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Characterizing rheological behavior of asphalt binder over a complete range of pavement service loading frequency and temperature

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HIGHLIGHTS

- The BBR data was converted into the complex shear moduli in frequency domain.
- The 2S2P1D model was adopted for simulating the combined BBR and DSR data.
- An analytical continuous retardation spectrum was derived from the 2S2P1D model.
- Combined data time-domain master curves were developed using continuous spectra.

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ABSTRACT

The present study presented a new procedure for characterizing the rheological properties of asphalt binders over the complete range of pavement service frequency and temperature. The proposed procedure involved two primary steps. In the first step, a modified windowing method (MWM) with a pre-smoothing operation and a modified windowing inter-conversion method (MWIM) with an accurate distribution of the time constants were developed to convert the flexural creep compliance observations from the bending beam rheometer (BBR) test into the corresponding complex shear moduli, so that these measurements could be well combined with the DSR test results. In the second step, the 2S2P1D model was adopted to construct the full master curves of the asphalt binders in frequency domain. To extend the application of the procedure for simulating the master curves in time domain, an existing continuous relaxation spectrum model and a derived continuous retardation spectrum model for the 2S2P1D model were employed. The results showed that the combination of the BBR and DSR data substantially expanded the scale of the complex shear modulus. The corresponding linear viscoelastic (LVE) master curves could be incorporated into the existing asphalt concrete complex modulus predictive equations for better pavement response analysis and performance assessment.

1. Introduction

Asphalt covers most paved roads in the world and the rheological properties of asphalt binders are intimately related to the performance of asphalt pavements [1–6]. As such, characterizing the rheological behavior of asphalt binder in an accurate and efficient way is critical for the subsequent mixture design, pavement response analysis and distress prediction. In most applications, asphalt paving materials are subjected to very small strains that can be characterized by the linear viscoelastic (LVE) theory [7]. Based upon this theory, the Strategic Highway Research Program (SHRP) contributed to a new grading system, i.e., the performance grading (PG) system, for asphalt binders at the beginning of the 1990s [8].

In lieu of the use of the conventional empirical tests, the PG specifications innovatively adopted simple rheological approaches to achieving the fundamental mechanical properties of asphalt binders [9]. Two primary testing methods were recommended for characterizing the LVE behavior of binders in the PG specifications:

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the bending beam rheometer (BBR) test and the dynamic shear rheometer (DSR) test. The BBR test [10], essentially, a three-point static bending creep test, is normally performed at low temperatures. From this test, the flexural creep stiffness $S(t)$ and the m-value that represents the slope of the creep stiffness curve on the log-log scale can be obtained. The two quantities jointly reflect the material resistance to the thermal cracking distress. Particularly, $S(t)$ and m-value at 60 s are employed in conjunction with DSR results at intermediate temperatures to evaluate the low temperature grade of a binder. On the other hand, the DSR test [11] is used to extract the LVE information of binders at intermediate and high temperatures. The test determines the rheological properties of asphalt binders in a steady-state cyclic (sinusoidal) loading mode. The storage shear modulus G' and loss shear modulus G'', or equivalently, the dynamic shear modulus $|G^*|$ and phase angle δ can be obtained under specific frequencies and temperatures. The results observed at intermediate and high temperatures respectively reflect the material resistances to the fatigue cracking and rutting distresses. When used for the PG grading purpose, the DSR tests are always conducted at 10 rad/s. The experimental measurements from the two tests cover the complete range of loading frequency (or time) and temperature that a binder may undergo under the in-service conditions; therefore, the test data, in theory, can be used for predicting any LVE behavior of interest for the material.

In the LVE domain, asphalt binders are typically taken as thermorheologically simple. Thus, analyses for the BBR and DSR test results are traditionally accomplished by constructing the corresponding LVE master curves [12–15]. By means of the time-temperature superposition principle (TTSP) [16], the BBR or DSR test data measured at different temperatures can be horizontally shifted to a given reference temperature to form a unique master curve. The shift distance is called the time-temperature shift factor. With the developed master curves, one can predict the LVE properties of the material over a frequency (or time) and temperature range much broader than that employed practically in a laboratory. Various models have been established for simulating these LVE master curves. For instance, the Christensen-Anderson-Marasteanu (CAM) model [14], the Christensen-Anderson-Sharrock (CAS) model [14] and the generalized Voigt (GV) model [17,18] are commonly used for characterizing the master curves of the BBR data; whereas, the Christensen-Anderson (CA) model [19], the sigmoidal model [12], the Rowe-Baumgardner-Sharrock (RBS) model [20], the 2S2P1D model [1,21] and the generalized Maxwell (GM) model [13,17] are widely adopted for fitting the master curves of the DSR results.

