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Optimization criterion of viscoelastic response model for asphalt binders

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HIGHLIGHTS

- We compared fitting results under optimization criteria based on dynamic, static data and all data.
- The viscoelastic response model under optimization criterion based on all data shows the best fitting result.
- The ranking of optimization criteria is criterion based on all data, dynamic data and then static data.

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ABSTRACT

The viscoelastic response model is widely used in characterizing the viscoelastic properties of asphalt binders. However, the viscoelastic response model parameters depend heavily on the optimization criterion. The predict ability of the models vary under different criteria. Most viscoelastic response model parameters were obtained by dynamic data or static data. The models determined by these methods can only well describe one type of viscoelastic properties of asphalt binders. In this paper, the generalized Maxwell model was employed as the viscoelastic response model for asphalt binders, and three types of optimization criteria were applied to get the model parameters. The advantages and disadvantages of these criteria were compared afterwards. Based on the results, it is concluded that the generalized Maxwell model under optimization criterion based on all data can well describe both dynamic and static behaviors of asphalt binder. Also, the rank of the optimization criteria is as follow: criterion under all data, criterion under dynamic test, and criterion under static test.

1. Introduction

Up till present, the viscoelastic response model of asphalt binders remains its popularity because it is able to predict the properties of asphalt binder under different conditions with a few number of laboratory testing. The researchers paid much attention to establishing a proper model, which can precisely predict one aspect of the properties of asphalt binders. However, they ignored the key factors when they were establishing the model such as optimization criterion. Different optimization criteria may result in different model parameter values.

Most of the viscoelastic response models for asphalt materials were established by the optimization criterion based on one aspect of test data such as creep compliance, relaxation modulus or dynamic modulus. While the prevalent accepted models are analytical viscoelastic models consisting different physical elements, such as the generalized Maxwell model, the generalized Kelvin model and so on. Badami and Greenfield obtained the model parameters by using the discrete generalized Maxwell model based on fitting the dynamic modulus master curves and calculated the relaxation modulus by using the parameters afterwards [1]. The dynamic modulus, creep compliance and relaxation modulus of the generalized Maxwell model or the generalized Kelvin model can also be represented by the Prony series, and by using the Prony series these three viscoelastic functions can be interchangeable. Some researchers used the Prony series representation to study the viscoelastic characteristic or viscoelastic model of asphalt materials. Mun and Zi used the Prony series representations of creep compliance and relaxation modulus for asphalt concrete, and obtained the Prony parameters by optimizing solution between the pre-smooth storage modulus data and predict storage modulus. The Prony series representations of creep compliance and relaxation modulus were compared to the lab testing data, and the comparison proved that it can well describe the creep and relaxation behaviors of asphalt concrete [2]. Ho and Romero obtained the Prony parameters of the generalized Maxwell models based on the optimization criterion of minimizing the sum of squared errors between the raw creep compliance and the fitted

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creep compliance, and used the Prony parameters to calculate the relaxation modulus [3]. Sun and Zhu used the generalized Maxwell model to describe the viscoelastic characteristics of asphalt mixture. They conducted the dynamic modulus test to obtain the Prony series parameters and then used them to calculate the creep compliance [4]. Zhao et al. used the modified Havriliak-Negami (MHN) model to pre-smooth the dynamic modulus master curve and then obtained the generalized Maxwell model or the generalized Kelvin model Prony series coefficients from either the storage or loss component collocation points. The results showed that the generalized Maxwell model and the generalized Kelvin model obtained from the approach are equivalent for the same asphalt mixture [5]. Some researchers used the Prony series representation of the generalized Maxwell model to describe the viscoelastic characteristics of asphalt materials when establishing the damage model of them, and they obtained the Prony parameters based on the dynamic test [6–8].

The Huet-Sayegh model is another analytical viscoelastic model that was proposed by Huet for characterizing the viscoelastic properties of materials [9]. It has two parallel branches, one is the elastic spring, and the other is formed by three elements in series: one elastic spring as the difference in the instantaneous elastic modulus and long-term modulus, and two parabolic dashpots. Pronk applied this model for four-point bending tests of different mixtures to fit and describe the stiffness modulus [10]. Xu and Solaimanian compared the Huet-Sayegh model to the Maxwell, Kelvin, generalized Maxwell, and generalized Kelvin models by fitting the master curves of dynamic modulus and phase angle [11]. Olard and Di Benedetto extended the Huet-Sayegh model by adding a linear dashpot in series with two variable dashpots and renamed the model 2S2P1D model (two springs, two variable dashpots and one linear dashpot) and used the dynamic test to obtain the model parameters [12]. Later, this model was developed to DBN model [13].

