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Asphalt Material Creep Behavior

Amir Golalipour

Abstract

Asphalt binder, as one of the load-carrying components of the pavement, is a viscoelastic, thermoplastic material characterized by a certain level of rigidity of an elastic solid body, but, at the same time, flows and dissipates energy by frictional losses as a viscous fluid. Due to its complexity and importance, many studies were conducted to understand and alleviate its performance. Creep tests have been used to characterize asphalt materials at different service temperatures. Permanent strain or rutting is one of the most important pavement distresses. It is believed that the accumulated strain in asphalt binder, as a consequence of traffic, is mainly responsible for the rutting of asphalt pavements. Repeated creep tests were developed to identify non-viscous flow that contributes to the permanent deformation from the total dissipated energy. The low-temperature cracking of asphalt pavements is a major pavement distress mechanism in cold regions. Since asphalt is a viscoelastic material, part of said stresses is dissipated through relaxation, but, eventually, they build up until they reach the strength of the material, leading to the formation of cracks to relieve these stresses. Conducting creep test at low temperatures is a common test method to characterize thermal cracking behavior of asphalt binders.

Keywords: asphalt, pavements, creep test, permanent strain, rutting, thermal cracking

1. Asphalt rutting resistance

Asphalt pavements are granular composites that contain mineral aggregates, asphalt binder and air voids. The two load-carrying components of the asphalt mixtures are the mineral aggregates and the binder. Asphalt binders are obtained from the refining of crude oil. They are produced from the heavy residue after the refining of fuels and lubricants. Asphalt is a thermoplastic material that demonstrates viscoelastic properties under most pavement operating conditions [1]. It is this fundamental property that makes them versatile binders for asphalt mixtures with the viscoelastic characteristics of the bituminous binders directly and significantly influencing the performance of the mixtures.

One of the distress modes of asphalt pavements is permanent deformation or rutting that occurs at high operating temperatures, and it is believed that the accumulated strain in asphalt binder is mainly responsible for the rutting. Rutting is defined as longitudinal surface depressions along a pavement's wheel paths. In asphalt pavements, rutting is defined as the progressive accumulation of longitudinal depressions in a wheel path under repetitive loading [2].

The majority of rutting problems result from plastic deformation of the surface course. It is characterized by shear deformation inside the asphalt mixture [3]. The permanent deformation per wheel passage correlates with the stiffness of the

asphalt binder used, and decreases with increasing number of wheel passages [4]. Also, permanent deformation in asphalt binder is highly dependent on the stress level. One of the most recent areas of investigation in pavement engineering is the relationship between asphalt rheology and rutting in pavements.

Asphalt mixture is a viscoelastic material that contains mineral aggregates, asphalt binder and air voids. Asphalt binder, as one of the load carrying components of the asphalt mixtures, is a viscoelastic, thermoplastic material that is characterized by a certain level of rigidity of an elastic solid body, but, at the same time, flows and dissipates energy by frictional losses as a viscous fluid [5]. Its characteristics are dependent on time and temperature [6]. At higher temperatures and longer loading times, the asphalt material softens and behaves more similar to a viscous fluid. At lower temperatures and faster loads, the asphalt material becomes stiffer and act more as an elastic material. Because of this, rutting is more critical during the hot season in a year and under slower moving traffic.

As the asphalt binder is responsible for the viscoelastic behavior of all bituminous materials, it plays a dominant part in determining many of the aspects of pavement performance, such as resistance to permanent deformation. Therefore, binder has a critical role against rutting in mixture. Also, as with any viscoelastic material, asphalt's response to stress is dependent on both temperature and loading time [5]. Therefore, permanent deformation in asphalt binder is highly dependent on the factors such as temperature, stress level, loading time etc.

1.1 Asphalt binder characterization and tests at high temperatures

Recognizing the limitation of the traditional asphalt binder characterization procedure in 1987, the Federal Highway Administration initiated a nationwide research program called the Strategic Highway Research Program, usually referred to as SHRP [6]. The final product of the SHRP research program was Superpave[®] (Superior Performance Asphalt Pavements). The Superpave[®] was designed to provide performance-related properties that can be related in a rational manner to pavement performance [5].

