

Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders

AASHTO Designation: PP 42-07¹



1. SCOPE

- 1.1. This practice covers the determination of low-temperature properties of asphalt binders using data from the bending beam rheometer (T 313) and the direct tension tester (T 314). This practice can be used on data from unaged material or from material aged using T 240 (RTFOT), R 28 (PAV), or T 240 (RTFOT) and R 28 (PAV). This practice can be used on data generated within the temperature range from +6°C to –36°C.
- 1.2. This practice is only valid for data on materials that fall within the scope of suitability for both test methods T 313 and T 314.
- 1.3. This practice can be used to determine the following:
 - 1.3.1. *PG Grade Determination of an Asphalt Binder*—The determination of a low-temperature grade or grades that are satisfied by an asphalt binder. The determination of the temperature corresponds to the specification parameter, T_{cr} , the critical cracking temperature.
 - 1.3.2. *Prequalification of an Asphalt Binder*—The procedure required to qualify an asphalt binder for supply.
 - 1.3.3. *Verification of an Asphalt Binder Grade*—The testing required to certify that a binder complies with an existing prequalified binder.
- 1.4. While this practice determines the critical cracking temperature for typical hot-mix asphalt (HMA), the intent of this practice is grading of asphalt binder according to M 320, not performance prediction for asphalt pavement. This practice should not be used in lieu of T 322.
- 1.5. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

Note 1—The algorithms contained in this standard require implementation by a person trained in the subject of numerical methods and visco-elasticity. However, due to the complexity of the calculations they must, of necessity, be performed on a computer. Software to perform the calculations may be written or purchased as a spreadsheet or as a stand-alone program.²

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 (Rolling Thin-Film Oven Test)
- T 313, Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)
- T 314, Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT)
- T 322, Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device

3. TERMINOLOGY

3.1. *Definitions of Terms Specific to This Standard:*

- 3.1.1. *Arrhenius parameter* (a_1)—this is the constant coefficient in the Arrhenius model for shift factors, $\ln(a_T) = a_1(1/T - 1/T_{\text{ref}})$.
- 3.1.2. *asphalt binder*—an asphalt-based cement that is produced from petroleum residue either with or without the addition of nonparticulate organic modifiers.
- 3.1.3. *coefficient of linear thermal expansion* (α)—the fractional change in size in one dimension associated with a temperature increase of 1°C.
- 3.1.4. *conventional unmodified asphalt binders*—asphalt binders for which the following two conditions are satisfied: (1) The difference between the temperature at which $S(60) = 300$ MPa and m value (60) = 0.300 is less than or equal to $\pm 2.0^\circ\text{C}$. The $S(60)$ and the m value are determined using the T 313 BBR test. (2) The failure strength determined using T 314 must be within 3.77 ± 0.77 MPa.
- 3.1.5. *creep compliance* [$D(T, t)$]*—the reciprocal of the stiffness of a material, $1/S(T, t)$, at temperature, T , and time, t . Creep compliance may also be expressed using reduced time, ξ , as $D(T_{\text{ref}}, \xi)$.*
- 3.1.6. *critical cracking temperature* (T_{cr})—the temperature, estimated using this practice, at which the induced thermal stress in a material exceeds its fracture stress. The critical cracking temperature is a “single event cracking” limit prediction that does not include the effect of low-temperature thermal fatigue.
- 3.1.7. *failure stress* (σ_f)—the tensile stress value at the point of failure obtained from T 314.
- 3.1.8. *glassy modulus*—the modulus at which the binder exhibits glass-like behavior, assumed to be 3×10^9 Pa for this procedure.
- 3.1.9. *induced thermal stress* (σ_{th})—the stress induced in a material by cooling it while it is restrained so that it cannot contract.
- 3.1.10. *master curve*—a composite curve at a single reference temperature, T_{ref} , which can be constructed by shifting, along the log time or log frequency axis, a series of overlapping modulus data curves at various test temperatures. The modulus data curve at the reference temperature is not shifted. The shifted smooth curve is called the master curve at the reference temperature.

