Standard Method of Test for

Estimating ~~Fatigue Resistance~~ Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep

AASHTO Designation: TP ~~2b xx (LAST)~~101-~~12~~14

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1. SCOPE

1.1. This test method covers how to determine asphalt binders' resistance to ~~fatigue damage~~ damage by means of cyclic loading employing ~~systematically,~~ linearly increasing load amplitudes. The amplitude sweep is conducted using the Dynamic Shear Rheometer at the intermediate pavement temperature determined from the performance grade (PG) of the asphalt binder according to M 320. The test method can be used with binder aged using T 240 (RTFOT) and R 28 (PAV) to simulate the estimated aging for in-service asphalt pavements.

1.2. The values stated in SI units are to be regarded as the standard.

1.3. *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 320, Performance-Graded Asphalt Binder
- R 28, Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
- T 240, Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
- T 315, Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)

2.2. *ASTM Standards*:

- D 8, Standard Terminology Relating to Materials for Roads and Pavements

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. Definitions of terms used in this practice may be found in ASTM D 8, determined from common English usage, or combinations of both.

4. SUMMARY OF TEST METHOD

4.1. Asphalt binder is first aged using T 240 (RTFOT) to represent short-term aging of asphalt pavements. The binder may be further aged using R 28 prior to testing in order to simulate long-term aging of asphalt pavements. A sample is prepared consistent with T 315 (DSR) using the 8-mm parallel plate geometry with a 2-mm gap setting. The sample is tested in shear using a frequency sweep to determine rheological properties. The sample is then tested using a series of oscillatory load cycles at ~~systematically~~ linearly increasing amplitudes at a constant frequency to cause accelerated fatigue damage. The continuum damage approach is used to calculate the fatigue resistance from rheological properties and amplitude sweep results.

5. SIGNIFICANCE AND USE

5.1. This method is intended to evaluate the ability of an asphalt binder to resist ~~fatigue~~ damage by employing cyclic loading at increasing amplitudes in order to accelerate damage. The characteristics of the rate of damage accumulation in the material can be used to indicate the fatigue performance of the asphalt binder given pavement structural conditions and/or expected amount of traffic loading using predictive modeling techniques.

6. APPARATUS

6.1. Use the apparatus as specified in T 315.

7. PROCEDURE

7.1. Condition the asphalt binder in accordance with T 240 (RTFOT) for short-term performance, or condition the asphalt binder in accordance with T 240 (RTFOT) followed by R 28 (PAV) for long-term performance.

7.2. *Sample preparation*—The sample for the Amplitude Sweep is prepared following T 315 for 8-mm plates. The temperature control also follows the T 315 requirements.

Note 1: In accordance to AASHTO T 315 provisions, it is suggested that spindle and plate temperature be raised to 64°C or higher before insertion of the asphalt sample to ensure sufficient adhesion is achieved, especially for highly modified and/or aged asphalt binders. Such provisions have been shown to prevent delamination in the majority of binders tested.

~~7.2.~~

7.2.1. This test may be performed on the same sample that was previously used to determine the rheological properties in the DSR on PAV residue as specified in M 320.

7.3. *Test protocol*—Two types of testing are performed in succession. The first test, a frequency sweep, is designed to obtain information on the rheological properties, and the second test, an amplitude sweep, is intended to measure the damage characteristics of the material.

7.3.1. *Determination of "alpha" parameter*—In order to perform the damage analysis, information regarding the undamaged material properties (represented by the parameter α) must be determined. The frequency sweep procedure outlined in Section 7.3.1.1 is used to determine the alpha parameter.

7.3.1.1. *Frequency sweep*—Frequency sweep test data is used to determine the damage analysis "alpha" parameter. The frequency sweep test is performed at the selected temperature and applies oscillatory shear loading at constant amplitude over a range of loading frequencies. For this test method, the frequency sweep test is selected from the DSR manufacturer's controller software, employing an applied load of 0.1 percent strain over a range of frequencies from 0.2–30 Hz. Data is sampled at the following 12 unique frequencies (all in Hz):

0.2 0.4 0.6 0.8 1.0 2.0 4.0 6.0 8.0 10 20 30

Complex shear modulus [|G*|, Pa] and phase angle [δ, degrees] are recorded at each frequency, as shown in Figure 1.

