated using Equations 7 and 8, with the user being responsible for selecting the appropriate level of binder strain level, γ_{max}. The decision is based upon the expected pavement strains due to pavement structure and traffic loading. For thinner pavements and/or high traffic loads, a larger value of binder strain must be selected. Recommended values will need to be based on calibration from historical pavement fatigue performance.

5. Number of cycles to failure can then be calculated using Equation 5, and can be measured against an acceptable threshold, again based on calibration of pavement performance.

It is apparent that further work still needs to be done to refine and verify this procedure for a larger set of binders and with performance data. It is believed, however, that the concept shown in this paper has the potential to be a viable alternative for current binder fatigue specifications. The binder linear amplitude sweep test takes only a few minutes, and the analysis is based on well-established fundamentals of damage mechanics. Future work will focus on the selection of appropriate binder strain levels for the fatigue model, as well as rational thresholds for incorporation into binder specifications. It should be mentioned that the mathematical formulations are very complex and the statistical fitting needs computer software. This complexity has been easily overcome by programming the analysis in a simple spreadsheet that requires input of the linear amplitude sweep and either frequency sweep or the results of a relaxation test of the binder. The same sample could be used to conduct the frequency sweep, or the relaxation test, followed by the linear amplitude sweep.

6 Concluding Remarks

This study has discussed a number of binder fatigue evaluation techniques using the DSR in an effort to define a practical binder fatigue specification test. The goal of this research is to explore methods to predict binder fatigue performance without having to run time-intensive test procedures. The linear amplitude sweep is found as a cyclic test method that can be analyzed using VECD concepts with relevant insight into fatigue behavior of binders. While characteristic curves derived from time sweep results did not coincide with the results from the linear amplitude sweep, parameters derived from analysis of linear amplitude sweep testing were shown to correlate well with time sweep results. A proposed preliminary framework for using linear amplitude sweep results in VECD-type analysis for indication of binder fatigue performance is presented, with the understanding that appropriate thresholds for specification parameters are still needed to refine its ability to accurately predict pavement fatigue life. The proposed framework includes the ability to account for pavement structure and traffic level, which is not currently available in binder specification.

6 Acknowledgements

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