- 3.1.11. *pavement constant* (C)—an empirical, constant factor that serves as a damage transfer function to convert the thermal stresses calculated from laboratory data to the thermal stresses generated in the pavement. The damage transfer function is needed to account for the differences in the strain rates experienced by the distribution of binder films in the pavement and the bulk strain rate used in the T 314 direct tension test (DDT). Critical cracking temperatures of conventional unmodified asphalt binders were used to determine the pavement constant, C . The value of the pavement constant, C , is the value that minimizes the difference between the critical cracking temperature, T_{cr} , determined using the procedure described in this practice and the T 313 bending beam rheometer (BBR) test. The T_{cr} from the BBR test is determined as the higher value between the temperature where $S(60)$ is 300 MPa and the temperature where the m value at 60 s is 0.3. Using the above procedure, the value of the pavement constant was determined to be 18. The pavement constant of 18 is based on the most current pavement performance data available. Federal Highway Administration (FHWA) and the Transportation Research Board (TRB) Binder Expert Task Group (ETG) continue to collect and analyze field-performance data.
- 3.1.12. *reduced time* (ξ)—the computed loading time at the reference temperature, T_{ref} , equivalent to actual loading at temperature T . The reduced time is determined by dividing actual loading time, t , at temperature T , by the shift factor, a_T , $\xi = t/a_T$.
- 3.1.13. *reference temperature* (T_{ref})—the temperature at which the master curve is constructed in degrees Kelvin.
- 3.1.14. *relaxation modulus* [$E(T, t)$]*—the modulus of a material determined using a strain-controlled (relaxation) experiment at temperature, T , and time, t . Relaxation modulus may also be expressed using reduced time as $E(T_{ref}, \xi)$.*
- 3.1.15. *shift factor* (a_T)—the shift in the time or frequency domain associated with a shift from temperature, T , to the reference, T_{ref} .
- 3.1.16. *specification temperature* (T_{spec})—the specified low-temperature grade of the binder being prequalified.
- 3.1.17. *stiffness modulus* [$S(T, t)$]*—the modulus (stress/strain) of a material at temperature, T , and time, t . Stiffness modulus may also be expressed using reduced time as $S(T_{ref}, \xi)$.*

4. SUMMARY OF THE PRACTICE

- 4.1. This practice describes the procedure used to calculate the relaxation modulus master curve and subsequently the thermally induced stress curve for an asphalt binder from data generated from the bending beam rheometer test.
- 4.2. The stiffness master curve is calculated from the stiffness versus time data measured in the BBR at two temperatures. The fitting procedure follows the Christensen-Anderson-Marasteanu (CAM) rheological model for asphalt binder. The stiffness master curve is then converted to the creep compliance curve by taking its inverse.
- 4.3. The creep compliance is converted to relaxation modulus using the Hopkins and Hamming method, which is fitted to the CAM model. The Hopkins and Hamming method is a numerical solution of the convolution integral.
- 4.4. The thermally induced stress is calculated by numerically solving the convolution integral. The thermal stress calculations are based on Boltzmann's superposition principle for linear visco-elastic materials. The calculated thermally induced stress is then multiplied by the pavement

constant to predict the thermal stress produced in the hot-mix asphalt pavement. A value of 18 is used for the pavement constant.

- 4.5. The calculated thermal stress is then compared to the failure stress from the direct tension test to determine the critical cracking temperature of the pavement.

5. SIGNIFICANCE AND USE

- 5.1. Estimated cracking temperature, as determined by this practice, is a criterion for specifying the low-temperature properties of asphalt binder in accordance with M 320.
- 5.2. This practice is designed to identify the temperature region where the induced thermal stress in a typical hot-mix asphalt subjected to rapid cooling (1°C/h) exceeds the fracture stress of the HMA.
- 5.3. For evaluating an asphalt binder for conformance to M 320, the test temperature for the bending beam rheometer (BBR) and direct tension test (DTT) data is selected from Table 2 of M 320 according to the grade of asphalt binder.

Note 2—Other cooling rates and test temperatures may be used to test asphalt binders for experimental purposes.