The Dynamic Shear Rheometer (DSR) was introduced in 1993 by Superpave[®] as a tool to measure the binder mechanical characterization. This device provided a useful method to evaluate binder rutting resistance capability. The principle used with the DSR is to apply sinusoidal, oscillatory stresses or strains over a range of temperatures and loading frequencies to a thin disc of bitumen, sandwiched between the two parallel plates of the DSR. Anderson et al. [6] assumed that rutting is caused by the total dissipated energy as calculated from the strain-stress curve.

$$W_i = \pi * \tau_0^2 * \frac{1}{\frac{G^*}{\sin \delta}} \quad (1)$$

where:

W_i = total energy dissipated at the i th cycle, τ_0 = maximum stress applied, G^* = complex modulus, δ = phase angle.

$|G^*|/\sin \delta$ was introduced as the rutting parameter. Equation 1 shows that increasing the rutting parameter $|G^*|/\sin \delta$ causes dissipated energy to decrease and, as a consequence, more rutting occurs.

Using cyclic reversible loading for viscoelastic materials can be misleading because although this test has the capability of estimation the total energy dissipated during a loading cycle, as it is unable to separate permanent deformation and delay elasticity in these materials. Rutting is a repeated mechanism with sinusoidal

loading pulse in which the pavement layer is not forced back to zero deflection but would recover some deformation due to elastic stored energy in the material of the layers. Under this type of loading, the energy is dissipated in damping and in permanent flow [7]. It was proposed that a creep and recovery test in the DSR could solve the above problems [8].

1.2 Repeated creep and recovery (RCR) test

The repeated creep test is proposed as a method of separating the dissipated energy and estimating the resistance to accumulation of permanent strain for asphalt binders. During the NCHRP 9-10 project, Bahia et al. [8] suggested the repeated creep recovery test (RCR) as a better tool to investigate the rutting resistance of asphalt binders using the dynamic shear rheometer (DSR). The NCHRP 9-10 project recommend a shear stress in the range of 30–300 Pa for 100 cycles at a rate of 1 (second) loading time followed by a 9 (seconds) unloading time [8].

This project introduced a new parameter G_v to characterize the rutting resistance of asphalt binders. This new parameter was derived from the four-element Burger model, which is a combination of a Kelvin model and Maxwell model. The total shear strain versus time is expressed as follows:

$$\gamma(t) = \gamma_1 + \gamma_2 + \gamma_3 = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1} \left(1 - e^{-\frac{tG_1}{\eta_1}} \right) + \frac{\tau_0}{\eta_0} t \quad (2)$$

where $\gamma(t)$ = total shear strain, γ_1 = elastic shear strain, γ_2 = delayed elastic strain, γ_3 = viscous shear strain, τ_0 = constant stress, G_0 = spring constant of Maxwell model, tG_1 = spring constant of Kelvin model, η_1 = dashpot constant of Kelvin model, t = time, η_0 = dashpot constant of Maxwell model.

Dividing Eq. (2) by the constant stress leads to the following equation:

$$J(t) = J_e + J_{de}(t) + J_v(t) \quad (3)$$

where J_e = elastic creep compliance, $J_{de}(t)$ = delayed elastic creep compliance, $J_v(t)$ = viscous creep compliance.

Instead of using J_v which has a unit of 1/Pa, the inverse of compliance G_v is used. G_v is defined as the viscous component of the creep stiffness [8].

D'Angelo showed that a single stress level did not completely account for the stress dependency of modified binders and multiple stress levels need to be used [9]. Testing binders at multiple stress level using the RCR test would require an extensive amount of time.

NCHRP 9-10 project recommended RCR testing using the DSR to evaluate the rutting resistance of asphalt binders using G_v parameter showing viscous component of the creep stiffness. This parameter has shown promising results to characterize the rutting behavior of asphalt binder, especially modified binders. The main benefits of RCR compared with the current test standard and parameter $|G^*|/\sin \delta$ are described in previous work [10] and can be summarized as follows:

- Better simulation of actual loading from truck on the pavement using repeated creep loading compared to dynamic shear procedure.
- It is simpler way to identify binder rutting resistance using permanent deformation derived from RCR test. This method highlights the effect of

delayed elasticity which is very important for modified binders and allows the binder to recover deformation during the rest period. The parameter $|G^*|/\sin \delta$ is unable to directly evaluate the delayed elasticity.

