Construction and Building Materials 95 (2015) 892–897

Contents lists available at ScienceDirect

Construction and Building Materials

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

Validation of a simplified method in viscoelastic continuum damage (VECD) model developed for flexural mode of loading

Farshad Haddadi [a,*], Mahmoud Ameri [a,b], Mohammad H. Mirabimoghadam [c], Hamid R. Amiri Hosseini [a]

[a] Department of Civil Engineering, Iran University of Science & Technology, Tehran, Iran
[b] Transportation and Safety Iran University of Science & Technology, Tehran, Iran
[c] Civil Engineering Department, Nikbakht College of Engineering, Sistan and Baluchestan University, Zahedan, Iran

HIGHLIGHTS

- Simplified VECD model using peak-to-peak values of stress and strain is applicable in flexural mode of loading.
- Material constant (α) has inverse relationship with slope of the central portion of the relaxation modulus curve obtained from the flexural dynamic test.
- There is only limited range of initial pseudostiffness (I) for which the errors in calculation of damage parameters could be neglected.

ARTICLE INFO

Article history:
Received 14 March 2015
Received in revised form 25 July 2015
Accepted 28 July 2015
Available online 31 July 2015

Keywords:
Asphalt concrete
Continuum damage
Fatigue
Bending beam
Relaxation modulus

ABSTRACT

Viscoelastic continuum damage (VECD) is a powerful method to describe fatigue behavior of asphalt concrete mixtures by implementing the fundamental mechanistic principles. In this study, peak-to-peak values of stress and strain are used to simplify the calculation of damage parameters in VECD model using cyclic flexural fatigue test. Fatigue tests have been conducted over a range of strain and frequency levels. It was observed that excluding the samples with initial pseudostiffness (I) less than 0.74, other specimens' characteristic curve overlaps on a unique curve for any set of loading. Also, the results showed that there is an inverse relationship between the material constant (α) and the slope of the central portion of the relaxation modulus curve obtained from a flexural dynamic test using 4-point bending beam apparatus.

1. Introduction

Fatigue cracking is a major type of structural distress which often occurs at the surface of the asphalt pavements. Due to increase concern with pavement cracking, the importance of introducing a reliable method for measuring fatigue parameters of asphalt mixtures has been widely recognized. For many years, researchers attempted to introduce a reliable method for predicting fatigue performance of asphalt mixture. Although some advancement has been achieved but there is no unanimously agreed approach to describe fatigue behavior and/or to investigate fatigue characteristics of asphalt concrete mixtures. To get better insight into the fatigue phenomena of asphalt mixtures a proper mechanistic model is required which could describe different levels of initiation, coalescing and propagation of crack under a repeated mode of loading. However, many asphalt agencies still use empirical techniques to estimate the fatigue life of asphalt pavement through their design procedure. These techniques usually characterize fatigue behavior of an asphalt mixture by plotting the maximum tensile strain or stress against number of load cycles to failure [1]. Such an approach not only could be time consuming but also it fails to account for the most fundamental aspects of the asphalt concrete such as its viscoelastic nature. On the other hand, the Continuum Damage Mechanic (CDM) is gaining momentum among most of the asphalt communities in recent years. It offers more fundamental explanation of damage than traditional fatigue approaches. Several studies have been undertaken to approve the applicability of CDM approach for evaluation of crack growth in the asphalt pavements based on Schapery's correspondence principle and the Work Potential Theory (WPT) [2–7].

Schapery adopted the well-known power law crack growth equation for viscoelastic materials, and developed his viewpoint mathematically through Eq. (1) to represent the damage evolution process of materials in viscoelastic media through the correspondence principle [8,9]:

* Corresponding author.
E-mail address: f_haddadi@civileng.iust.ac.ir (F. Haddadi).

http://dx.doi.org/10.1016/j.conbuildmat.2015.07.184

$$\frac{dS}{dt} = \left(-\frac{\partial W^R}{\partial S}\right)^{\alpha} \tag{1}$$

where, S is internal state variable (or damage parameter), W^R is pseudostrain energy density and α is the material constant. Some researchers used trial an error procedure to defined the α value as a constant which could generate the unique damage curve for various load amplitudes [4,7]. Other researchers attempted to relate material constant to the slope (m) of the central portion of relaxation modulus master curve [10,11]. They also observed that if the material's fracture energy and failure stress are constant, then the α value could be defined as $1 + 1/m$. On the other hand, if the fracture process zone size and fracture energy are constant, then the α value could be defined as $1/m$. Swamy et al. used the rigorous calculation of pseudostrain (Eq. (2)) for calculating damage parameters and reported $1 + 1/m$ as the proper definition of α at controlled strain amplitude in flexural dynamic test [12]:

$$\varepsilon^R(t) = \frac{1}{E_R}\int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{2}$$

where, E_R is the reference modulus, $E(t)$ is the relaxation modulus, ε is the physical strain, t the elapsed time between the beginning time of loading and the time of interest and τ is the time when the loading began.