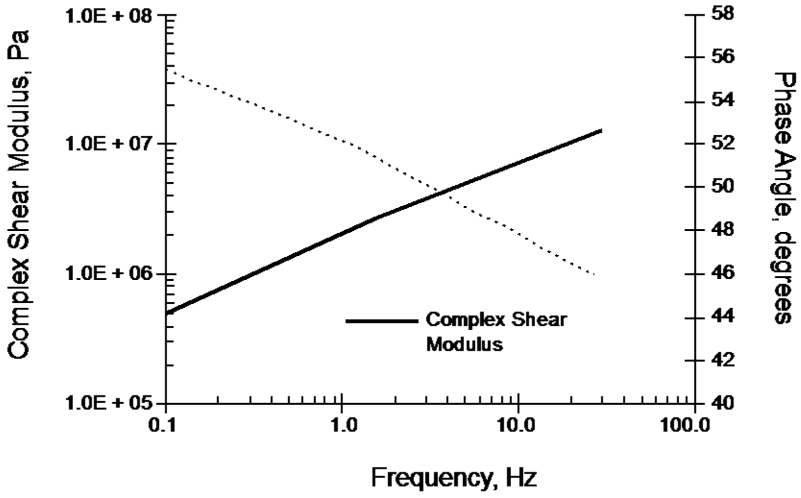
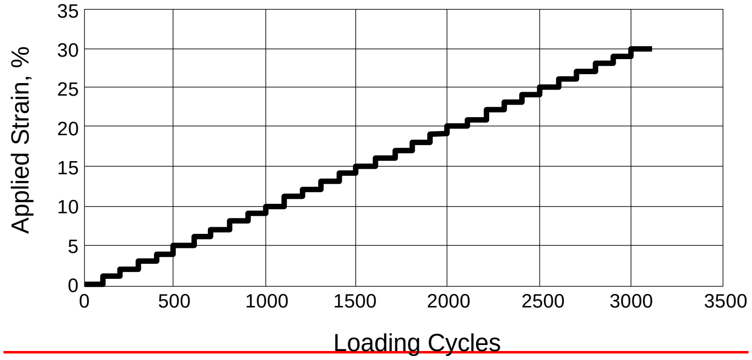


Figure 1—Example Output from Frequency Sweep Test

7.3.2. *Amplitude sweep*—The second test is run at the selected temperature using oscillatory shear in strain-control mode at a frequency of 10 Hz. The loading scheme consists of a continuous oscillatory strain sweep. Loading is increased linearly from zero to 30% over the course of 3,100 cycles of loading. The loading scheme consists of 10-second intervals of constant strain amplitude, where each interval is followed by another interval of increased strain amplitude as follows: 0.1 percent, 1.0 percent, 2.0 percent, 3.0 percent, 4.0 percent, 5.0 percent, 6.0 percent, 7.0 percent, 8.0 percent, 9.0 percent, 10 percent, 11 percent, 12 percent, 13 percent, 14 percent, 15 percent, 16 percent, 17 percent, 18 percent, 19 percent, 20 percent, 21 percent, 22 percent, 23 percent, 24 percent, 25 percent, 26 percent, 27 percent, 28 percent, 29 percent, 30 percent. Peak shear strain and peak shear stress are recorded every 10 load cycles (1 sec), along with phase angle [δ, degrees] and dynamic shear modulus [|G*|, Pa].