It is not fully understood if testing at low stress levels is representative of binder rut resistance behavior as happens in the field since the stresses and strains in the binder can be very high and non-linear. Permanent deformation in asphalt binder is highly dependent on the stress level. Determining the stress level at which the binder is exposed in the mixture is an important matter [11]. Permanent deformation is not a linear viscoelastic phenomenon and therefore measurement of linear viscoelastic binder properties are not likely to correlate with it [12].

The RCR test provides valuable information about the asphalt material rutting resistance when temperature changes happen. However, since the loading on pavement in the field is not consistent, multiple stresses are required to accurately characterize the asphalt binder rutting behavior. These stresses should be selected to capture the properties of the asphalt in linear and in nonlinear domain.

1.3 Multiple stress creep and recovery (MSCR)

The MSCR test was developed to reduce the number of samples at each stress level and it is the following development of RCR test. The test uses 1 (second) creep loading followed by 9 (seconds) recovery for the following stress levels: 25, 50, 100, 200, 400, 800, 1600, 3200, 6400, 12,800 and 25,600 Pa at 10 cycles for each stress level. The test starts at the lowest stress level and increase to the next stress level at the end of every 10 cycles, with no rest periods between creep and recovery cycles or changes in stress level [11].

D'Angelo selected two stress levels, 0.1 and 3.2 kPa, upon correlation between binder and mixture rutting results for performing the MSCR test. Ten cycles are run for each stress level for a total of 20 cycles. **Figure 1** shows the typical results from MSCR test.

The average non-recoverable strain for the 10 creep and recovery cycles is then divided by the applied stress for those cycles yielding the non-recoverable creep compliance (J_{nr}). J_{nr} for 0.1 kPa is calculated by divided the strain after 10 cycles to 0.1 kPa. Equations (4) and (5) show the calculation method for J_{nr} at 0.1 kPa.

$$J_{nr}(0.1, N) = \frac{\varepsilon_{10}}{0.1} \quad (4)$$

$$J_{nr0.1} = \frac{SUM[J_{nr}(0.1, N)]}{10} \text{ for } N = 1 \text{ to } 10 \quad (5)$$

where $\varepsilon_{10} = \varepsilon_r - \varepsilon_o$, ε_r = strain value at the end of the recovery portion (i.e., after 10.0 seconds) of each cycle strain, ε_o = initial strain value at the beginning of the creep portion of each cycle.

The definition for the J_{nr} at 3.2 kPa is analogous. The J_{nr} parameter was suggested as a measure of the binder contribution to mixture permanent deformation [13].

Later, Shenoy [14] used non-recoverable compliance to characterize the propensity of asphalt binder to resist permanent deformation in the pavement. He proposed measuring the non-recoverable compliance through the dynamic oscillatory test using a frequency, time, strain or sweep test. Mathematical formula was used to calculate non-recoverable compliance from the complex modulus and phase angle. Also Shenoy showed that the unrecoverable strain in a binder that is during a creep and recovery test could be calculated directly from the dynamic oscillatory

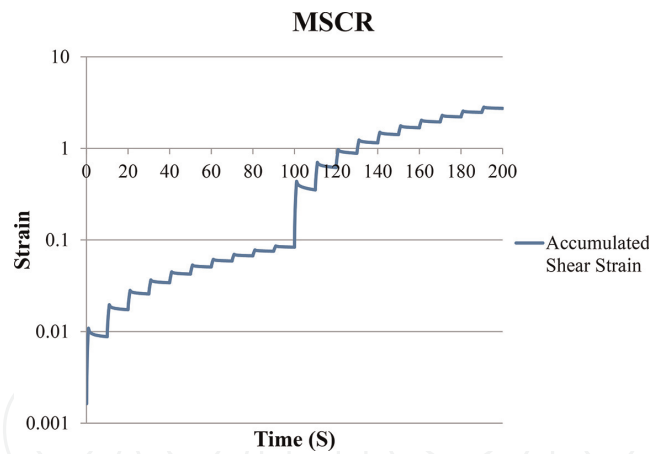


Figure 1.
 MSCR response curve.

test using a frequency test [15]. The percent-unrecovered strain is calculated as follows:

$$\% \gamma_{\text{unr}} = \frac{100 \sigma_0}{|G^*|} \left(1 - \frac{1}{\tan \delta \sin \delta} \right) \quad (6)$$

