



Standard Practice for Determining Low-Temperature Performance Grade (PG) of Asphalt Binders¹

This standard is issued under the fixed designation D6816; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the calculation of low-temperature properties of asphalt binders using data from the bending beam rheometer (see Test Method [D6648](#)) (BBR) and the direct tension tester (see Test Method [D6723](#)) (DTT). It can be used on data from unaged material or from material aged using Test Method [D2872](#) (RTFOT), Practice [D6521](#) (PAV), or Test Method [D2872](#) (RTFOT) and Practice [D6521](#) (PAV). It can be used on data generated within the temperature range from +6 °C to –36 °C. This practice generates data suitable for use in binder specifications such as Specification [D6373](#).

1.2 This practice is only valid for data on materials that fall within the scope of suitability for both Test Method [D6648](#) and Test Method [D6723](#).

1.3 This practice can be used to determine the following:

1.3.1 Critical cracking temperature of an asphalt binder, and

1.3.2 Whether or not the failure stress exceeds the thermal stress in a binder at a given temperature.

1.4 This practice determines the critical cracking temperature for a typical asphalt binder based on the determination of the temperature where the asphalt binder's strength equals its thermal stress as calculated by this practice. The temperature so determined is intended to yield a low temperature PG Grade of the sample being tested. The low temperature PG grade is intended for use in purchase specifications and is not intended to be a performance prediction of the HMA (Hot Mix Asphalt) in which the asphalt binder is used.

1.5 The development of this standard was based on SI units. In cases where units have been omitted, SI units are implied.

1.6 *This standard may involve hazardous materials, operations, and equipment. 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 This practice is under the jurisdiction of ASTM Committee [D04](#) on Road and Paving Materials and is the direct responsibility of Subcommittee [D04.44](#) on Rheological Tests.

Current edition approved Dec. 15, 2016. Published December 2016. Originally approved in 2002. Last previous edition approved in 2011 as D6816 – 11. DOI: 10.1520/D6816-11R16.

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

2. Referenced Documents

2.1 *ASTM Standards*:³

[C670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials](#)

[D8 Terminology Relating to Materials for Roads and Pavements](#)

[D2872 Test Method for Effect of Heat and Air on a Moving Film of Asphalt \(Rolling Thin-Film Oven Test\)](#)

[D6373 Specification for Performance Graded Asphalt Binder](#)

[D6521 Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel \(PAV\)](#)

[D6648 Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer \(BBR\)](#)

[D6723 Test Method for Determining the Fracture Properties of Asphalt Binder in Direct Tension \(DT\)](#)

3. Terminology

3.1 *Definitions*—For definitions of general terms used in this standard, refer to Terminology [D8](#).

3.2 *Definitions of Terms Specific to This Standard*:

3.2.1 *Arrhenius parameter, a_T, n* —this is the constant coefficient in the Arrhenius model for shift factors: $\ln(a_T) = a_1 \cdot ((1/T) - (1/T_{ref}))$.

3.2.2 *coefficient of linear thermal expansion, α, n* —the fractional change in size in one dimension associated with a temperature increase of 1 °C.

² The sole source of supply of the software package TSAR known to the committee at this time is Abatech, Incorporated. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee¹, which you may attend.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.3 *creep compliance*, $D(T,t)$, n —the reciprocal of the stiffness of a material, $1/S(T,t)$, at temperature T and time t , which may also be expressed using reduced time, ξ , as $D(T_{ref},\xi)$.

3.2.4 *critical cracking temperature*, T_{cr} , n —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 which does not include the effect of low temperature thermal fatigue.

3.2.5 *failure stress*, σ_f , n —the tensile stress value at the point of failure obtained from Test Method **D6723**.

3.2.6 *glassy modulus*, n —the modulus at which the binder exhibits glass-like behavior, which is assumed to be equal to 3×10^9 Pa.

3.2.7 *induced thermal stress*, σ_{th} , n —the stress induced in a material by cooling it while it is restrained so that it cannot contract.

3.2.8 *master curve*, n —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.