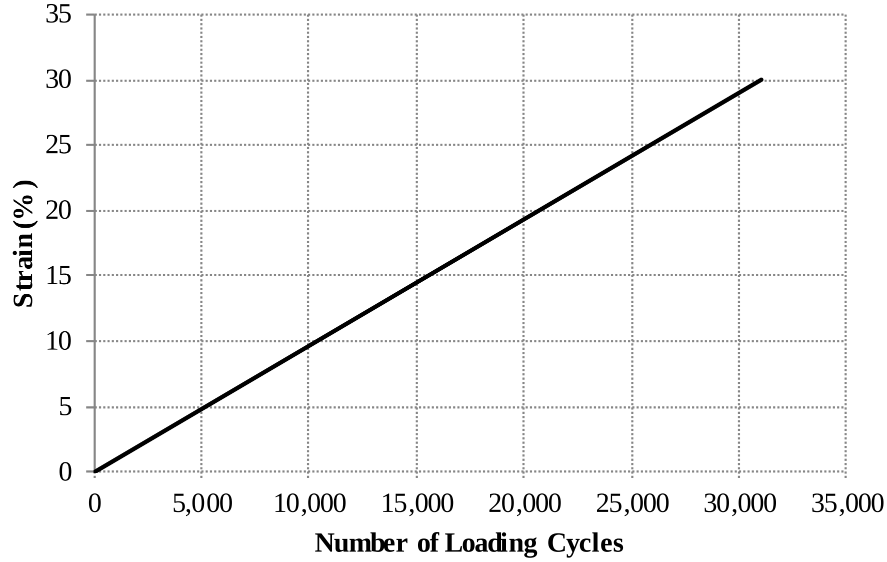


Figure 2—Loading Scheme for Amplitude Sweep Test

8. CALCULATION AND INTERPRETATION OF RESULTS

8.1. VECD Analysis:

~~7.4.~~8.1.1. In order to determine the parameter α from frequency sweep test data, the following calculations are performed:

~~7.4.1.~~8.1.2. First, data for the dynamic modulus [|G*|(ω)] and phase angle [δ(ω)] for each frequency is converted to storage modulus, G′(ω):

$$G'(\omega) = |G^*|(\omega) \times \cos \delta(\omega)$$

~~7.4.2.~~8.1.3. A best-fit straight line is applied to a plot with log ω on the horizontal axis and log G′(ω) on the vertical axis using the form:

$$\log G'(\omega) = m(\log \omega) + b$$

~~7.4.3.~~8.1.4. The value obtained for *m* is recorded and the value of α is obtained by performing the following transformation:

~~$\alpha = 1 + \frac{1}{m}$~~

$$\alpha = 1/m$$

~~7.5.~~8.1.4.1. For the results of the amplitude sweep test, the data is analyzed as follows:

Note—The following damage calculation method is adapted from Kim, et al. (see Section 11.1).

~~7.5.1.~~8.1.5. The damage accumulation in the specimen is calculated using the following summation:

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

where:

~~I_D~~ $C(t)$ = $\frac{|G^*| \cdot \sin\delta(t)}{|G^*| \cdot \sin\delta_{initial}}$ =which is |G*|~~·sinδ~~ at time, t divided by the initial "undamaged" value of |G*|~~·sin δ. initial value of |G*| from the 1.0 percent applied strain interval, MPa~~

γ_0 = applied strain for a given data point, percent

|G*| = Complex shear modulus, MPa

α = value reported in Section ~~7~~8.1.~~3~~4

t = testing time, second

Note 2: The initial "undamaged" value of |G*| is the second data point, as the first point after change of material condition from rest differs from the undamaged modulus of material at the target loading frequency.

~~7.5.2.~~8.1.6. Summation of damage accumulation begins with the first data point ~~for the 1.0 percent applied strain interval~~. The incremental value of $D(t)$ at each subsequent point is added to the value of $D(t)$ from the previous point. This is performed up until the final data point from the test at 30 percent applied strain.

~~7.5.3.~~8.1.7. For each data point at a given time t, values of ~~|G*| • sin δ~~ $C(t)$ and $D(t)$ are recorded (it is assumed that ~~|G*| • sin δ~~ C at $D(0)$ is equal to ~~the average undamaged value of |G*| • sin δ from the 0.1 percent strain interval~~one, and $D(0) = 0$). The relationship between ~~|G*| • sin δ~~ $C(t)$ and $D(t)$ can then be fit to the following power law:

$C_{(t)}$ ~~|G*|·sin δ~~ $= C_0 - C_1 (D)^{C2}$

where:

C_0 = 1, the initial value of C ~~the average value of |G*| • sin δ from the 0.1 percent strain interval~~

C_1 and C_2 = curve-fit coefficients derived through linearization of the power law adapted from Hintz, et al., in the form shown below:

$$\log(C_0 - |G^*| \cdot \sin\delta C(t)) = \log(C_1) + C_2 \cdot \log(D(t))$$

Using the above equation, C_1 is calculated as the anti-log of the intercept and C_2 is calculated as the slope of line formed as $\log(C_0 -$ ~~|G*| • sin δ~~ $C(t))$ versus $\log(D(t))$. For calculation of both C_1 and C_2, data corresponding to damages less than 10~~0~~ are ignored.