To minimize the unrecoverable strain, the following term (the inverse of the non-recoverable compliance, $\% \gamma_{\text{unr}} / \sigma_0$) needs to be maximized:

$$\frac{|G^*|}{1 - \frac{1}{\tan \delta \sin \delta}} \quad (7)$$

$|G^*| / (1 - (1 - \tan \delta \sin \delta))$ was proposed as a refinement to the Superpave[®] specification for performance grading of asphalts. The drawback of this parameter is that at $\delta < 52^\circ$, the model would predict unrealistic negatives values of $(1 - (1 - \tan \delta \sin \delta))$ [15].

Bouldin et al. [16] developed a semi empirical method to predict the rut resistance (R) as a function of loading (time and load) and temperature from data at single frequency. This approach is based on the assumption that the strain accumulation rate depends on the binder stiffness and viscoelastic contribution $f(\delta)$, and these two contributions are independent

$$R = (1/\gamma_{\text{acc}})(t_{\text{load}}, t_{\text{rest}}) = G^*(\omega) f[\delta(\omega)] \quad (8)$$

$$(1/\gamma_{\text{acc}}) = k G^* \left(Y_0 + a \left\{ 1 - \exp \left[-|\delta - X_0 + b \ln(2)^{1/c} / b \right]^c \right\} \right) \quad (9)$$

where k = constant, γ_{acc} = accumulated strain, δ = phase angle, Y_0 , X_0 , a , b , c = empirical fitting parameters.

The disadvantage of this parameter is that at phase angles between 40 and 75° this parameter does not fully capture the viscoelastic nature of many modified binders [16].

The MSCR is proposed as a better test to evaluate modified binders and estimate their role in pavement performance. The MSCR has received many positive feedbacks as a good candidate for rutting evaluation and shown a great promise. However, this test has faced few challenges regarding implementation, especially in terms of analysis of the result and interpretation.

While results of the MSCR test are promising [9, 11, 13, 17, 18], there are important concerns about current testing and analysis protocols. It is not clear that

testing at a low stress levels (0.1 and 3.2 kPa) is the best way to characterize the rutting resistance of an asphalt binder. The stresses and strains in the binder can be high, much higher than the linear limit for the material. Permanent deformation in asphalt binder is highly dependent on the stress level. Determining the stress level at which the binder is exposed in the mixture is an important matter [19, 20]. Permanent deformation is not a linear viscoelastic phenomenon and, therefore, measurement of linear viscoelastic binder properties are not likely to correlate with it [21]. The selection of two stress levels is not necessarily based on the stresses that asphalt binder experiences inside the pavement. The number of cycles and the time of loading do not provide full picture of characterizing long term deformation in the material. The recovery time may need to be longer to fully capture delayed elastic behavior of modified binders; some binders are still recovering after 9 (seconds) of recovery [22]. Golalipour [23] investigated these factors and provided some improvements for the MSCR test protocol.

In the latest version of AASHTO standard T 350 standard “Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” or American Society for Testing and Materials standard (ASTM) 7405, the test consists of 20 cycles of 0.1 kPa stress creep and recovery, followed immediately by another 10 cycles of 3.2 kPa stress creep and recovery. Each cycle consists of 1 second of loading and 9 seconds of recovery upon instantaneous unloading [24, 25].

The non-recoverable creep compliance, J_{nr} , and the percent recovery, $R\%$, are two of the parameters calculated from the measured strain under different stress cycles [9, 11]. The J_{nr} parameter was suggested as a measure of the binder contribution to mixture permanent deformation. Different factors can have significant impact on J_{nr} value such as the duration of the creep interval, the duration of the recovery interval, the number of loading cycles and, of course, the entity of the applied shear stress. In other words, J_{nr} depends on the mechanical history of the experiment.

2. Asphalt thermal cracking behavior

The low-temperature cracking of asphalt concrete pavements is a major pavement distress mechanism in cold regions costing hundreds of millions of dollars in rehabilitation costs to various agencies. It usually occurs in the form of regularly spaced transverse cracks, initiating at the surface of the asphalt layer and further propagating downward. Consequences of thermal cracking are an immediate increase of the roughness of the pavement surface (i.e., a reduction of the comfort and safety of the ride) and the loss of the sealing function of the pavement for the underlying layers. However, predictions of this distress have not been accurate enough, often resulting in premature road failures. It is believed that the excessive brittleness due to the increase in stiffness and decrease in the ability to relax stress leads to the buildup of thermally induced stress and ultimately cracking of mixtures in pavements.

