Designation: D6816 – 02

Standard Practice for
Determining Low-Temperature Performance Grade (PG) of Asphalt Binders[1]

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.*

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_1, 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.

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) ex-

periment 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's method (4), 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.

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

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

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/Shaw (3)—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:

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

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

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:

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

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

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

7.1.6 For all 12 values S (T,t) obtained then becomes S (T_{ref},ξ) 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:

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

where:
S_{glassy} = the assumed glassy modulus for the binder: $S_{glassy} = 3\times10^9$ Pa.

7.1.8 Fit the resulting master curve data to this equation using a non-linear 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},ξ)=$1/S$ (T_{ref},ξ) to relaxation modulus E (T_{ref},ξ).

NOTE 6—This procedure is described in Ref (4).

7.2.2 The glassy modulus value of 3×10^9 Pa shall be adopted in the analysis for S (T_{ref},1×10^{-8} s) = E (T_{ref},1×10^{-8} s). Calculate relaxation modulus data points using the following iterative formula from $t = 1\times10^{-8}$ to $t = 1\times10^7$ s with intervals of 4 points per decade—1.000, 1.778, 3.162 and 5.623 ($10^{0.0}$,$10^{0.25}$,$10^{0.5}$,$10^{0.75}$)

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

where,

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

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°C,

(c) Increment -0.2°C,

(d) Coefficient of linear thermal expansion, $\alpha = 1.7\times10^{-4}$ m/m/°C,

(e) Δt = 720 s,

(f) Strain per increment, $\varepsilon = \Delta T_i \cdot \alpha = 3.4\times10^{-4}$ m/m, and

(g) Strain rate = 4.72×10^{-8} m/m/s.

7.3.1.2 For the Nth increment the initial temperature shall be T^N = -0.2·(N-1).

7.3.1.3 Divide each increment N into sub-steps.

7.3.1.3.1 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°C to 9 sub-steps at -45°C.

7.3.1.3.2 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 $t_0+\Delta t$.

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

7.3.1.3.4 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_{Ti} as follows:

7.3.1.4.1 Calculate the second-order gauss-points as follows:

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

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

7.3.1.4.2 Denote the temperatures at these points as T_{p1} and T_{p2} where:

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

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

7.3.1.4.3 The shift factors at these points are then:

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

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

7.3.1.4.4 The shift factor for the increment is then approximated by:

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

where:

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

and,

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

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

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

7.3.1.6 Calculate the average modulus for the increment.

7.3.1.6.1 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.

7.3.1.6.2 The reduced time at each point is then:

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

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

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

7.3.1.6.4 Finally, the average relaxation modulus for the increment is given by the numerical sum:

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

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

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

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:

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

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:

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

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*: