



Investigation of Prony series model related asphalt mixture properties under different confining pressures

Linglin Li^a, Wenlong Li^a, Hao Wang^{b,*}, Jingnan Zhao^b, Zhongyuan Wang^a, Mansheng Dong^a, Ding Han^c

^a School of Automotive & Transportation Engineering, Hefei University of Technology, Hefei, China

^b Department of Civil & Environmental Engineering, Rutgers University, Piscataway, NJ, USA

^c School of Civil Engineering, Hefei University of Technology, Hefei, China

HIGHLIGHTS

- Construed master curves of complex modulus and phase angle simultaneously.
- Calculated Prony series model of relaxation modulus under different confining pressures.
- Analyzed the effect of confining pressure on asphalt pavement responses.

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ABSTRACT

The objective of this paper is to investigate linear viscoelastic properties of asphalt mixtures measured under different confining pressures with respect to master curves of complex modulus, relaxation time and modulus of Prony series model. A modified collocation method is utilized to calculate the relaxation modulus of Prony series representation after the relaxation time is selected. The relaxation moduli of two asphalt mixtures under different confining pressures are compared at a wide range of reduced loading times. Finite element simulation is employed to fully investigate the effect of confining pressure on mechanical responses of asphalt pavement. The results show that the construction method of master curves of complex moduli is effective and reliable. The relaxation modulus calculated from the smoothed experimental storage and loss moduli of the same complex moduli are slightly different, and it is impossible to obtain the accurate relaxation time and modulus to well agree with the test data of storage and loss moduli simultaneously at the full range of reduced angular frequencies. As the confining pressure increases, the relaxation modulus does not always increase at the full range of reduced loading time due to the effect of phase angle. As the confining pressure increases, the tensile strains and shear strains in the asphalt layer decrease in the practical speeds of vehicular loading.

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1. Introduction

Asphalt mixture (AM) consists of aggregates, air voids, fillers, modifiers, fibers, and of course the bitumen most of which are residuals of petroleum refinery [1]. Although different constituent combinations of AMs will end up with substantially different properties and performances, they all can be categorized into viscoelastic materials [2–4]. The new mechanistic-empirical pavement design guide uses complex modulus (E^*) as the design stiffness parameter and the complex modulus tests are now playing a very dominant role in the material characterization behavior of AMs [5].

It has been found that complex modulus is highly related to pavement performance over a range of vehicle loading and climate conditions [6–8]. Therefore, to study the viscoelastic nature of AMs comprehensively and apply it into theoretical and numerical calculations of asphalt pavement responses, the characteristics of shear and bulk modulus should be investigated in detail [9–11].

The complex modulus tests are conducted to obtain the master curves, including the ones of magnitude and phase angle and allowing an estimation of mechanical properties at wide ranges of temperatures and frequencies. Sigmoidal function has been used widely to construct the master curve of magnitude of AM complex modulus [12–15]. Christensen, Anderson and Marasteanu [16,17] proposed the CAM model to depict the master curve of magnitude of complex modulus and the applicability of this model was successfully verified by comparing the calculated results of pavement

* Corresponding author at: Rutgers State Univ, Dept Civil & Environm Engrn, 96 Frelinguysen Rd, Piscataway, NJ 08854, USA.

E-mail address: hwang.cce@rutgers.edu (H. Wang).

performance with the observed ones [18]. As for the phase angle of complex modulus, Bahia et al. [19] developed a model representing a bell-shaped curve symmetric on a log-log plot of phase angle versus reduced angular frequency. A more general model called β -model was developed by Zhang et al. [20], because they thought that the master curve of phase angle may not be symmetric on a log-log plot and approach zero at an angular frequency of zero or infinite. Naik and Biligiri [21] developed a beta distribution model to estimate the phase angles of different AMs, and the performance and accuracy of the predicted phase angle model were assessed by comparing the model and test results from past studies.

Given a set of data of master curves of magnitude and phase angle of complex modulus, parameters of model representation (i.e., Prony series model) needed to be calibrated in order to apply this model into the theoretical and numerical investigations. Tobolsky and Murakami [22] proposed a method to obtain the relaxation modulus. The main disadvantage of this method is that it must start from the data in a given set usually least reliably determined, so the validity of this method must be checked by the reconstruction of the original test data. Cost and Becker [23] proposed a multidata method which can use all of the observation data and result in the reduction of error in the determination of relaxation modulus of AMs compared with the previous method. Emri and Tschögl [24] proposed an iterative computer algorithm to calculate the relaxation modulus from given test data, and they thought that the main advantage of this algorithm lies in its avoidance of unwanted negative values of relaxation modulus. Schapery [25] discussed an easily used collocation method for fitting the response of finite-element viscoelastic models to experimental stress-strain curves, and the proposed collocation method can be widely utilized with relaxation, creep, and steady-strain oscillation data.