The prediction of asphalt pavement thermal cracking has been the subject of numerous studies that date back to the early 1960's [26]. In many of these studies, attempts were made to introduce a procedure to predict pavement cracking based on the stress-strain-time—temperature relationship. A number of methods have been introduced throughout the years to model the viscoelastic behavior of asphalt binders and mixtures to estimate the accumulation of thermal stress during cooling cycles and predict the temperature at which cracking occurs [27–29].

2.1 Asphalt binder characterization and tests at low temperatures

It has been shown that the characteristic of the asphalt binder can significantly impact the low temperature behavior of asphalt pavement. During the service life of the pavement, asphalt is exposed to low temperatures, which tend to alter the rheological behavior. Different studies have concluded that asphalt binder behavior is the dominant component for low-temperature performance of the asphalt pavement mixtures [30]. Therefore, it is very important to study the asphalt binder characterize at low temperatures to have a clear picture of factors that affect the low temperature behavior of pavement.

Based on the concept that asphalt binder properties play the major role in cracking, several studies have focused on investigating the effect of rheological and other parameters of asphalt binder on low temperature performance. A quantitative method is necessary in order to study the complex role of asphalt binder in the pavement and to relate its properties to low temperature cracking phenomenon.

It is believed that thermal stresses causing cracking are due to constrained thermal strains. When the temperature drops, the pavement tends to contract its volume, following its thermal expansion/contraction coefficient. However, the layer underneath opposes some resistance due to friction, therefore thermal strains within the asphalt layer are not free to take place leading to co-active stresses proportional to the stiffness of the material. Since asphalt is a viscoelastic material, part of said stresses are dissipated through relaxation, but eventually they build up until they reach the strength of the material, leading to the formation of cracks to relieve these stresses [31].

A number of methods have been introduced throughout the years to model the viscoelastic behavior of asphalt binders and mixtures to estimate the accumulation of thermal stress during cooling cycles and predict the temperature at which cracking occurs. Shoor et al. [32] studied the penetration measurement to investigate the low temperatures behavior of asphalt binder. Majidzadeh and Schweyer [33] investigated asphalt low temperature properties using more fundamental approach using viscoelastic models. They studied few asphalt binders' behavior at the temperature range of -9 – 5°C using cylindrical specimens. At the lowest temperatures, the asphalt binders exhibited some instantaneous elastic deformation. Pink et al. [34] used a Rheometric Mechanical Spectrometer (RMS) to make accurate low-temperature viscoelastic measurements on asphalt down to -94°C . They developed a methodology to construct a dynamic master curve to separate the effect of time and temperature. Button et al., also used the RMS to measure viscosity of asphalts from 0 to -46°C . Thus, most of the predicting low-temperature cracking methods involve measured asphalt stiffness, predicted asphalt stiffness, or consistency and temperature susceptibility parameters that indirectly establish asphalt stiffness [35].

During the SHRP project, several studies have focused on developing a new device for measuring low temperature stiffness of binders. Finally, these studies led to the development a device to determine the properties and response of asphalt binders at low temperatures in the 1980's. This device was later modified and updated as part of the SHRP binder research [36]. The resulting machine was named the Bending Beam Rheometer (BBR).

2.2 Bending beam rheometer (BBR) test

The data acquisition system of the BBR records the load and deflection test results and calculates two parameters: (1) Creep Stiffness, $S(t)$, which is a measure of how the asphalt binder resists the creep loading, and (2) m -value, which is

a measure of the rate at which the creep stiffness changes with loading time (Figure 2).