In addition to the aforementioned models, more complex models were established to better describe different characteristics of asphalt materials. Darabi et al. established a thermo-viscoelastic-damage-healing model, and used creep, creep-recovery and repeated creep-recovery tests to obtain the model parameters and validate the model [14]. They also established a VP hardening relaxation model which is coupled with Schapery's viscoelastic model and the classical Perzyna's VP model, and validated it with repeated creep and recovery tests at different stress levels, loading times, and rest periods [15]. Motamed et al. modified Schapery's nonlinear viscoelastic model [16], obtained the model parameters by conducting creep and recovery snapshots at different levels of octahedral shear stress, and then used it to predict the materials response under oscillatory and ramp load [17].

In summary, most of the viscoelastic response models were established by studying one or two tests, and validated by using the same test with different loading levels. Few of them analyzed the effects of tests employed, namely, the optimization criterion on the model establishment. In fact, the model parameters obtained by different criteria are not the same; it contributes to the difference of predictable ability of the models. From this consideration, the generalized Maxwell model was chosen as the viscoelastic response model, then the model parameters obtained by different optimization criteria are compared and analyzed. The optimization criteria are compared with each other and the better criterion is revealed.

2. Materials and test method

In this study, two neat asphalt binders were prepared. In the following part, they are referred to generic binders A and B. All of the materials are standard, unmodified asphalt materials. To be specific, A is 60 ~ 80 penetration asphalt, while B is 80 ~ 100 penetration asphalt, referred to the Chinese penetration grade system. In order to simulate the effects of mixing and compaction, these asphalt binders were aged in a rolling thin-film oven (i.e., RTFO-aged) in advance. The TA instruments DHR-2 rheometer were employed to the laboratory tests; all tests were performed with an 8-mm diameter parallel plate geometry and a 2-mm gap setting. Three types of tests were conducted: the frequency sweep test, creep test and relaxation test.

2.1. Frequency sweep test

Frequency sweep tests were performed with frequencies between 0.01 Hz and 50 Hz and temperatures of −10 °C, 5 °C, 20 °C, 35 °C and 50 °C. This combination of temperatures and frequencies ensures sufficient overlap in the material responses so that the data could be horizontally shifted to obtain master curves of the key properties. Prior to performing these frequency sweep tests, a stress sweep test was performed at different temperature to ensure all frequency sweep tests were conducted in the linear range.

2.2. Creep test

Creep tests were conducted at both 20 °C and 25 °C. The stress value was fixed during the test until terminating and the stress value of 100 Pa was chosen to obtain the creep characteristics of the studied asphalt binders. The stress level is low to ensure measurements are conducted in the linear viscoelastic range.

2.3. Relaxation test

Relaxation tests also were conducted at both 20 °C and 25 °C. The strain value was fixed during the test until terminating and the strain value of 1% was chosen to obtain the relaxation characteristics of the studied asphalt binders.

3. The viscoelastic response model

The generalized Maxwell model was selected to study the optimization criterion of viscoelastic response model. The generalized Maxwell model consists of n Maxwell elements connected in parallel. The structure of the model is illustrated in Fig. 1, where G is the elastic modulus of the spring; η is the viscosity parameter of the dashpot.

The corresponding mathematical equations of the dynamic modulus, storage modulus and loss modulus for the generalized Maxwell model are listed in Eqs. (1)–(3) respectively.

$$G^{*}(\omega)=\sqrt{\left(\sum_{i=1}^{n}\frac{G_i\omega^2\rho_i^2}{1+\omega^2\rho_i^2}\right)^2+\left(\sum_{i=1}^{n}\frac{G_i\omega\rho_i}{1+\omega^2\rho_i^2}\right)^2} \tag{1}$$

$$G'(\omega)=\sum_{i=1}^{n}\frac{G_i\omega^2\rho_i^2}{1+\omega^2\rho_i^2} \tag{2}$$

$$G''(\omega)=\sum_{i=1}^{n}\frac{G_i\omega\rho_i}{1+\omega^2\rho_i^2} \tag{3}$$

where ω is the angular frequency; ρ_i and G_i are the relaxation time and stiffness of the i th Maxwell element, respectively. $\rho_i=\eta_i/G_i$ and η_i is the coefficient of viscosity of the i th Maxwell element. It is noted that when the time–temperature superposition is taken into consideration, ω in Eqs. (1)–(3)is the reduced angular frequency [18].

The relaxation modulus of the generalized Maxwell model has the form of Prony series as shown in Eq. (4). Based on the relationship between relaxation modulus and creep compliance as shown in Eq. (5), the representation of creep compliance can be described by Eq. (6). The method to obtain the relaxation modulus parameters can be found in the reference [19].

$$G(t)=\sum_{i=1}^{m}G_i e^{-(t/\rho_i)} \tag{4}$$

$$\int_0^t G(t-\tau)D(\tau)d\tau=t \tag{5}$$