3.2.9 *pavement constant*, C , n —a 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 Test Method **D6723** DTT test. Full details on the determination of the pavement constant may be found in Refs (1)⁴ and (2), copies of which are on file at ASTM International. After extensive analysis, the most appropriate pavement constant was determined to be 18. The pavement constant of 18 is based on the most current available pavement performance data. The Federal Highway Administration (FHWA) and the Transportation Research Board (TRB) Binder Expert Task Group (ETG) continue to collect and analyze field performance data. In the future, based on these analyses, the pavement constant will be adjusted as appropriate. The pavement constant is an empirical factor required to relate binder thermal stress to the pavement thermal stress.

NOTE 2—Research suggests that changing the pavement constant from 16 to 24 results in a 2 to 4 °C change in the critical cracking temperature, which is less than one low temperature grade interval (6 °C).

3.2.10 *reduced time*, ξ , n —the computed loading time at the reference temperature, T_{ref} , equivalent to actual loading at temperature T , which is determined by dividing actual loading time, t , at temperature T , by the shift factor, a_T , $\xi = t/a_T$.

3.2.11 *reference temperature*, T_{ref} , n —the temperature at which the master curve is constructed.

3.2.12 *relaxation modulus*, $E(T,t)$, n —the modulus of a material determined using a strain-controlled (relaxation) experiment at temperature T and time t , which may also be expressed using reduced time as $E(T_{ref},\xi)$.

3.2.13 *shift factor*, a_T , n —the shift in the time or frequency domain associated with a shift from temperature T to the reference, T_{ref} .

3.2.14 *stiffness modulus*, $S(T,t)$, n —the modulus (stress/strain) of a material at temperature T and time t , which may also be expressed using reduced time as $S(T_{ref},\xi)$.

3.2.15 *specification temperature*, T_{spec} , n —the specified low-temperature grade of the binder being verified.

4. Summary of 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 on the BBR.

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 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 (3), 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.

4.5 The thermal stress calculations are based on Boltzmann’s Superposition Principle for linear viscoelastic 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 (eighteen) is used for the Pavement Constant.

4.6 The calculated thermal stress is then compared to the failure stress from DTT to determine the critical cracking temperature of the pavement.

5. Significance and Use

5.1 Estimated critical cracking temperature, as determined by this practice, is a criterion for specifying the low-temperature properties of asphalt binder in accordance with Specification **D6373**.

5.2 This practice is designed to identify the temperature region where the induced thermal stress in a typical HMA subjected to rapid cooling (1 °C/h) exceeds the fracture stress of the HMA.

5.3 For evaluating an asphalt binder for conformance to Specification **D6373**, the test temperature for the BBR and DTT data is selected from Table 1 of Specification **D6373** according to the grade of asphalt binder.

NOTE 3—Other rates of elongation and test temperatures may be used to test asphalt binders for research purposes.

⁴ The boldface numbers in parentheses refer to the list of references at the end of this standard.

6. Methodology and Required Data

6.1 This practice uses data from both BBR and DTT measurements on an asphalt binder.

6.1.1 The DTT data required is stress at failure obtained by testing at a strain rate of 3 %/min. For continuous grade and PG grade determination, DTT results are required at a minimum of two test temperatures. The DTT tests shall be conducted at Specification **D6373** specification test temperatures at the 6 °C increments that represent the low temperature binder grade. For pass-fail determination, DTT results are required at a single temperature that is 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 s. The BBR test temperatures T and T minus 6 °C ($T - 6$) are selected such that $S(T, 60) < 300$ MPa and $S(T - 6, 60) > 300$ MPa. T shall be one of the Specification **D6373** specification test temperatures at the 6 °C increments that represent the low temperature binder grade.

7. Calculations

7.1 Calculation of the Stiffness Master Curve:

7.1.1 **BBR Compliance Data**— $D(T, t)$ = compliance at time t and temperature 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 **BBR Stiffness Data** is calculated as $S(T, t) = 1/D(T, t)$

7.1.3 Let the shift factor at the reference temperature $a_T = 1$. Determine a_{T-6} , the shift factor for the data at temperature $T - 6$ °C, numerically using Gordon and Shaw's method to produce master curves. 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 m/m/°C. The glass transition temperature is taken as -20 °C.