Thermo-mechanical properties of the asphalt samples can be measured using the Bending Beam Rheometer to evaluate the low temperature properties based on the ASTM D6648 and AASHTO T 313 [37, 38]. The stiffness, $S(t)$, is a measure of the thermal stresses developed in the asphalt pavements as result of thermal contraction. Classic beam analysis theory is used to calculate the creep stiffness of the asphalt binder beam at 60 seconds loading time [5]. The BBR loads the beams for 240 seconds and report the stiffness values at loading times of 8, 15, 30, 60, 120 and 240 seconds. These values were chosen because they are fairly equally spaced on a logarithmic time scale. These data points, along with the following equation, are used to determine the shape of the stiffness (creep compliance) master curve for the asphalt binder (Eq. (10)).

$$S(t) = A + B \log(t) + C [\log(t)]^2 \quad (10)$$

where $S(t)$ = asphalt binder stiffness, T = time (s), A , B and C = constants.

The slope of the stiffness curve, m , is a measure of the rate of stress relaxation by asphalt binder flow. The m -value indicates the rate of change of the stiffness, $S(t)$, with loading time. In other words, the m -value is the slope of the log creep stiffness versus log time curve at any time. Since the time dependency of asphalt binder varies, the shape of the stiffness master curve as well as the stiffness at 2 hours loading time are important to take into consideration. Therefore, the slope of the stiffness master curve is also used for specification purposes [39].

In the current PG specification, two parameters from BBR test are used to characterize the binder low temperature rheological behavior. Apparent stiffness, S , and the slope of the log stiffness versus log time, the m -value are determined at a loading time of 60 seconds. The temperature at which $S(60) \leq 300$ MPa and $m(60) \geq 0.3$ is specified as the critical temperature + 10°C (Figure 3). These limits were established based on data from previous studies as well as the data obtained by SHRP (Bahia and [6]).

The effect of these two specification parameters, $S(t)$ and m -value, on thermal cracking is analogous to the effect of G^* and δ on rutting and fatigue cracking. As $S(t)$ increases, the thermal stresses developed in the pavement due to thermal shrinking also increase, and thermal cracking becomes more likely. On the other hand, as the m -value decreases, so does the rate of stress relaxation. In other words,

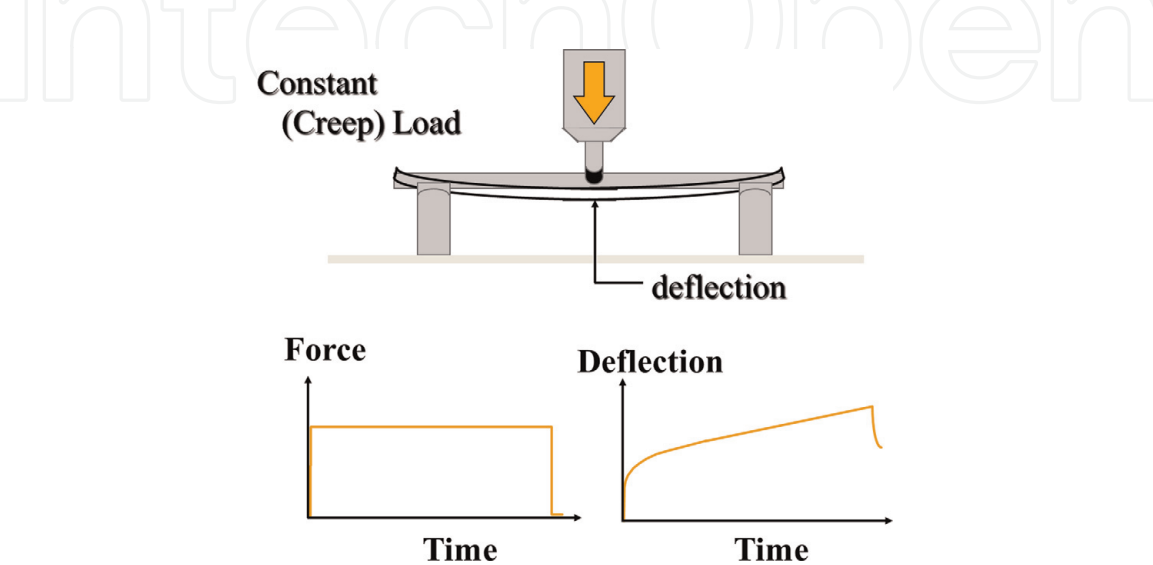


Figure 2.
BBR test principles.