Although the CDM has many advantages over empirical methods, application of this approach to a large number of cyclic load data is sometimes problematic issue since using the hereditary integral (Eq. (2)) through entire loading history demands a huge computation memory. Furthermore, noises of the output data could adversely affect the results of the experiment and cause considerable errors [6]. Some studies have been conducted to overcome these problems. Christensen and Bonaquist presented a number of practical applications of the modified continuum damage based on works of Kim et al. [13] Kutay et al. used peak-to-peak values of stress and strain to construct damage curves in cyclic uniaxial laboratory fatigue tests and proved its sufficient accuracy [5]. Underwood et al. improved earlier versions of simplified approaches and developed a more accurate method [6].

Most of the aforementioned studies were based on the results of uniaxial fatigue test on cylindrical samples but very few have applied VECD approach into the flexural mode of loading. In this study, the 4-point bending beam fatigue test is employed to investigate the possibility of using peak-to-peak strain and stress data values (instead of entire loading history) so as to simplify damage calculation in VECD model. In addition, the beam fatigue apparatus was utilized in order to construct the relaxation modulus master curve by conducting a dynamic flexural test.

2. Laboratory test program

2.1. Materials

The aggregate used in this study is limestone with a maximum nominal aggregate size of 19-mm obtained from the stockpiles of a local asphalt plant. The gradations and characteristics of aggregate are presented in Tables 1 and 2, respectively. Two types of base binder (unmodified) with different Performance Grade (PG) status were used in this study. Also, 4% ethylene vinyl acetate (EVA) copolymer by weight of bitumen was used to modify the two base binders, utilizing laboratory high shear mixer. EVA used in this study had vinyl acetate content of 18% by mass, specific gravity of 0.938 g/cm^3, melt indices (MI) of 2.5 g/10 min and melting point of 85 °C. P1 and P2 will denote the mixtures made with modified PG64-16 and PG58-22 base binders, respectively.

Table 1
Aggregate gradation of the mixtures.

Sieve size (mm)	25	19	12.5	9.525	4.75	2.375	0.3	0.075
Percent passing (%)	100	95	–	61	44	32	7	5

Table 2
Aggregates characteristics.

Properties	Test method	Results
Coarse aggregate		
Los Angeles abrasion (%)	AASHTO-T96 [14]	20
Angularity (%)	ASTM-D5821 [15]	100
Flat and elongated (%)	ASTM-D4791 [16]	11
Bulk specific density (g/cm^3)	AASHTO-T85 [17]	2.655
Water absorption (%)	AASHTO-T85 [17]	1
Fine aggregate		
Plastic index	ASTM-D4318 [18]	Non-plastic
Bulk specific density (g/cm^3)	AASHTO-T84 [19]	2.611
Water absorption (%)	AASHTO-T84 [19]	1.3
Filler		
Plasticity index	ASTM-D4318 [18]	Non-plastic
Bulk specific density (g/cm^3)	AASHTO-T84 [19]	2.701

Table 3
Asphalt mixture characteristics.

Mix type	Bitumen	PG grade	Bitumen content (%)	Air void (%)
C1	Unmodified	64-16	4.8	5.2
C2	Unmodified	58-22	4.6	4.9
P1	EVA	82-10	5	5.7
P2	EVA	76-16	4.9	5.4

2.2. Sample preparation

The optimum bitumen content of the mixtures determined using standard Marshall mix design procedure (ASTM D1559) [20]. All data collected in this study including LVE characteristics and fatigue parameters of the mixtures were obtained from testing of asphalt concrete beam specimens with dimensions of $5 \times 6 \times 39$ cm. The samples were originally fabricated with dimensions of $5 \times 30 \times 40$ cm using wheel track compactor and then were sawn to the desired dimensions. Table 3 summarizes mixtures type, bitumen content, bitumen grade and air void of the samples tested in this study.

2.3. Dynamic modulus and fatigue test

Traditional four-point bending beam fatigue testing apparatus was used to characterize LVE property and fatigue behavior of asphalt mixtures. The specimens were subjected to 70 microstrain ($\mu\varepsilon$) sinusoidal cyclic loading at frequencies of 0.1, 0.5, 1.0, 5.0, 10.0, 15 and 20 Hz; and temperatures of −10 °C to 40 °C in 10 °C increments to obtain their dynamic modulus $|E^*|$ and phase angle. To allow for specimen recovery, a pause period of four minute was applied before implementing each level of frequency. In the next stage, the beam fatigue tests were conducted in accordance with AASHTO-T 321 [21] at 20 °C using 400, 700 and 900 microstrain and sinusoidal loading at 7, 10 and 13 Hz. Three replicates were used for each test.

3. Results and discussion

3.1. LVE characterization

Time–temperature superposition principle was utilized to construct the dynamic storage modulus master curve at a reference