NOTE 4—This procedure is described in Gordon and Shaw (4)—the master curve procedure is the SHIFTT routine found in Chapter 5. The value of -20 °C is used for the glass transition temperature but has no effect on the calculation as the linear expansion coefficient is assumed to be the same either side of this temperature. Although a constant value of the linear coefficient of thermal expansion alpha is assumed, asphalt binders may have variable values of alpha. The alpha for mixes, however, has been shown by various researchers to be approximately constant and does not vary with asphalt binders.

7.1.4 From a_{T-6} calculate the Arrhenius parameter from the following equations:

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

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

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 in the following equation:

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

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

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

7.1.6 For all 12 values $S(T, t)$ obtained then becomes $S(T_{ref}, \xi)$ with time being replaced by reduced time.

7.1.7 The values are fitted to the Christensen-Anderson-Marasteanu (CAM) (5) model for asphalt master curves in the following equation:

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

where:

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

7.1.8 Fit the resulting master curve data to this equation using a nonlinear least squares fitting method to achieve a root mean square error, rms(%), of less than or equal to 1.25 %. **Appendix X1** contains an example calculation of this error criterion.

7.2 Convert Stiffness Master Curve to Tensile Relaxation Modulus Master Curve:

7.2.1 Use Hopkins and Hamming's method to convert creep compliance values $D(T_{ref}, \xi) = 1/S(T_{ref}, \xi)$ to relaxation modulus $E(T_{ref}, \xi)$.

NOTE 6—This procedure is described in Ref (3).

7.2.2 The glassy modulus value of 3×10^9 Pa shall be adopted in the analysis for $S(T_{ref}, 1 \times 10^{-8} \text{ s}) = E(T_{ref}, 1 \times 10^{-8} \text{ s})$. Calculate relaxation modulus data points using the following iterative formula from $t = 1 \times 10^{-8}$ to $t = 1 \times 10^7$ s with intervals of 4 points per decade—1.000, 1.778, 3.162 and 5.623 ($10^{0.0}$, $10^{0.25}$, $10^{0.5}$, $10^{0.75}$).

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

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 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 viscoelastic materials.

7.3.1 Stress Generation:

7.3.1.1 Use the following constants:

(a) Starting temperature 0 °C,

(b) End temperature $-45\text{ }^{\circ}\text{C}$,
(c) Increment $-0.2\text{ }^{\circ}\text{C}$,
(d) Coefficient of linear thermal expansion, $\alpha = 1.7 \times 10^{-4}$ m/m/ $^{\circ}\text{C}$,

(e) $\Delta t = 720$ s,

(f) Strain per increment, $\varepsilon = \Delta T_i \cdot \alpha = 3.4 \times 10^{-4}$ m/m, and

(g) Strain rate = 4.72×10^{-8} m/m/s.

7.3.1.2 For the N th increment the initial temperature shall be $T^N = -0.2 \cdot (N - 1)$.

7.3.1.3 Divide each increment N into sub-steps.

(1) Use n sub-steps where $n = 20 - 0.048(N - 1)$ truncated to an integer. The number of sub-steps n varies from 20 sub-steps at $0\text{ }^{\circ}\text{C}$ to 9 sub-steps at $-45\text{ }^{\circ}\text{C}$.

(2) Divide the increment logarithmically so that each sub-step is twice the size of the previous one. This defines $n + 1$ points in the increment.

NOTE 8—For example, with 9 sub-steps, the 10 points are $t_0, t_0 + \Delta t/255, t_0 + 2\Delta t/255, t_0 + 4\Delta t/255, t_0 + 8\Delta t/255, t_0 + 16\Delta t/255, t_0 + 32\Delta t/255, t_0 + 64\Delta t/255, t_0 + 128\Delta t/255$, and $t_0 + \Delta t$.

(3) Define the midpoint of each sub-step as the arithmetic midpoint. This defines additional n points.