Compared with the complex modulus, Poisson's ratio (signed ratio of transverse strain to axial strain) was less focused on by road engineering researchers. We usually assumed that the Poisson's ratio is time (or frequency) and temperature-independent for its simplicity [4,26], which was not accurate because of the viscoelastic nature of AMs. Recently, some investigations on AMs found that the viscoelastic nature of Poisson's ratio cannot be neglected [11,27,28]. Kassem et al. [29], thought that the time-dependent behavior of AMs is controlled primarily by the binder properties. Aili et al. [30] defined two different kinds of Poisson's ratio (i.e., relaxation and creep Poisson's ratio), and gave the exact relationship between the above two kinds of Poisson's ratio. Allou et al. [31] developed a three-dimensional linear viscoelastic constitutive equation, validated by comparing the simulation results with test data on AMs, to characterize the complex Poisson's ratio. Islam et al. [32], performed relaxation tests at different temperatures in diametrical model, and the results showed that measured Poisson's ratio matched well with the predicted Poisson's ratio by the AASHTOware Pavement ME Design. Zhang [20] proposed triple testing protocols to investigate the complex Poisson's ratio of anisotropic AMs and found that the newly proposed experiments were much quicker and more efficient than the conventional anisotropic test methods using multiple specimens cored in different directions.

The time (or frequency) and temperature-dependence characteristics of AM have been investigated and used to analyze pavement responses in the mechanistic analysis of pavement structure [33–36]. However, the existing research results seldom cover mechanical behavior of asphalt mixture under different confining pressures which better represent the realistic stress state in the asphalt pavement. Lacroix et al. [37] experimentally investigated the effect of confinement on dynamic modulus of AM and proposed the reduced test protocol to predict the confined dynamic modulus from the measured unconfined dynamic modulus and the modified universal material model. Zeiada et al. [38] found that the effect of confinement on dynamic modulus is

affected by the type of AM, such as dense-, gap-, or open-graded asphalt mixture. Different from the above researches, this study is to investigate viscoelastic characterization of AMs under different confinements regarding to dynamic moduli and relaxation moduli in terms of Prony series representation and to analyze the effect of confining pressure on mechanical responses of asphalt pavement under vehicular loading.

2. Objective and methodology

The objective of this paper is to investigate linear viscoelastic properties of two asphalt mixtures measured under different confining pressures with respect to master curves of complex modulus, relaxation time and modulus of Prony series model. A modified collocation method is utilized to calculate the relaxation modulus of Prony series representation after the relaxation time is selected. The relaxation moduli of two asphalt mixtures under different confining pressures are compared at wide enough range of reduced loading time scale. Finite element (FE) simulation is employed to fully investigate the effect of confining pressure on mechanical responses of asphalt pavement. The methodology employed in this paper is illustrated in Fig. 1.

3. Theoretical background

In terms of the linear viscoelasticity theory, there are several different but equivalent methods of expressing mechanical properties which represent the stress strain constitutive relations. The most fundamental descriptions of mechanical properties are probably those given by time- (or frequency) and temperature-dependent relaxation function (or creep function) and complex modulus formulations. Both of these can be determined by experimental observations directly or indirectly. This section is to introduce the related theoretical backgrounds of time-temperature superposition, rheological master curve, and complex and relaxation modulus and of Prony series representation.

Owing to the rheological nature of AM behavior, the master curve of complex modulus related characterization allows comparison of AMs when testing has been conducting at different test temperatures and loading frequencies. Time-temperature superposition is a very useful method to construct the master curve of AM over a broad range of times or frequencies by shifting data obtained at several temperatures to a arbitrarily selected reference temperature T_0 . The shifted test data are not dependent on both frequency and temperature any longer but instead are a function only of reduced frequency, defined in Eq. (1) [12].

$$\omega_R = \alpha(T)\omega \quad (1)$$

where ω_R is reduced angular frequency, $\alpha(T)$ is temperature shift factor, ω is angular frequency, and T is temperature.

The sigmoidal function expressed in Eq. (2) is adopted widely to characterize the whole master curve of the magnitude of the complex modulus, $|E^*|$ [12].

$$\log_{10}(|E^*|) = \delta + \frac{\lambda}{1 + \exp[\beta + \gamma \log_{10}(\omega_R)]} \quad (2)$$

where δ and λ are minimum value and span of $\log_{10}(|E^*|)$, respectively, and β , γ are shape parameters.

Bahia and his colleagues [19] introduced a function to model the behavior of phase angle of complex modulus of AM, as shown in Eq. (3).

$$\phi = \phi_m \left\{ 1 + \left[\frac{\log_{10}(\omega_m/\omega_R)}{R_d} \right]^2 \right\}^{-m_d/2} \quad (3)$$

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