Construction and Building Materials 165 (2018) 372–384

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Establishing continuous relaxation spectrum based on complex modulus tests to construct relaxation modulus master curves in compliance with linear viscoelastic theory

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HIGHLIGHTS

- Derived relaxation spectrum model based on its relationship with storage modulus.
- Identified asymmetry of continuous relaxation spectrum curves.
- Developed numerical model of relaxation modulus using trapezoidal rule.
- Proved compliance of constructed master curves with linear viscoelastic theory.
- Verified satisfactory accuracy of generated relaxation modulus master curves.

ARTICLE INFO

Article history:
Received 3 October 2017
Received in revised form 17 December 2017
Accepted 27 December 2017

Keywords:
Asphalt mixture
Complex modulus test
Continuous relaxation spectrum
Relaxation modulus
Master curve
Linear viscoelastic theory
Approximate Kramers-Kronig relation

ABSTRACT

A number of methods have been developed to determine the relaxation modulus, which is a fundamental material property that characterizes the rheological behavior of viscoelastic materials. However, the relaxation modulus master curves constructed using the current methods are likely to be accompanied by evident deficiencies. To correct these deficiencies, this study developed a method of using complex modulus tests to construct the master curve model of the relaxation modulus with a continuous relaxation spectrum that complied with the linear viscoelastic theory and allowed possible asymmetry in the relaxation spectrum curve. Using the data of the complex modulus tests, master curve models of the storage modulus and loss modulus were developed according to an approximate Kramers-Kronig relation. Based on the relationship between the relaxation modulus and the complex modulus, a specific model form of the continuous relaxation spectrum was established in terms of the same model parameters as those of the master curve models of the storage modulus and loss modulus. The established spectrum was found to be asymmetric and was ensured to be compliant with the linear viscoelastic theory. With the established relaxation spectrum, the master curve model of the relaxation modulus was formulated, and its numerical solution was determined as a function of the loading time; the master curves of the relaxation moduli were therefore constructed. The accuracy of the constructed master curves of the relaxation moduli were evaluated in a fairly wide time range and at the boundaries. The evaluation results demonstrated that the numerical method used to obtain the numerical solution of the relaxation modulus model produced negligible errors and that the approximate Kramers-Kronig relation provided a satisfactory representation of the mathematical interrelation of the viscoelastic parameters.

The method developed in this study can be utilized to construct an accurate master curve of the relaxation modulus of any linear viscoelastic material. The constructed master curve of the relaxation modulus complies with the linear viscoelastic theory; specifically, it satisfies the approximate Kramers-Kronig relation and addresses the complete linear viscoelastic information delivered by both storage modulus and loss modulus.

1. Introduction

Relaxation modulus is a fundamental material property that characterizes the rheological behavior of viscoelastic materials. It

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https://doi.org/10.1016/j.conbuildmat.2017.12.204
0950-0618/

has been extensively utilized in the constitutive modeling of asphalt mixtures, such as the Boltzmann superposition principle and the extended elastic-viscoelastic correspondence principle [1,2]. These constitutive relations have been widely applied to the investigation of the damage evolution in the asphalt mixtures subjected to repeated load applications [3–5]. As a result, it is critical to accurately determine the relaxation modulus in order to ensure the accuracy of the damage identification and performance evaluation of asphalt mixtures.

Usually the relaxation modulus is not directly measured using the relaxation test because of the heterogeneous nature of asphalt mixtures, which leads to challenges in precisely controlling the overall strain of the specimen at a constant level. Instead, creep tests and complex modulus tests are alternatives to determine the relaxation modulus via interconversion among the viscoelastic parameters (i.e., creep compliance, relaxation modulus, storage modulus, loss modulus, etc.) based on the linear viscoelastic theory [1,6,7]. This paper focuses on a study that used complex modulus tests to accurately determine the relaxation moduli of asphalt mixtures.

The relaxation modulus determined from the complex modulus tests is traditionally presented using a discrete model, such as the Prony series model [6,7]. The determination of the discrete model of the relaxation modulus generally consists of three major steps [8–10]. First, a master curve model (such as the sigmoidal model) is established for the storage modulus based on the complex modulus test data; the master curve of the storage modulus is therefore plotted at the reference temperature. Second, the constitutive relations of the generalized Maxwell model are employed to derive the discrete model form of the storage modulus in the frequency domain. Third, the derived discrete model is utilized to fit the master curve of the storage modulus to determine the unknown parameters in the discrete model; with the determined parameters of the storage modulus model, the Prony series model of the relaxation modulus is therefore constructed via interconversion from the storage modulus to the relaxation modulus.