(4) The endpoints and midpoints of the sub-steps now define $2n + 1$ points in the increment. Define T_i^N and t_i^N for $i = 0$ to $2n$ as the temperature and time, respectively, at each of these points in order.

7.3.1.4 For each increment calculate the shift factor a_{T_i} as follows:

(1) Calculate the second-order gauss-points as follows:

$$t_{p1} = \Delta t \frac{\left(\frac{1-1}{\sqrt{3}}\right)}{2} \quad (8)$$

$$t_{p2} = \Delta t \frac{\left(\frac{1+1}{\sqrt{3}}\right)}{2} \quad (9)$$

(2) Denote the temperatures at these points as T_{p1} and T_{p2} where:

$$T_{p1} = T^N + \Delta T \frac{\left(\frac{1-1}{\sqrt{3}}\right)}{2} \quad (10)$$

$$T_{p2} = T^N + \Delta T \frac{\left(\frac{1+1}{\sqrt{3}}\right)}{2} \quad (11)$$

(3) The shift factors at these points are then:

$$a_{T_{p1}} = e^{(a_1 \left(\frac{1}{T_{p1}} - \frac{1}{T_{ref}}\right))} \quad (12)$$

$$a_{T_{p2}} = e^{(a_1 \left(\frac{1}{T_{p2}} - \frac{1}{T_{ref}}\right))} \quad (13)$$

(4) The shift factor for the increment is then approximated by:

$$a_T = b_0 + b_1 t \quad (14)$$

where:

$$b_1 = \frac{(a_{T_{p2}} - a_{T_{p1}})}{(t_{p2} - t_{p1})} \quad (15)$$

and,

$$b_0 = a_{T_{p1}} - t_{p1} b_1 \quad (16)$$

7.3.1.5 The reduced time at time t from the start of the increment is then given by:

$$\xi(t) = \left(\frac{1}{b_1}\right) \cdot \ln(b_0 + b_1 t) \quad (17)$$

7.3.1.6 Calculate the average modulus for the increment.

(1) Calculate t_i^N for $i = 0$ to $2n$ as $t_0^N = 0$; $t_{2i}^N = 2^{(i/(N-1))} \Delta t$ and $t_{2i-1}^N = (t_{2i} + t_{2i-2})/2$ for $i = 1$ to n .

(2) The reduced time at each point is then:

$$\xi(t_i^N) = \frac{1}{b_1} \ln(b_0 + b_1 t_i^N) \quad (18)$$

(3) The relaxation modulus at each point is then given by the CAM fitted master curve:

$$E(\xi_i^N) = E_{glassy} \left[1 + \left(\frac{\xi_i^N}{\lambda}\right)^\beta \right]^{-\kappa/\beta} \quad (19)$$

(4) Finally, the average relaxation modulus for the increment is given by the numerical sum:

$$\bar{E} = \frac{\sum_{i=1}^n [(E_{2i-2} + 4E_{2i-1} + E_{2i})(t_{2i} - t_{2i-2})]}{(6\Delta t)} \quad (20)$$

7.3.1.7 The generated stress at increment N , σ_{str}^N , is determined as follows:

$$\sigma_{str}^N = \bar{E}^n \cdot \varepsilon = \bar{E}^n \cdot \Delta T \cdot \alpha \quad (21)$$

7.3.1.8 This cycle is repeated for all increments.

7.3.2 *Stress Relaxation:*

7.3.2.1 The stress relaxation of the stress generated in each individual strain increment N is modeled.

7.3.2.2 The stress relaxation is approximated by evaluating the equation, as follows:

$$\sigma(t) = \varepsilon E[\xi(t) - \tau] \quad (22)$$

7.3.2.3 The first operation in the stress relaxation calculation is to obtain the correction term τ in Eq 22.

7.3.2.4 This correction term τ is the difference between $\xi(\Delta t)$, the reduced time at the cessation of increment strain, and ξ_m , the reduced time at which the increment strain multiplied by relaxation modulus equals the stress generated in the initial time step of the strain increment N . This is shown by the following equation:

$$\tau = \xi(\Delta t) - \xi_m \quad (23)$$

7.3.2.5 The value of τ is calculated immediately after the numerical quadrature defined by Eq 20 has been carried out, by storing temporarily the E and ξ values needed to estimate the integral. Interpolating in these values for the reduced time ξ_m at which $E[\xi_m]$ equals the value of the integral yields the amount of reduced time to be carried forward to the relaxation time steps, and accounts for the term τ .

