
Standard Method of Test for

Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep

AASHTO Designation: T 391-20¹

AASHTO

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1. SCOPE

- 1.1. This test method covers the determination of an asphalt binder's resistance to fatigue damage by means of cyclic loading employing systematic, linearly increasing load amplitudes. The amplitude sweep is conducted using the Dynamic Shear Rheometer (DSR) 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 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 concerns, 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.*
- 1.4. *The quality of the results produced by this standard are dependent on the competence of the personnel performing the procedure and the capability, calibration, and maintenance of the equipment used. Agencies that meet the criteria of R 18 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with R 18 alone does not completely assure reliable results. Reliable results depend on many factors; following the suggestions of R 18 or some similar acceptable guideline provides a means of evaluating and controlling some of those factors.*

2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards:*
 - M 320, Performance-Graded Asphalt Binder
 - R 18, Establishing and Implementing a Quality Management System for Construction Materials Testing Laboratories
 - 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)

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- 2.2. *ASTM Standard:*
■ D8, Standard Terminology Relating to Materials for Roads and Pavements

3. TERMINOLOGY

- 3.1. *Definitions:*
- 3.1.1. Definitions of terms used in this test method may be found in ASTM D8, 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 (PAV) prior to testing in order to simulate long-term aging of asphalt pavements. A sample is prepared according to 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 its rheological properties. The sample is then tested using a series of oscillatory load cycles at systematically increasing amplitudes at a constant frequency to cause accelerated fatigue damage. The continuum damage approach is used to calculate the fatigue resistance from the 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.
- 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 are 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 to 30 Hz. Data are 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.

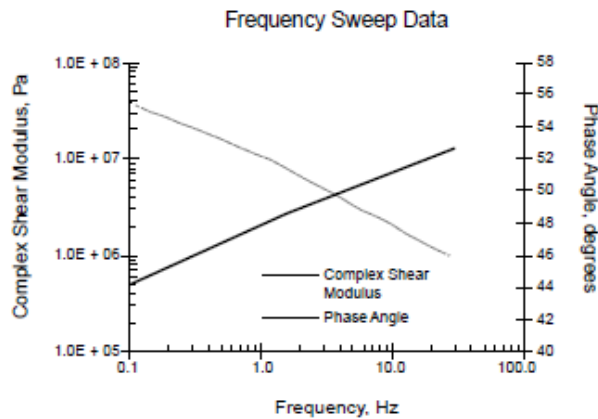


Figure 1—Example Output from Frequency Sweep Test

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 10-s 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 s), along with phase angle [δ , degrees] and dynamic shear modulus [G^* , Pa].

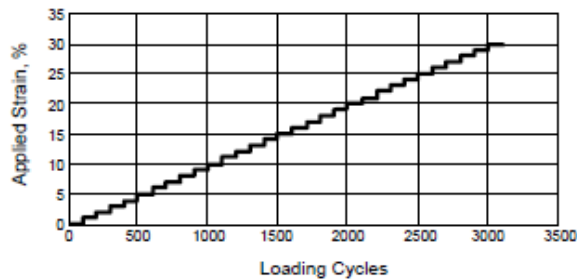


Figure 2—Loading Scheme for Amplitude Sweep Test

8. CALCULATION AND INTERPRETATION OF RESULTS

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

8.1.1. First, data for the dynamic modulus [$G^*(\omega)$] and phase angle [$\delta(\omega)$] for each frequency are converted to storage modulus, $G'(\omega)$:

$$G'(\omega) = |G^*(\omega)| \times \cos \delta(\omega) \quad (1)$$

8.1.2. A best-fit straight line is applied to a plot with $\log \omega$ on the horizontal axis and $\log G'(\omega)$ on the vertical axis using the form:

$$\log G'(\omega) = m(\log \omega) + b \quad (2)$$

8.1.3. The value obtained for m is recorded and the value of α is obtained by performing the following transformation:

$$\alpha = 1 + \frac{1}{m} \quad (3)$$

8.2. For the results of the amplitude sweep test, the data are analyzed as follows:

Note 1—The following damage calculation method is adapted from Kim et al. (see Section 12.1).

8.2.1. The damage accumulation in the specimen is calculated using the following summation:

$$D(t) \cong \sum_{i=1}^n \left[\pi I_D \gamma_0^3 \left(|G^*| \sin \delta_{i-1} - |G^*| \sin \delta_i \right) \right]^{\frac{\alpha}{1-\alpha}} (t_i - t_{i-1})^{\frac{1}{1-\alpha}} \quad (4)$$

where:

I_D = 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 7.1.3; and

t = testing time, s.

8.2.2. 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.

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

$$|G^*| \cdot \sin \delta = C_0 - C_1 (D)^{C_2} \quad (5)$$

where:

C_0 = the average value of $|G^*| \cdot \sin \delta$ from the 0.1 percent strain interval; and

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:

$$\log(C_0 - |G^*| \cdot \sin \delta) = \log(C_1) + C_2 \cdot \log(D) \quad (6)$$

Using the above equation, C_1 is calculated as the antilog of the intercept and C_2 is calculated as the slope of line formed as $\log(C_0 - |G^*| \cdot \sin \delta)$ versus $\log(D)$. For calculation of both C_1 and C_2 , data corresponding to damages less than 100 are ignored.

