Construction and Building Materials 47 (2013) 779–788

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Effect of confinement pressure on the nonlinear-viscoelastic response of asphalt concrete at high temperatures

Eisa Rahmani [a], Masoud K. Darabi [b,*], Rashid K. Abu Al-Rub [c], Emad Kassem [b], Eyad A. Masad [a,d], Dallas N. Little [a]

[a] *Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA*
[b] *Texas A&M Transportation Institute, Texas A&M University System, College Station, TX 77843, USA*
[c] *Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates*
[d] *Mechanical Engineering Program, Texas A&M University at Qatar, Doha, Qatar*

HIGHLIGHTS

- Effect of confinement stress levels on nonlinear viscoelastic response of asphalt concrete is investigated.
- A model is proposed to express nonlinear viscoelastic responses as a function of triaxiality ratio.
- A simple and straightforward method is proposed to calibrate the model.
- Analysis show that the triaxiality ratio has substantial effect on the nonlinear strain response of asphalt concrete.

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form 13 May 2013
Accepted 20 May 2013

Keywords:
Nonlinear viscoelasticity
Asphalt concrete
Confinement pressure
Repeated creep-recovery test
Triaxiality ratio

ABSTRACT

Asphalt concrete materials exhibit nonlinear viscoelastic responses at high stress/strain levels. The traffic loading induces multi-axial stress states within the asphalt concrete pavement structure. Therefore, it is imperative to characterize the nonlinear viscoelastic responses of asphalt concrete under the realistic multi-axial stress states. Available methods in the literature for characterizing the viscoelastic nonlinearity are mostly based on simple uniaxial creep-recovery tests without considering the effect of confinement stress levels.

In this paper, the nonlinear viscoelastic properties of asphalt concrete materials are characterized considering the effects of confinement pressure. It is shown that the confinement pressure significantly affects the nonlinear viscoelastic response of asphalt concrete materials. The viscoelastic nonlinearity is characterized as a function of triaxiality ratio in order to capture the combined effects of confinement level and deviatoric stress. Cyclic creep-recovery tests are performed at 55 °C and at different confinement levels. An equation is proposed to relate the nonlinear viscoelastic parameters to the triaxiality ratio based on the test results. The analyses showed that the triaxiality ratio has substantial effect on the nonlinear strain response of the asphalt concrete.

Published by Elsevier Ltd.

1. Introduction

Asphalt concrete is a complex material consisting of aggregates, asphalt binder, and air voids. It is well-known that the mechanical response of asphalt concrete is time-, rate-, and temperature-dependent and exhibits nonlinear behavior under different loading conditions [1]. The complex microstructure of the asphalt concrete along with the difference between the stiffness moduli of binder and aggregate phases induces strain/stress localization in the binder phase as the material deforms. This increase in the stress/strain level in the binder phase contributes in the nonlinear behavior of binder which subsequently leads to the nonlinear mechanical response of asphalt concrete [2–4]. At high temperatures, the stiffness of asphalt concrete significantly drops making the material more prone to rutting (i.e. permanent deformation) under cyclic loading conditions. On the other hand, at lower temperatures, asphalt concrete becomes more brittle and more prone to fatigue damage (i.e. evolution of micro-cracks and micro-voids). The time-dependent viscoelastic response of asphalt concrete significantly affects the evolution rate of both fatigue damage and rutting. Therefore, robust modeling of the mechanical response of asphalt concrete over a wide range of temperatures requires accurate characterization of the nonlinear viscoelastic properties in addition to the fatigue and rutting properties.

---

* Corresponding author. Tel.: +1 979 847 5806; fax: +1 979 862 7696.
E-mail address: masouddrb@neo.tamu.edu (M.K. Darabi).

0950-0618/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.conbuildmat.2013.05.090

As shown by several researchers [e.g. 5], traffic loading induces multi-axial state of stresses within the pavement structure. Therefore, the nonlinear viscoelastic response of asphalt concrete should be characterized under general multi-axial state of stresses to mimic realistic stress states inducing in pavement structures during traffic. In this case, representation of the nonlinear viscoelastic model should to be acquired from experiments which, to high extent, mimic the realistic loading conditions. This paper investigates the nonlinear behavior of the asphalt concrete at high temperature under general multi-axial state of stresses with especial focus on the effect of confinement level. Surprisingly, few attempts have been made in the literature to investigate the significance of confinement stresses on the nonlinear response of asphalt concrete materials [6–8]. In the first study, the nonlinear parameters were identified using triaxial repeated creep-recovery tests emphasizing these parameters were highly influenced by variations of deviatoric and confinement stresses. However, no relationship was provided between the nonlinear parameters and stress levels. The second study also investigated the effect of bulk and octahedral shear stresses at intermediate and high temperatures on the variations of nonlinear dynamic modulus through imposing a stress dependent relation into sigmoidal-type master curve. The last study explored the importance of the confinement pressure on the viscoelastic response of the asphalt concrete under cyclic and static creep test. They concluded that the material stiffness changes at different confinement stresses. This study characterizes the nonlinear viscoelastic response of asphalt concrete through analyzing a comprehensive set of experimental data that mimics the realistic multi-axial stress levels occurring under traffic. Variation of nonlinear parameters is presented in terms of the triaxiality ratio that considers the combined effects of mode of loading and confinement level (i.e. first stress invariant and von Mises equivalent stress).