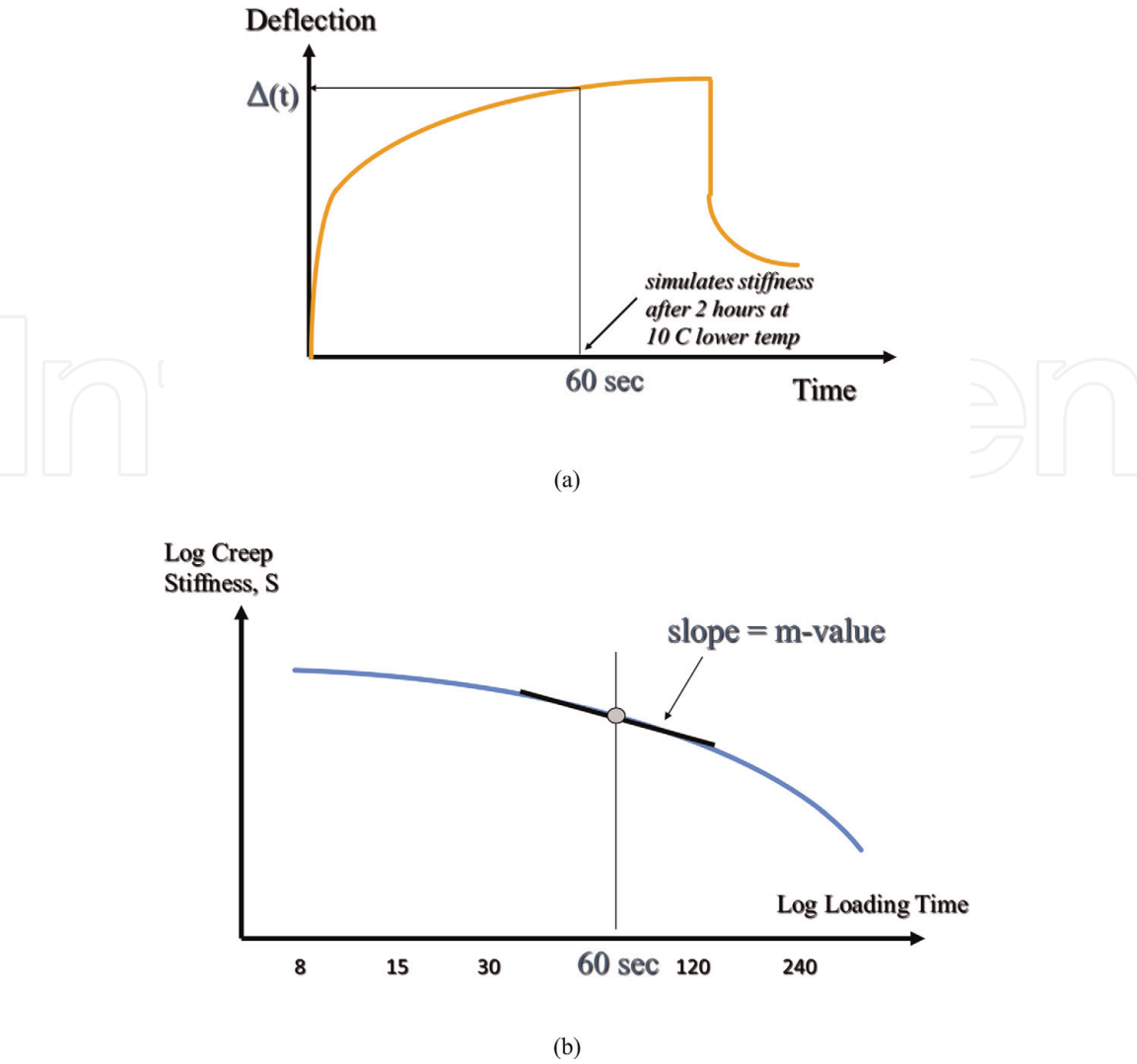


Figure 3.
BBR data analysis: (a) stiffness; (b) *m*-value.

as the slope of the asphalt binder stiffness curve flattens, the ability of the asphalt pavement to relieve thermal stresses by flow decreases. This again would increase the propensity of thermal cracking in the pavement.

Author details

Amir Golalipour
Federal Highway Administration (FHWA)/Engineering and Software Consultants,
Inc., McLean, VA

*Address all correspondence to: amir.golalipour.ctr@dot.gov

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