- 8.3. The value of $D(t)$ at failure, D_f , is defined as the $D(t)$ that corresponds to a 35 percent reduction in undamaged $|G^*| \cdot \sin \delta$ (C_0). The calculation is as follows:

$$D_f = (0.35) \left(\frac{C_0}{C_1} \right)^{\frac{1}{C_2}} \quad (7)$$

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

$$A_{35} = \frac{f(D_f)^k}{k(\pi I_D C_1 C_2)^\alpha} \quad (8)$$

where:

f = loading frequency (10 Hz);

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

B = 2α .

- 8.5. The binder fatigue performance parameter N_f can now be calculated as follows:

$$N_f = A_{35}(\gamma_{\max})^{-B} \quad (9)$$

where:

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

9. REPORT

- 9.1. Report the following:
- 9.1.1. Sample identification;
- 9.1.2. PG grade;
- 9.1.3. Test temperature, nearest 0.1°C;
- 9.1.4. Fatigue model parameters A_{35} and B , four significant figures; and

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

10. PRECISION AND BIAS

10.1. To be determined on results of interlaboratory testing.

11. KEYWORDS

11.1. Asphalt binder; continuum damage; DSR; fatigue; performance grading.

12. REFERENCES

- 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.
- 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. 96–106.

APPENDIXES

(Nonmandatory Information)

X1. SAMPLE CALCULATIONS

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

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

Testing Time, s	Shear Stress, MPa	Shear Strain, %	$ G^* $, MPa	Phase Angle, degrees	$ G^* \cdot \sin \delta$, 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:*

$$D(33) = 10.77$$

$$\alpha = 2.58$$

$$I_D = 8.345 \text{ MPa}$$

$$|G^*| \cdot \sin \delta_{t=33} = 8.075 \text{ MPa}$$

X1.3. *Sample calculations:*

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

$$D(34) = D(33) + \left[\pi I_D \gamma_0^2 \left(|G^*| \sin \delta_{t-1} - |G^*| \sin \delta_t \right) \right]^{\frac{2}{1+2}} (t - t_{-1})^{\frac{1}{1+2}}$$

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

$$D(34) = 12.36$$

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, s	Shear Stress, MPa	Shear Strain, %	Complex Modulus, MPa	Phase Angle, degrees	$ G^* \cdot \sin \delta$, MPa	$D(t)$
34	0.212	1.996	10.646	49.18	8.057	12.36
35	0.212	2.001	10.619	49.22	8.041	13.79
36	0.212	2.003	10.595	49.26	8.028	15.06
37	0.211	2.003	10.574	49.29	8.016	16.26
38	0.211	2.004	10.555	49.32	8.005	17.35
39	0.211	2.003	10.539	49.34	7.995	18.40
40	0.210	2.003	10.524	49.37	7.987	19.26

X2. EXAMPLE PLOTS

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

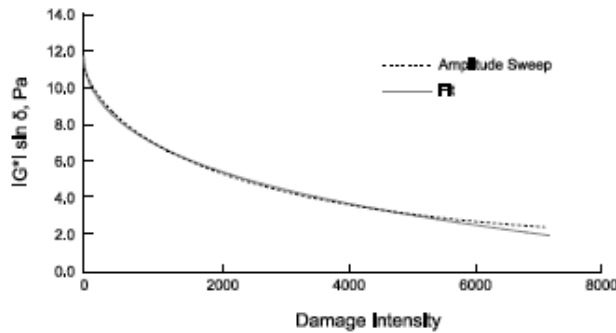


Figure X2.1—Example $|G^*| \cdot \sin \delta$ versus Damage Plot with Curve-Fit from Section 7.2

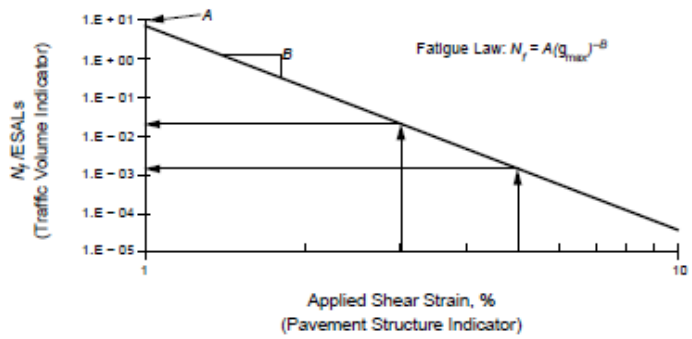


Figure X2.2—Plot of Fatigue Parameter N_f (Normalized to 1 million ESALs) versus Applied Binder Shear Strain on a Log-Log Scale (Allowable fatigue life can be determined for given strain amplitudes, as shown by the arrows.)

¹ Formerly AASHTO Provisional Standard TP 101. First published as a full standard in 2020.