The relaxation modulus model constructed using the above procedure is likely to be accompanied by three deficiencies: 1) negative model parameters, which are against the physical significances of the generalized Maxwell model; 2) waviness of the master curve, which is against the nature of the relaxation modulus; and 3) incomplete interpretation of the linear viscoelastic information, since only storage modulus is used in the construction of the relaxation modulus master curve without taking into account the loss modulus [11]. The first two deficiencies originate from the discrete nature of the relaxation modulus model. They cannot be fundamentally corrected despite the applications of advanced mathematical algorithms [12–15].

Consequently, continuous relaxation spectrums have been established and incorporated into the relaxation modulus models. This approach successfully avoids negative parameters in the Prony series models and generates non-wavy master curves of the relaxation moduli [16–20]. Two methods have been identified in the literature to establish the continuous relaxation spectrums. In the first method, the relaxation spectrum is established in terms of the storage modulus, which is represented in the form of a sigmoidal model, based on the integral transforms [16,17]. Unfortunately, this relaxation spectrum is not compliant with the linear viscoelastic theory since it misses the linear viscoelastic information associated with the loss modulus. In the second method, the relaxation spectrum is pre-supposed to be a three-parameter function, in terms of which both storage modulus and loss modulus are formulated to fit the wicket plot of the measured complex modulus data; the three parameters in the pre-supposed relaxation spectrum are therefore determined by minimizing the fitting errors [18–20]. The relaxation spectrum established in this method is indeed compliant with the linear viscoelastic theory. However, the pre-supposed three-parameter function restricts the relaxation spectrum curve to a symmetric shape, which may not be applicable to most asphalt mixtures.

Therefore, the objective of this study was to develop a method of constructing the master curve model of the relaxation modulus with a continuous relaxation spectrum that complied with the linear viscoelastic theory and allowed possible asymmetry in the relaxation spectrum curve. The next section details the complex modulus tests conducted on selected types of asphalt mixtures to obtain their storage moduli and loss moduli. The subsequent section explains the construction of the master curve models of the storage moduli and loss moduli and the establishment of the continuous relaxation spectrum. The following section describes the construction of the master curves of the relaxation moduli based on the established relaxation spectrum. The succeeding section presents the evaluation of the constructed relaxation modulus master curves to confirm their accuracy. The final section summarizes the major findings of this study and highlights ongoing investigations based on these findings.

2. Performance of complex modulus tests

2.1. Preparation of asphalt mixture specimens

Two types of dense-graded asphalt mixtures were prepared in this study for the complex modulus tests. Both mixture types were fabricated using the same limestone aggregates from a quarry located in Fangxian, Hubei Province, China. The nominal maximum aggregate sizes were 13.2 mm and 19 mm for Type I and Type II mixtures, respectively. The asphalt binder for Type I mixtures was an unmodified #70 petroleum asphalt (graded based on penetration) with an optimum binder content of 4.4%. The asphalt binder used in Type II mixtures was the #70 petroleum asphalt modified with the styrene-butadienestyrene (SBS) modifier, and the optimum binder content was determined to be 4.3%. The air void content of both mixture types was 4.0 ± 0.5%.

Three replicate specimens were fabricated for each mixture type in order to verify the repeatability of the complex modulus tests. The fabrication of every replicate specimen consisted of a number of steps including mixing, short-term oven aging, compaction, coring and cutting. First of all, each batch of aggregates was mixed with the corresponding asphalt binder to make the loose mix, which was then stored in an oven for 2 h to simulate short-term aging. The mixing temperatures for Type I and Type II mixtures were 155 °C and 170 °C, respectively, while the aging temperatures were 140 °C and 155 °C for Type I and Type II mixtures, respectively [21,22]. Subsequently, a Superpave Gyratory Compactor was employed to compact the loose mix after short-term oven aging into a cylindrical raw specimen with 150 mm in diameter and 170 mm in height. In order to achieve a more uniform air void distribution, the raw specimen was cored and cut into a test specimen with 100 mm in diameter and 150 mm in height. The air void content of each test specimen was then measured to ensure that only qualified specimens were provided for the complex modulus tests.

2.2. Protocol of complex modulus tests

Complex modulus tests were performed on the prepared test specimens using the Dynamic Testing System (DTS) following the specification of the American Association of State Highway and Transportation Officials (AASHTO) TP 79–12 [23]. All specimens were subjected to the haversine compressive loading at four