~~7.6.~~8.1.8. The value of $D(t)$ at failure, D_f, is defined as the $D(t)$ which corresponds to ~~a 35 percent~~the reduction in ~~undamaged~~ initial |G*| ~~• sin δ (C_0).~~ at the peak shear stress. The calculation is as follows:

~~$D_f = (0.35)(C_0/C_1)^\wedge(1/C_2)$~~

$$D_f = \left(\frac{C_0 - C \text{ at Peak Stress}}{C_1}\right)^{1/C_2}$$

~~7.7.~~8.1.9. The following parameters (A_{35} and B) for the binder fatigue performance model can now be calculated and recorded as follows:

$$A_{35} = \frac{f\left(D_f\right)^k}{k\left(\pi I_D C_1 C_2\right)^{\alpha}}$$

$$A = \frac{f\,(D_f)^k}{k(\pi C_1 C_2)^{\alpha}}$$

where:

f = loading frequency (10 Hz),

k = $1 + (1 - C_2)\alpha$, and

B = 2α

~~7.8.~~8.1.10. The binder fatigue performance parameter N_f can now be calculated as follows:

$N_f = A(\gamma_{max})^{-B}$

where:

γ_{max} = the maximum expected binder strain for a given pavement structure, percent

~~8.~~9. REPORT

~~8.1.~~9.1. *Report the following*:

~~8.1.1.~~9.1.1. Sample identification,

~~8.1.2.~~9.1.2. PG grade,

~~8.1.3.~~9.1.3. Test temperature, nearest 0.1°C,

~~8.1.4.~~9.1.4. Fatigue model parameters A and B, four significant figures, and

~~8.1.5.~~9.1.5. Binder fatigue performance parameter N_f, nearest whole number.

~~9.~~10. PRECISION AND BIAS

~~9.1.~~10.1. To be determined upon results of interlaboratory testing.

~~10.~~11. KEYWORDS

~~10.1.~~11.1. asphalt binder; continuum damage; DSR; fatigue; performance grading.

~~11.~~12. REFERENCES

~~11.1.~~12.1. Kim, Y., H. J. Lee, D. N. Little, and Y. R. Kim. A simple testing method to evaluate fatigue fracture and damage performance of asphalt mixtures. *Journal of Association of Asphalt Paving Technologists*, Vol. 75, 2006, pp. 755–788.

~~11.2.~~12.2. Hintz, C., R. Velasquez, C. Johnson, and H. Bahia. Modification and Validation of the Linear Amplitude Sweep Test for Binder Fatigue Specification. In *Transportation Research Record TBD: Journal of the Transportation Research Board*. Transportation Research Board, National Academies of Sciences, Washington, DC, 2011, pp. TBD.

APPENDIX

(Nonmandatory Information)

X1. SAMPLE CALCULATIONS

X1.1. Example data from the amplitude sweep test is given in Table X1.1.

Table X1.1—Example Data Output From Amplitude Sweep Test

Testing Time, second	Shear Stress, MPa	Shear Strain, percent	~~|G*|, MPa~~	Phase Angle, degree	|G*| ~~• sin δ~~, MPa
34	0.212	1.996	~~10.646~~	49.18	8.057
35	0.212	2.001	~~10.619~~	49.22	8.041
36	0.212	2.003	~~10.595~~	49.26	8.028
37	0.211	2.003	~~10.574~~	49.29	8.016
38	0.211	2.004	~~10.555~~	49.32	8.005
39	0.211	2.003	~~10.539~~	49.34	7.995
40	0.210	2.003	~~10.524~~	49.37	7.987

X1.2. *The following values have already been assumed*:

D(33) = 10.77

α = 2.58

$|G^*|_{t=0}$ = ~~I_D =~~ 8.345 MPa

|G*| ~~• sin δ~~$_{t=33}$ = 8.075 MPa

X1.3. *Sample calculations*:

X1.3.1. To calculate the accumulation of damage from *t* = 33 sec to *t* = 34 sec:

$$D(34) = D(33) + [\pi \cancel{I_D} \gamma_0^2 (\cancel{|G^*|\sin\delta}\, C_{i-1} - \cancel{|G^*|\sin\delta}\, C_i)]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}}$$

$$D(34) = D(33) + [\pi \cancel{(8.345)} (1.996)^2 (8.075 - 8.057)/(8.345)]^{\frac{2.58}{1+2.58}} (34 - 33)^{\frac{1}{1+2.58}}$$

$D(34) = 10.84$ ~~$D(34) = 12.36$~~

X1.3.2. This procedure is repeated, giving the following results shown in Table X1.2.