7.3.2.6 The increase in reduced time during each relaxation time step is found using the same linearization of a_T versus t as described previously for the stress-generating time step of the strain increment.

NOTE 9—in order to use Eq 17, the linearization is calculated afresh for each time step, as specified by Eq 8-16.

7.3.2.7 The increase of reduced time during a time step is calculated with Eq 17 and added to the reduced time brought

forward from the previous time step. The resulting reduced time is substituted in the CAM equation and the modulus obtained is multiplied by the increment strain to obtain the relaxed stress at the end of the time step.

7.3.3 Stress Summation:

7.3.3.1 The generated stress for interval N is summed with the stress relaxation from all the preceding intervals.

$$\sigma^N = \sigma_{str}^N + \sum_{i=1}^{N-1} \sigma_{rel}^{i,N} \quad (24)$$

7.3.3.2 These calculations yield the calculated binder thermal stress at temperatures from 0 °C to –45 °C, at 0.2 °C increments.

7.3.3.3 The stress resulting from the calculation is multiplied by a constant of 18 to yield the thermally induced stress to which all comparisons shall be made in subsequent sections of this practice. The generated stress in the pavement for interval n is summed with the stress relaxation from all the preceding intervals as described in 7.3.3.

$$(\sigma^n)_{pavement} = \left(\sigma_{str}^n + \sum_{i=1}^{n-1} \sigma_{rel}^{i,n} \right) \cdot C \quad (25)$$

8. Critical Cracking Temperature Determination of an Asphalt Binder

8.1 Grading of an asphalt binder requires BBR data at two test temperatures and DTT data at a minimum of two test temperatures.

NOTE 10—The temperatures to be selected for the DTT tests may not be consistent with the BBR test temperatures as defined in 6.1.2 and additional tests may be required. The example given in Appendix X2 requires that one of the DTT test temperatures be lower than that used for the BBR tests.

8.2 Using a linear relationship between the DTT test results, determine the intercept with the thermally induced stress curve using linear interpolation. The intercept, rounded to the nearest 0.1 degree, shall be reported as the estimated critical cracking temperature, T_{cr} .

8.3 In the case of no intercept being determined, additional DTT tests shall be performed at 6 °C increments higher or lower in temperature as appropriate until an intercept is determined as described in 8.2.

8.4 The grades that the low temperature grade meets are evaluated by comparing the T_{cr} value to the 6 °C temperature grade intervals given in Specification D6373. The grades met are those which have a higher temperature than T_{cr} .

NOTE 11—For example, if a binder has a T_{cr} value of –24.5 °C it meets the specification at –22, –16, and –10.

9. Pass-Fail Determination for the PG Grade of an Asphalt Binder

9.1 This section describes the testing and analysis required for pass-fail determination of an already known PG grade of an asphalt binder at a specified low temperature grade, T_{spec} .

9.2 Pass-fail determination of an asphalt binder PG grade requires BBR data at two test temperatures and DTT data at one test temperature.

9.3 To pass at the specification temperature, the failure stress shall be greater than the thermal stress at the specifica-

tion temperature of the binder. The thermal stress at the specification temperature shall be determined as follows.

9.3.1 Execute the procedure given in Section 7 using BBR data at both test temperatures.

9.3.2 Determine the failure stress using the DTT at a test temperature that is 10 °C higher than the specification temperature, $T_{spec} + 10$ °C.

9.3.3 Compare the failure stress from DTT to the calculated thermally induced stress at the specification temperature, T_{spec} . If the failure stress exceeds the thermally induced stress, the asphalt binder shall be deemed a “PASS” at the specification temperature. If the failure stress does not exceed the thermally induced stress, the asphalt binder shall be deemed a “FAIL” at the specification temperature.