However, a principal concern about these approaches to analyzing the BBR and DSR data is that the two types of test results are usually investigated separately in time and frequency domains. This is known to be quite inconvenient for those who need an overall picture for the rheological behavior of a binder over the complete range of pavement service loading frequency and temperature. Another critical issue is that the existing predicted methods of asphalt concrete dynamic modulus are mostly dependent on the master curve of asphalt binder $|G^*|$ [22–28]; however, in most studies, only the DSR data at intermediate and high temperatures is applied to these predicted equations due to the lack of practical procedures for combining the two test results. Obviously, the limited scale of $|G^*|$ would significantly reduce the predictive ability of these approaches at low temperatures. To resolve the aforementioned problems, this study proposed a new procedure that could effectively and efficiently combine the BBR and DSR data. By means of this procedure, the rheological properties of the asphalt binders over the complete range of pavement loading frequency and temperature were accurately characterized.

2. Theoretical background

2.1. GM model

As a typical mechanical model, the GM model is generally used to simulate the relaxation behavior of LVE materials. Mathematically, the relaxation modulus $E(t)$ in time domain, the complex modulus $E^*(\omega)$ in frequency domain and the operational modulus $\tilde{E}(s)$ in Laplace transform domain can be easily expressed with a discrete relaxation spectrum$\{\rho_i,\ E_i\}$ ($i = 1, \ldots, N$), as follows [17]:

$$E(t) = E_e + \sum_{i=1}^{N} E_i e^{-t/\rho_i} = E_g - \sum_{i=1}^{N} E_i \left(1 - e^{-t/\rho_i}\right) \tag{1}$$

$$E^*(\omega) = E'(\omega) + \mathrm{i}E''(\omega) \tag{2}$$

$$E'(\omega) = E_e + \sum_{i=1}^{N} E_i \frac{\omega^2 \rho_i^2}{1 + \omega^2 \rho_i^2} = E_g - \sum_{i=1}^{N} E_i \frac{1}{1 + \omega^2 \rho_i^2} \tag{3}$$

$$E''(\omega) = \sum_{i=1}^{N} E_i \frac{\omega \rho_i}{1 + \omega^2 \rho_i^2} \tag{4}$$

$$\tilde{E}(s) = E_e + \sum_{i=1}^{N} E_i \frac{s\rho_i}{1 + s\rho_i} = E_g - \sum_{i=1}^{N} E_i \frac{1}{1 + s\rho_i} \tag{5}$$

where t is the time; ω is the angular frequency; s is the Laplace transform variable; E_e is the equilibrium modulus, which is equal to zero for viscoelastic liquids; E_g is the glassy modulus; ρ_i is the relaxation time; E_i is the relaxation strength; $\mathrm{i} = \sqrt{-1}$ is the imaginary unit; $E'(\omega)$ and $E''(\omega)$ are the storage modulus and loss modulus, respectively.

2.2. GV model

The GV model is easier to characterize the creep behavior of the material. Similar to the above modulus functions, in the GV model the compliance functions can be conveniently formulated using a discrete retardation spectrum $\{\tau_i,\ D_i\}$ ($i = 1, \ldots, N$), as shown below [17]:

$$D(t) = D_e - \sum_{i=1}^{N} D_i e^{-t/\tau_i} + \frac{t}{\eta_0} = D_g + \sum_{i=1}^{N} D_i \left(1 - e^{-t/\tau_i}\right) + \frac{t}{\eta_0} \tag{6}$$

$$D^*(\omega) = \frac{1}{E^*(\omega)} = D'(\omega) - \mathrm{i}D''(\omega) \tag{7}$$

$$D'(\omega) = D_e - \sum_{i=1}^{N} D_i \frac{\omega^2 \tau_i^2}{1 + \omega^2 \tau_i^2} = D_g + \sum_{i=1}^{N} D_i \frac{1}{1 + \omega^2 \tau_i^2} \tag{8}$$

$$D''(\omega) = \sum_{i=1}^{N} D_i \frac{\omega \tau_i}{1 + \omega^2 \tau_i^2} + \frac{1}{\eta_0 \omega} \tag{9}$$

$$\tilde{D}(s) = \frac{1}{\tilde{E}(s)} = D_e - \sum_{i=1}^{N} D_i \frac{s\tau_i}{1 + s\tau_i} + \frac{1}{\eta_0 s} = D_g + \sum_{i=1}^{N} D_i \frac{1}{1 + s\tau_i} + \frac{1}{\eta_0 s} \tag{10}$$

where $D(t)$ is the creep compliance; D_e is the equilibrium compliance; D_g is the glassy compliance; η_0 is the long-term viscosity, which tends to infinity for LVE solids; τ_i is the retardation time; D_i is the retardation strength; $D^*(\omega)$ is the complex compliance; $D'(\omega)$ and $D''(\omega)$ are the storage compliance and loss compliance; $\tilde{D}(s)$ is the operational compliance. Traditionally, the time-domain