During the past decades, different linear/nonlinear models have been proposed to predict the viscoelastic behavior of asphalt concrete materials. In this paper, Schapery's nonlinear viscoelastic model [9–11] is used to characterize the nonlinear viscoelastic response of asphalt concrete materials. Characterization of Schapery's nonlinear viscoelastic model parameters has been broadly studied. Several researchers [10,12,13] used the shifting approach to characterize the short-term and long-term nonlinear viscoelastic behavior of asphalt concrete. In these cases, using a simple creep-recovery test, the long term behavior of asphalt concrete was characterized by horizontal shifting of strain/stress responses to a reference stress/strain level. Nonlinear parameters were identified by vertically shifting the response to the same reference point. Alternatively, other researchers used only the recovery part of repeated creep-recovery tests to obtain the linear and nonlinear material parameters [14–17]. However, most of these studies identify the nonlinear viscoelastic response of asphalt concrete under uniaxial state of stresses without realistically considering the effect of multi-axial state of stresses on the nonlinear performance of the material.

This paper proposes an equation to relate the nonlinear viscoelastic parameters to the triaxiality ratio. The numerical algorithm for the proposed nonlinear viscoelastic model is implemented in the Pavement Analysis using Nonlinear Damage Approach program (PANDA) to model the effect of viscoelastic nonlinearity on the complex mechanical response of asphalt concrete materials. PANDA was developed and continues to be refined by the authors and their collaborators and includes Schapery's nonlinear viscoelasticity [10], Perzyna-type [18] viscoplasticity, and the viscodamage model proposed by Darabi et al. [15]. Readers are referred to previous publications by the authors for more details regarding PANDA and the procedures required for the identification of the model parameters. [15,19,20].

2. Testing procedure and methods

2.1. Test specimens

Cylindrical specimens were prepared in laboratory using a Superpave Gyratory Compactor (SGC). The SGC was used to compact 15.2 cm diameter by 17.8 cm height specimens. These specimens were cored and cut to 10 cm diameter by 15.2 cm height. The average percent air voids of the test specimen was 7.0 ± 0.5%. Limestone aggregate and binder PG 67–22 were used to prepare the test specimens. The aggregate blend includes 30% Type C rock, 36% Type F rock, 24% washed screening, and 10% of manufactured sand. This mixture is used as a surface course with a nominal maximum aggregate size of 19.0 mm. Table 1 and Fig. 1 summarize the sieve analysis and mixture gradation.

2.2. Dynamic Modulus Test (DMT)

The dynamic modulus test was used to identify the linear viscoelastic model parameters including the Prony series coefficients and the temperature coupling terms (i.e. time–temperature shift factor). This test was conducted at five different temperatures (−10, 4, 21, 37 and 54 °C) and five frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) for each temperature. In this study, the dynamic modulus test was conducted in compression in the strain controlled loading mode without confining pressure. The effect of confinement stresses will be captured through analysis of comprehensive cyclic creep-recovery test results. The strain amplitude in DMT test was kept low enough (i.e. 50–75 $\mu\varepsilon$) to assure that the material does not get damaged and the response remains within the viscoelastic realm. Two replicates were performed for each test. The values of the dynamic moduli and phase angles were averaged using the results of two replicates. The testing was conducted according to AASHTO TP-62 [21].

2.3. Repeated Creep-Recovery Test at Variable Stress levels (RCRT-VS) in compression

The loading and unloading times were kept constant during the RCRT-VS test. This test was conducted at 55 °C with loading time of 0.4 s followed by 30 s unloading time. The number of loading blocks varies depending on the confinement level at which the test was conducted. Each loading block includes eight creep-recovery cycles with increasing applied axial stresses. This test was conducted in compression at four confinement levels (i.e. 0, 70, 140, 380 kPa) which were kept constant during the test. Specimens were pre-conditioned for 2 h under the confinement pressure until the strain response reached a constant value. After 2 h, according to Fig. 2 the cyclic creep and recovery loading history was applied. The axial stress level starts from 140 kPa at the beginning of the first loading block and increases with the factor of 1.2 for the next axial stress until it reaches the last creep-recovery within that block. For the next loading block, the first axial stress level is identical to the third axial stress level in the previous block. Fig. 2 schematically illustrates the applied stress history for the RCRT-VS test. Each test was conducted on two replicates. The strain response reported in this study is the average of the strain responses obtained from each replicate.

Three axial and three radial LVDTs were 120° spaced and mounted on the specimen to capture axial and radial strain responses during this test. Fig. 3 shows the experimental testing setup.

3. Nonlinear viscoelastic model

This study uses Schapery's nonlinear viscoelastic model to characterize nonlinear viscoelastic response of asphalt concrete materials, such that:

$$\varepsilon^t = g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D(\psi^t - \psi^\tau) \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau \qquad (1)$$

where superscripts t and τ designate responses at specific times; ε and σ are strain and stress responses, respectively; D_0 and ΔD are the instantaneous and transient creep compliances; and g_0, g_1, and g_2 are nonlinear stress dependent parameters. The nonlinear parameter g_0 describes the effect of stress levels on the instantaneous compliance; g_1 operates on the transient compliance and captures the effect of the stress level on the transient strain response of material; and g_2 controls the effects of loading rate on the strain response. The term ψ is the reduced time which is a function of time–temperature shift factor, stress shift factor, and environmental shift factors. For the numerical convenience, the transient compliance is expressed in terms of the Prony series, such that: