Construction and Building Materials 93 (2015) 35–48

Contents lists available at ScienceDirect

Construction and Building Materials

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

A unified procedure for rapidly determining asphalt concrete discrete relaxation and retardation spectra

Yiren Sun [a], Baoshan Huang [b,*], Jingyun Chen [a]

[a] *School of Transportation and Logistics, Dalian University of Technology, Dalian 116024, China*
[b] *Dept. of Civil and Environmental Engineering, University of Tennessee, Knoxville, 419 John D. Tickle Building, 851 Neyland Drive, Knoxville, TN 37996-2313, USA*

HIGHLIGHTS

- A complex modulus model was employed to construct linear viscoelastic function master curves.
- A modified windowing method was proposed for determination of discrete relaxation spectra.
- Very few parameters are required for initial inputs.
- No empirical adjustments or selections are required for Prony series constants.
- Spectrum oscillations and negative spectrum lines were avoided.

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form 22 April 2015
Accepted 24 April 2015

Keywords:
Asphalt concrete
Complex modulus
Relaxation spectrum
Retardation spectrum
Prony series
Havriliak–Negami model

ABSTRACT

This paper presents a unified procedure that can rapidly determine the discrete relaxation and retardation spectra of asphalt concrete. The new procedure involves three consecutive steps: (1) pre-smoothing the complex modulus data with the Havriliak–Negami (HN) model, (2) identifying the discrete relaxation spectrum from the smoothed data with a modified windowing method (MWM) and (3) converting the obtained spectrum into the corresponding discrete retardation spectrum. The HN model adopted furnishes reasonable analytical representations for all the complex modulus components and allows an asymmetrical inflection point for the dynamic modulus and storage modulus master curves on the log–log scale, effectively overcoming the drawbacks of the conventional sigmoidal function in characterizing the asphalt concrete linear viscoelastic (LVE) behavior. Also, the HN model can well predict the phase angle from the dynamic modulus data, substantially extending the application of the old data lacking the phase angle information in the LVE analysis. Additionally, the MWM offers a more appropriate estimation approach for the glassy modulus, successfully avoiding the undesirable spectrum oscillations and negative spectrum lines. A distribution of the time constants with 0.5 decade intervals was implemented in this procedure, completely excluding the waviness in the bell-shaped master curves of the generalized Maxwell (GM) and generalized Voigt (GV) models. Very few parameters are required for the initial inputs in the procedure and no empirical adjustments or selections are required for the GM or GV model constants during the whole computation process. The convergence of the iterations for determining the discrete spectra proved to be very fast.

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1. Introduction

Asphalt concrete is a typical particulate composite material that displays viscoelastic and viscoplastic behavior over a wide range of temperature and frequency. As a most commonly used paving mixture, it is normally subjected to very small strain amplitudes under traffic loading. Therefore, the linear viscoelastic (LVE) constitutive relationship is commonly employed for engineering and research practice [1,2]. In the LVE theory, a discrete relaxation spectrum associated with the generalized Maxwell (GM) model and a discrete retardation spectrum linked to the generalized Voigt (GV) model, both of which contain the complete LVE information from given test data, are widely used to respectively characterize the relaxation and retardation behaviors of materials due to their high stability and powerful efficiency for computation [3,4]. With these discrete spectra, the related modulus and compliance functions, such as the relaxation modulus, creep compliance and complex modulus, can be determined readily. Also, the time-domain

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* Corresponding author. Tel.: +1 (865) 974 7713.
E-mail addresses: sunyiren0104@sina.com (Y. Sun), bhuang@utk.edu (B. Huang), chenjy@dlut.edu.cn (J. Chen).

http://dx.doi.org/10.1016/j.conbuildmat.2015.04.055
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expressions of the GM and GV models in terms of the discrete spectra, often called the Prony series, can significantly facilitate the hereditary integral of the LVE constitutive relationship according to the semi-group property [5]. Due to these obvious advantages, the discrete spectra are incorporated into many commercial finite element programs as well as some other numerical methods for LVE analysis [6–9]. Thus, identifying the discrete spectra from available asphalt concrete testing results in an accurate and efficient manner is critical for the subsequent pavement structural response analysis and performance prediction.

There have been numerous approaches reported in the literature for the determination of the discrete spectra. Schapery [10] presented the collocation method to extract the discrete spectra from the laboratory data by solving a group of linear equations. Cost and Becker [11] designed the multidata method utilizing all the experimental observations through a least squares scheme. Emri and Tschoegl [12] and Tschoegl and Emri [13] proposed a novel recursive algorithm considering the graphical characteristics of the exponential and Lorentzian kernel functions. Other methods were reported to resolve the ill-posed (i.e., non-unique) issues during the spectral identification, e.g., the Tikhonov regularization method [14], the quadratic programming regularization method [15] and the maximum entropy method [16]. In addition, given that the discrete relaxation and retardation spectra are mathematically equivalent [4], some researchers indirectly obtained one discrete spectrum from the other by using different inter-conversion methods [17–22].

However, a primary concern with these approaches is that undesirable negative spectrum lines may be created during the curve fitting, since the methods are generally effective for only completely or relatively smooth data; whereas, experimental data of asphalt concrete typically exhibit significant variability [23]. Therefore, pre-smoothing techniques have to be introduced into the fitting procedures. Park and Kim [3] applied a power-law series representation to the relaxation and creep test data prior to the Prony series fitting. Nevertheless, the static tests usually require robust test equipment and longer testing time. In contrast, the frequency-domain complex modulus test is much more popular. Conventionally, a sigmoidal function offered by Mechanistic-Empirical Pavement Design Guide (MEPDG) is adopted to pre-smooth the complex modulus data [24]. However, this function has proven not applicable to all the mixes [25]. Other pre-smoothing methods can be found elsewhere [23,26–28]. Another critical issue is that the existing fitting methods mostly involve sophisticated rheological expertise and empirical operations, which significantly reduces the efficiency for analysis. For instance, to avoid the negative spectrum, the time constants and viscoelastic constants (e.g., the glassy modulus) are usually determined through a trial and error process. This is rather inconvenient for those who need quick solutions for high-quality discrete spectra of asphalt concrete.

To overcome the above mentioned problems, the present study proposed a unified procedure for rapidly determining the discrete relaxation and retardation spectra of asphalt concrete. The proposed approach, without rendering negative spectral lines, is easy to implement. Very few parameters are required for the initial inputs and no empirical adjustments or selections are required for the GM or GV model parameters during the whole computation process.

2. Asphalt concrete complex modulus test

The complex modulus test, involving a steady-state cyclic (haversine) loading applied to a cylindrical specimen, has been extensively used to characterize the LVE behavior of asphalt concrete. Currently, AASHTO test specification TP-62 describes the detailed procedures for complex modulus testing [29]. The dynamic modulus $|E^*|$ and the phase angle δ can be calculated from the stress input and strain response, and have the following relationships with the real and imaginary components of complex modulus:

$$E^* = E' + iE'',\ E' = |E^*|\cos\delta,\ E'' = |E^*|\sin\delta \text{ and } \tan\delta = E''/E' \qquad (1)$$

where E^* is the complex modulus; E' is the storage modulus; and E'' is the loss modulus.

In order to demonstrate the procedure presented herein, complex modulus test results of three dense-graded asphalt mixtures were collected from different sources. The first dataset was obtained from the Federal Highway Administration (FHWA) project DTFH61-05-H-00019 [2]. The mix had a nominal maximum aggregate size (NMAS) of 12.5 mm and an unmodified PG70-22 binder. The mixture was designated as Control-2006 to reflect the date of aggregate acquisition. Final specimens had an air void content of about 4%. The tests were performed employing five temperatures levels: −10, 5, 20, 40 and 54 °C, and six test frequencies for each temperature: 25, 10, 5, 1, 0.5 and 0.1 Hz. The axial strain amplitudes were kept between 50 and 70 $\mu\varepsilon$ to ensure the LVE responses.

The second test results were collected from a summary report [30]. The mixture selected was from Cell34 at the Minnesota Road test site with a NMAS of 12.5 mm and a modified PG58-34 binder. This mixture is designated as Mn-34 according to the test section. Four replicate specimens with an average air void of 4.3% were prepared and tested in the lab. Complex moduli were measured at six temperatures: −20, −10, 4, 20, 40 and 54 °C, and five loading frequencies: 25, 10, 1, 0.1 and 0.01 Hz. The test results under two testing conditions, namely, at 10 Hz and 40 °C as well as at 0.01 Hz and 54 °C, were not available. The applied load was adjusted to keep the resulting strains within the range of 50–150 $\mu\varepsilon$.

The third set of test data was selected from a dissertation [31]. The test results were obtained from Lane 1 at the Accelerated Loading Facility (ALF) test section at FHWA Pavement Research Facility at McLean, Virginia. The mix denoted as ALF-1 had a 19 mm NMAS and a neat AC-5 binder graded by viscosity at 60 °C. Two specimens with an average air void content of 6.1% were fabricated for testing in the lab. The complex modulus testing was conducted at five temperatures: −9, 4.4, 21.1, 37.8 and 54.4 °C, and six frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz. Through trial and error, the strain responses induced were all less than 150 $\mu\varepsilon$. All specimens from the three sources were compacted by Superpave Gyratory Compactor (SGC), and then cored and trimmed to cylindrical specimens of 150 mm in height and 100 mm in diameter. All the aforementioned tests were carried out in a stress-controlled compressive mode following the AASHTO TP-62 protocol.

3. Constitutive models

3.1. Generalized Maxwell model

The generalized Maxwell (GM) model (or Wiechert model), consisting of a spring and N Maxwell components connected in parallel, is commonly used to represent the relaxation behavior of LVE materials. The relaxation modulus of this model can be expressed in the form of a Prony series as follows [4]:

$$E(t) = E_g - \sum_{i=1}^{N} E_i\left(1 - e^{-t/\rho_i}\right) = E_e + \sum_{i=1}^{N} E_i e^{-t/\rho_i} \qquad (2)$$

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