6. METHODOLOGY AND REQUIRED DATA

- 6.1. This practice uses data from both bending beam rheometer and direct tension measurements on an asphalt binder.
- 6.1.1. The DTT data required is the stress at failure obtained by testing at a strain rate of three percent per minute. For continuous grade and PG determination, DTT results are required at a minimum of two test temperatures. The DT tests shall be conducted at the test temperatures from M 320 at 6°C increments corresponding to the low-temperature binder grade. For prequalification and verification, DTT results are required at a single temperature that is equal to the low temperature grade plus 10°C.
- 6.1.2. Two BBR data sets at two different temperatures are required with deflection measurements at 8, 15, 30, 60, 120, and 240 seconds. The BBR test temperatures, T and $T - 6^\circ\text{C}$, are selected such that $S(T, 60) \leq 300$ MPa and $S(T - 6, 60) > 300$ MPa. T shall be the appropriate test temperatures from M 320 at 6°C increments corresponding to the low-temperature binder grade.

Note 3—It is helpful to begin testing at a temperature that is 6°C lower than the critical low cracking temperature for a given grade in Table 2 of M 320. Depending upon the result, perform the next test either at the critical low cracking temperature for a given grade in Table 2 of M 320 or 12°C lower than that temperature. Additional tests may be necessary to bracket 300 MPa.

Using a PG xx-22 as an example, test the first set of BBR beams at a test temperature of -18°C . If $S(-18^\circ\text{C}, 60) > 300$ MPa, test the next set of BBR beams at a test temperature of -12°C . If $S(-8^\circ\text{C}, 60) \leq 300$ MPa, test the next set of BBR beams at a test temperature of -24°C .

7. CALCULATIONS

- 7.1. *Calculation of the Stiffness Master Curve:*
- 7.1.1. Calculate the BBR compliance data in accordance with T 313 to obtain the following data:
 $D(T, t)$ = compliance at temperature, T , and time, t .

$D(T,8), D(T,15), D(T,30), D(T,60), D(T,120),$
 $D(T,240), D(T-6,8), D(T-6,15), D(T-6,30), D(T-6,60),$
 $D(T-6,120), D(T-6,240)$

- 7.1.2. Calculate the BBR stiffness data in accordance with T 313 as:

$$S(T,t) = 1/D(T,t)$$

- 7.1.3. Determine a_{T-6} , the shift factor for the data at temperature $T-6^{\circ}\text{C}$, numerically using the Gordon and Shaw method (Gordon and Shaw, 1994) to produce a master curve. The reference temperature shall be the higher of the two test temperatures. The linear coefficient of thermal expansion, above and below the glass transition temperature shall be $0.00017 \text{ m/m}^{\circ}\text{C}$. The glass transition temperature is taken as -20°C .

Note 4—This procedure is described in Gordon/Shaw, *Computer Programs for Rheologists*, Hanser/Gardner (1994). The SHIFTT routine, which can be found in Chapter 5 of *Computer Programs for Rheologists*, is to be used. The value of -20°C is used for glass transition but has no effect on the calculation since the linear expansion coefficient is assumed to be the same either side of this temperature. Experimental data has indicated that some binders may have a variation in their glass transition temperature and α value. For research purposes, these values may be determined and the measured values used in the calculations.

- 7.1.4. From a_{T-6} , calculate the Arrhenius parameter as:

$$\ln(a_{T-6}) = a_1 \left(\frac{1}{T_{\text{ref}} - 6} - \frac{1}{T_{\text{ref}}} \right) \quad (1)$$

where:

$$a_1 = \frac{\ln(a_{T-6})}{\left[\frac{1}{T_{\text{ref}} - 6} - \frac{1}{T_{\text{ref}}} \right]} \quad (2)$$

Note 5—The Gordon/Shaw method uses a shift factor (a_T) in the form of a base 10 log ($\log_{10}$). However, this specification is based on the natural log ($\ln$ or $\log_e$).