10. Report

10.1 Report the following information:

10.1.1 Sample identification,

10.1.2 Identifying information for the BBR and DTT data sets used,

10.1.3 Date and time of calculations,

10.1.4 Pavement Constant, C ,

10.1.5 The rms(%) error as defined in Appendix X1,

10.1.6 Low temperature grade being determined,

10.1.7 Estimated thermal stress at this temperature,

10.1.8 DTT failure stress to the nearest 0.01 MPa,

10.1.9 Whether the comparison of these two values results in a PASS or a FAIL,

10.1.10 If determined, the estimated critical cracking temperature to the nearest 0.1 °C.

11. Precision and Bias

11.1 *Precision*—The precision of this practice depends on the precision of Test Method D6648 and Test Method D6723. A multi-laboratory (nine laboratories) round robin was conducted to determine the reproducibility of the critical cracking temperatures determined using this practice. The results of this round robin may be considered preliminary, as the requirements of Practice C670 were not followed in experiment design or data analysis from this round robin (see Table 1).

11.2 *Bias*—There are no acceptable reference values for the properties determined in this test method so bias for this test method cannot be determined.

12. Keywords

12.1 asphalt binder; bending beam rheometer; critical cracking temperature; direct tension; failure; failure stress; fracture; thermal cracking; thermally induced stress

TABLE 1 Results of Round Robin Conducted to Determine the Reproducibility of the Critical Cracking Temperature^A

Asphalt Binder	Critical Cracking Temperature, °C	Standard Deviation, °C	Acceptable Range of Test Results, °C
A—Unmodified	–31.9	0.8	2.26
B—Modified	–29.9	0.3	0.85

^A Nine laboratories participated.

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLE OF RMS CALCULATION

X1.1 In this example, a binder is being evaluated for a PGXX-34 grade. Two BBR data sets are collected according to the prescribed method. The data collected is as follows in **Table X1.1**:

TABLE X1.1 BBR Data Required to Determine the Critical Cracking Temperature of a PG XX-34 Asphalt Binder^A

<i>t</i> , s	<i>T</i> = -24 °C	<i>T</i> = -30 °C
8	456	760
15	390	670
30	321	581
60	262	493
120	211	412
240	168	338

^A At *t* = 60 s the stiffness conforms to the 300 MPa criteria specified in 6.1.2.

X1.2 The data is shifted to obtain a master curve in accordance with Section 7. The results are as follows in **Table X1.2**:

TABLE X1.2 Shifted BBR Master Curve Data Obtained Using Time-Temperature Superposition Method Applied to Data in Table X1.1

<i>S(t)</i> Mastercurve points by determined by non-linear fit		
<i>t</i> , s	<i>S(t)</i> , MPa	CAM fit <i>S(t)</i>
0.746762829	777.956079	780.1128634
1.400180304	685.8297012	686.7969332
2.800360608	594.7269499	590.3342984
5.600721215	504.6478249	501.4979943
11.20144243	421.7340849	420.9415568
22.40288486	345.9857299	349.0372177
8	456	458.9964638
15	390	389.5836724
30	321	321.3666772
60	262	261.8456021
120	211	210.7390985
240	168	167.5525635

X1.2.1 In **Table X1.2** the fit was obtained using computer software. The CAM fit parameters, for this example, are as follows in **Table X1.3**:

TABLE X1.3 CAM Model Parameters Obtained by Fitting the Master Curve (Table X1.2) to the CAM Model

CAM fit to <i>S(t)</i> master curve	
λ	35.04887058
β	0.176793727
κ	0.581197694

X1.3 The relative error is determined by the following equation:

$$Error = \frac{(S(t) - S(t)_{fitted})}{S(t)} \quad (X1.1)$$

X1.4 The square of the relative error is determined. These values for this data set are given in **Table X1.4**.