Table X1.2—Example Data Output and Damage Calculation from Amplitude Sweep Test

Testing Time, second	Shear Stress, MPa	Shear Strain, percent	~~Complex Modulus, MPa~~	Phase Angle, degree	|G*| ~~• sin δ~~, MPa	*D*(*t*)
34	0.212	1.996	~~10.646~~	49.18	8.057	~~12.36~~10.84

35	0.212	2.001	~~10.619~~	49.22	8.041	10.91~~13.79~~
36	0.212	2.003	~~10.595~~	49.26	8.028	10.97~~15.06~~
37	0.211	2.003	~~10.574~~	49.29	8.016	11.03~~16.26~~
38	0.211	2.004	~~10.555~~	49.32	8.005	11.08~~17.35~~
39	0.211	2.003	~~10.539~~	49.34	7.995	11.13~~18.40~~
40	0.210	2.003	~~10.524~~	49.37	7.987	11.17~~19.26~~

X2. EXAMPLE PLOTS

X2.1. *The following example plots may be useful in visualizing the results*:

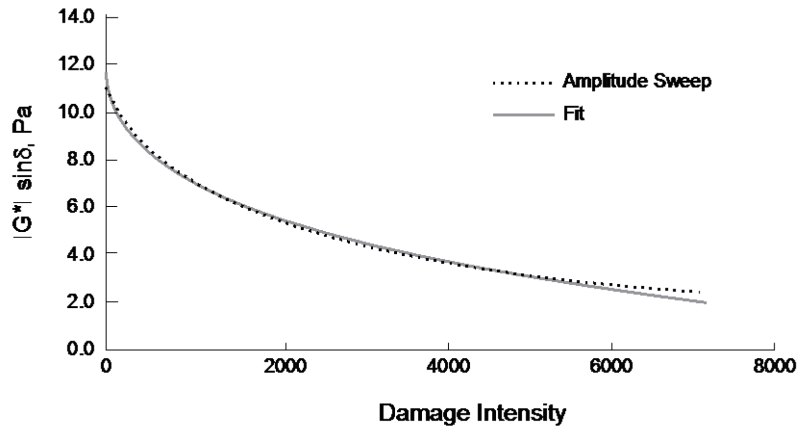


Figure X2.1—Example |G*| • sin δ versus Damage Plot with Curve-Fit from Section 7.2

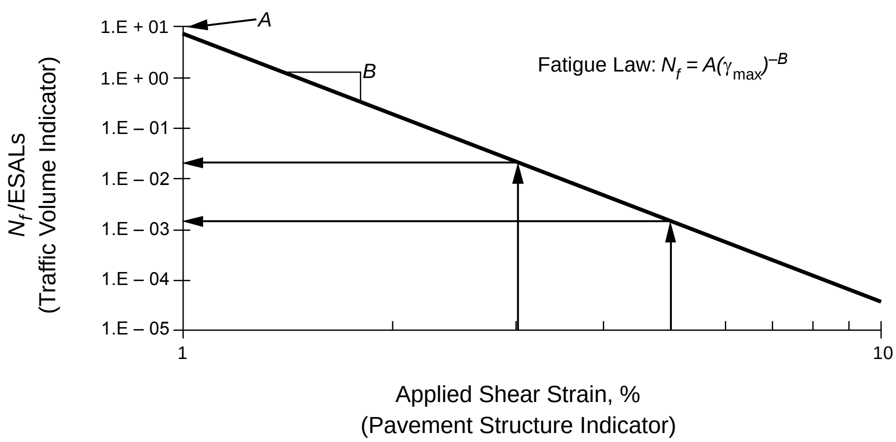


Figure X2.2—Plot of Fatigue Parameter N_f (Normalized to 1 million ESALs) versus Applied Binder Shear Strain on a Log-Log Scale (Allowable fatigue life can be determined for given strain amplitudes, as shown by the arrows.)