- 7.1.5. Reduced time, ξ , for data at temperature, T , is determined by integrating the reciprocal of the shift factor with respect to time as:

$$\xi(t) = \int_0^t \frac{dt'}{a_T} \quad (3)$$

When T is constant with time, this reduces to the equation, as follows:

$$\xi(t) = \frac{t}{a_T} \quad (4)$$

- 7.1.6. All 12 values for $S(T,t)$ obtained, as described in Section 7.1.1, are converted to $S(T_{\text{ref}},\xi)$ with time being replaced by reduced time.

- 7.1.7. The values are fitted to the Christensen-Anderson-Marasteanu (CAM) model for asphalt master curves solving three parameters (λ , κ , and β):

$$S(T_{\text{ref}},\xi) = S_{\text{glassy}} [1 + (\xi/\lambda)^{\beta}]^{-\kappa/\beta} \quad (5)$$

where:

S_{glassy} is the assumed glassy modulus of the binder: $S_{\text{glassy}} = 3 \times 10^9$ Pa.

- 7.1.8. Fit the resulting stiffness master curve data to this equation using a non-linear least squares fitting method to achieve a root mean square error, rms(percent), of less than or equal to 1.25 percent. Appendix X1 contains an example calculation of this error criterion. Appendix X2 contains a routine for curve fitting which may be used.

7.2. *Convert Stiffness Master Curve to Relaxation Modulus Master Curve:*

- 7.2.1. Use the Hopkins and Hamming method to convert creep compliance obtained from the master curve values $D(T_{\text{ref}}, \xi) = 1/S(T_{\text{ref}}, \xi)$ to relaxation modulus $E(T_{\text{ref}}, \xi)$.

Note 6—This procedure is described in the reference L. L. Hopkins and R. W. Hamming, “On Creep and Relaxation,” *Journal of Applied Physics*, Vol. 28, No. 8, pp. 906–909, August 1957.

- 7.2.2. The glassy modulus value of 3×10^9 Pa shall be adopted in the analysis for $S(T_{\text{ref}}, 1 \times 10^8 \text{ s}) = E(T_{\text{ref}}, 1 \times 10^8 \text{ s})$. Calculate relaxation modulus data points using the following iterative formula from $t = 1 \times 10^8$ to $t = 1 \times 10^7$ seconds with intervals of four points per decade—1.000, 1.778, 3.162, and 5.623 ($10^{0.0}$, $10^{0.25}$, $10^{0.5}$, $10^{0.75}$ seconds).

$$E(t_{n+\frac{1}{2}}) = \frac{t_{n+1} - \sum_{i=0}^{n-1} E(t_{i+\frac{1}{2}}) [f(t_{n+1} - t_i) - f(t_{n+1} - t_{i+1})]}{f(t_{n+1} - t_n)} \quad (6)$$

where:

$$f(t_{n+1}) = f(t_n) + \frac{1}{2} [D(t_{n+1}) + D(t_n)] [t_{n+1} - t_n] \quad (7)$$

Use the same time intervals as above and use $f(t_0) = 0$. A cubic spline has been found to be suitable for interpolation.

- 7.2.3. Fit the relaxation modulus values to the CAM as described in Sections 7.1.7 and 7.1.8.

7.3. *Calculation of Thermal Stress:*

Note 7—The calculation of thermal stress is performed using three procedures: stress generation, stress relaxation, and stress summation. Stress calculations are based on Boltzmann’s superposition principle for linear visco-elastic materials.

7.3.1. *Stress Generation:*

- 7.3.1.1. Use the following seven constants:

- Start temperature, 0°C ;
- End temperature, -45°C ;
- Temperature increment, $\Delta T^N = 0.2^\circ\text{C}$;
- Coefficient of linear thermal expansion, $\alpha = 1.7 \times 10^{-4} \text{ m/m/}^\circ\text{C}$;
- Time per increment, $\Delta t = 720 \text{ s}$;
- Strain per increment, $\epsilon = \Delta T_i \alpha = 3.4 \times 10^{-5} \text{ m/m}$; and
- Strain rate $= 4.72 \times 10^{-8} \text{ m/m/s}$.