TABLE X1.4 Error Estimates Obtained During the Fitting of the CAM Model to Data from Table X1.2

Relative Error of <i>S(t)</i>	Square of Relative Error
-0.002772373	7.68605E-06
-0.001410309	1.98897E-06
0.007385997	5.4553E-05
0.006241641	3.89581E-05
0.001879213	3.53144E-06
-0.008819693	7.7787E-05
-0.006571192	4.31806E-05
0.001067507	1.13957E-06
-0.001142296	1.30484E-06
0.000589305	3.4728E-07
0.0012365	1.52893E-06
0.002663312	7.09323E-06

X1.5 The sum of the square of the relative error (SSRE) is computed and from this the rms(%) is determined in the following equation:

$$rms(\%) = 100 \sqrt{\frac{SSRE}{12}} \quad (X1.2)$$

X1.5.1 For the data in this example the computed rms(%) is 0.45 %. This fit of the master curve is illustrated in **Fig. X1.1**. The rms% shall be less than or equal to 1.25 % for the data set to be deemed acceptable.

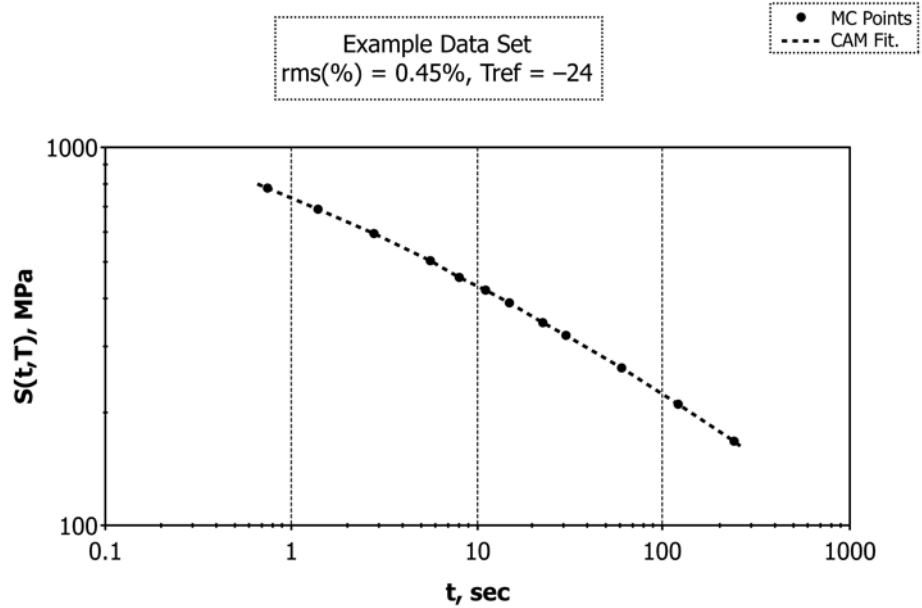


FIG. X1.1 Plot of CAM Model Fitted to the Shifted Master Curve in Table X1.2

X2. EXAMPLE OF RESULTS FOR THE EXAMPLE DATA SET

X2.1 In addition to BBR data sets the DTT testing was performed at two temperatures. This data is as follows in Table X2.1:

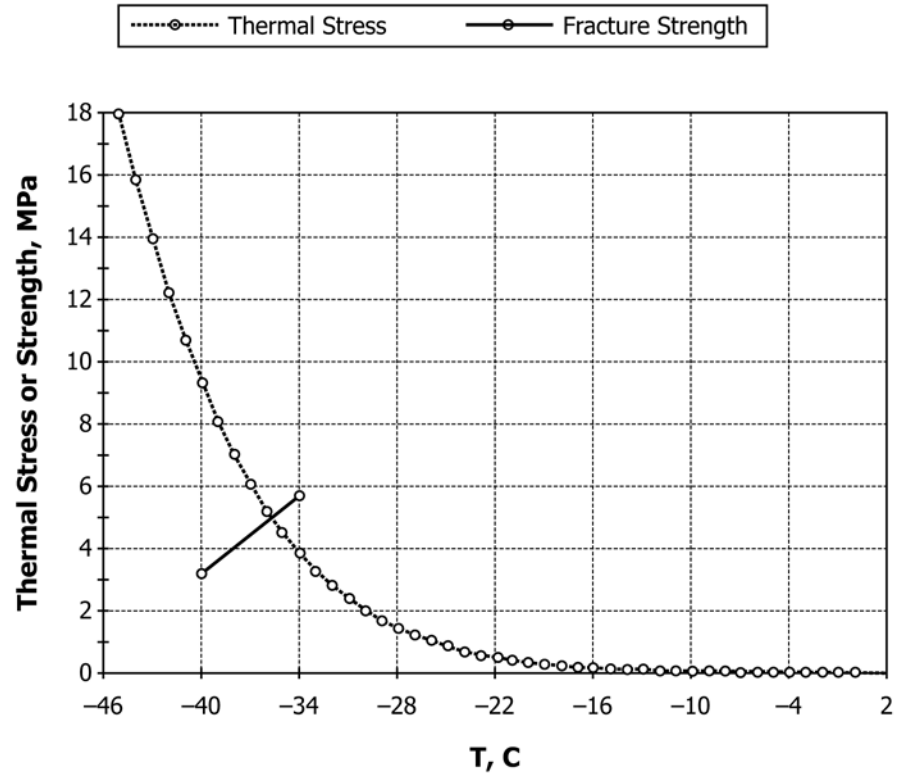
TABLE X2.1 Binder Strength Data from the DTT at Two Test Temperatures

Temperature, °C	DTT Failure Stress, MPa
-24	5.713
-30	3.238

X2.2 The graph obtained from the stress calculation is plotted below with the DTT test points. Using linear interpolation the intersection is determined to be -35.7 °C.

X2.3 At -34 °C (the grade for which this binder would be evaluated) report:

- X2.3.1 The sample ID.
- X2.3.2 The BBR and DTT data sets as given in Appendix X2.
- X2.3.3 The date and time of the calculations.
- X2.3.4 The rms(%) error as 0.45 %.
- X2.3.5 The grade being determined as PGXX-34.
- X2.3.6 The estimated stress at -34 °C as 3.88 MPa.
- X2.3.7 The DTT failure stress at -34 °C as 5.71 MPa.
- X2.3.8 The result is a PASS.
- X2.3.9 The critical cracking temperature is -35.7 °C.



**Fracture Strength & Thermal Stress, MPa
Critical Temperature -35.7 C**

FIG. X2.1 Graphical Illustration of the Procedure Used to Calculate the Critical Cracking Temperature

REFERENCES

- (1) Bouldin, M. G., Dongré, R., Sharrock, M. J., Dunn, L., Anderson, D. A., Marasteanu, M. O., Rowe, G. M., Zanzotto, L., and Kluttz, R. Q., Report for the FHWA Binder ETG, “A Comprehensive Evaluation of the Binders and Mixtures Placed on the Lamont Test Sections,” Federal Highway Administration, Washington, DC, 1999.
- (2) Dongré, R., Bouldin, M. G., Anderson, D. A., Reinke, G. H., D’Angelo J., Kluttz, R. Q., and Zanzotto, L., Report for the FHWA Binder ETG, “Overview of the Development of the New Low-Temperature Binder Specification,” Federal Highway Administration, Washington, DC, 1999.
- (3) Hopkins, L. L., and Hamming, R. W., “On Creep and Relaxation,” *Journal of Applied Physics*, Vol 28, No. 8, 1957, pp. 906–909.
- (4) Gordon, G. V. and Shaw, M. T., “Superposition of Linear Properties,” chap. 5 in *Computer Programs for Rheologists*, Hanser Gardner Publications, Cincinnati, OH, 1994.
- (5) Marasteanu, M. O., Anderson, D. A., “Improved Model for Bitumen Rheological Characterization,” Eurobitume Workshop on Performance-Related Properties for Bituminous Binders, paper no. 133, Luxembourg, 1999.
- (6) Rowe, G. M., Sharrock, M. J., Bouldin, M. G., and Dongré, R., “Advanced Techniques to Develop Master Curves from the Bending Beam Rheometer,” *The Asphalt Yearbook 2000*, Institute of Asphalt Technology, Stanwell, Middlesex, England, 2000, pp. 21-26.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; <http://www.copyright.com/>