Construction and Building Materials 183 (2018) 102–113

Contents lists available at ScienceDirect

Construction and Building Materials

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

Introducing a stress-dependent fractional nonlinear viscoelastic model for modified asphalt binders

Pouria Hajikarimi [a], Fereidoon Moghadas Nejad [a,*], Ali Khodaii [a], Ellie H. Fini [b]

[a] Department of Civil & Environmental Engineering, Amirkabir University of Technology, Hafez Avenue, Tehran, Iran
[b] Department of Civil & Architectural Engineering, North Carolina A&T State University, 1601 E. Market St., Greensboro, NC 27411, United States

HIGHLIGHTS

- Using creep-recovery test to capture nonlinear viscoelastic behavior of asphalt binders.
- Developing a fractional viscoelastic model for nonlinear characterization of asphalt binders.
- Modeling both creep and recovery behavior of neat and modified asphalt binders using a same model.
- Investigating the effect of modification on nonlinear properties of neat asphalt binder.

ARTICLE INFO

Article history:
Received 27 February 2018
Received in revised form 15 June 2018
Accepted 19 June 2018

Keywords:
Nonlinear viscoelastic
Fractional
Crumb rubber
SBS
PPA
Creep and recovery

ABSTRACT

Asphalt binders generally behave in a linear viscoelastic manner under conventional stress and strain level. There are several researches and technical protocols consistent with linear viscoelastic theorem. However, two main reasons can affect this well-known behavior of asphalt binders: 1) modification of asphalt binder with some additives causing a change in its microstructure and 2) higher order stress and strain level induced to asphalt binder under heavy traffic or climate loading. It is important to consider non-linear viscoelastic behavior of asphalt binder and its effect on conventional characteristics of asphalt especially two constitutive functions of creep compliance and relaxation modulus. In this research, nonlinear viscoelastic properties of asphalt binders modified with crumb rubber, styrene-butadiene-styrene and polyphosphoric acid are investigated to evaluate the variation in non-linear viscoelastic parameters due to addition of these modifiers. For this purpose, a specified research program was defined to consider non-linear behavior of one neat asphalt binder as well as nine modified ones. Based on a robust literature review and some prior experiences, three different extents selected for each modifier and then specimens were made. Implementing a simple creep-recovery test with creep loading time of 1 s and 100 s and 999 s unloading to simulate traffic load by using a dynamic shear rheometer at different stress levels of 0.1, 1, 10, 20 and 30 kPa, non-linear viscoelastic behavior of neat and modified asphalt binder was captured. The generalized fractional nonlinear viscoelastic model is introduced and successfully implemented to simulate creep and recovery behavior of neat and modified asphalt binders. Addition of all modifiers to the neat asphalt binder alters its non-linear viscoelastic behavior and properties. For short time creep loading, crumb rubber and polyphosphoric acid amplify non-linear behavior while SBS control it and for long creep loading time all asphalt modifiers increases non-linearity of asphalt binder's viscoelastic behavior.

1. Introduction

Asphalt concrete is a three-phase solid containing aggregates, asphalt binder and air void. By altering rheological and mechanical characteristics of asphalt binder using some additives, asphalt mixture properties can thoroughly be changed in terms of fatigue, rutting or low-temperature performance [1,2]. Asphalt binder is a viscoelastic material and its behavior is directly depended on time, temperature and loading rate [3]. As a viscoelastic material, asphalt binder can behave linear or non-linear. In linear viscoelastic material, the strain is proportional to the stress for a specific time and temperature. However, in non-linear viscoelastic material there is no direct relation between variation in the applied stress level and the corresponding strain variation [4]. Generally, asphalt

* Corresponding author.
E-mail addresses: phajikarimi@aut.ac.ir (P. Hajikarimi), moghadas@aut.ac.ir (F. Moghadas Nejad), khodaii@aut.ac.ir (A. Khodaii), efini@ncat.edu (E.H. Fini).

https://doi.org/10.1016/j.conbuildmat.2018.06.166
0950-0618/

binder behaves linearly at low stress level and shows non-linear behavior at high stress level [5].

It is well-known that superpave protocol is used for characterizing asphalt binders. Low amount of applied strain, very low stresses and short time are selected in superpave protocol's test to ensure capturing asphalt binder's rheological properties in the linear viscoelastic region [3]. There were two main reasons for performing these experimental tests in the linear region namely 1) the deformation of the pavement layers should be limited in an appropriate pavement design and 2) analyzing and interpreting test results in the linear region is much simpler and more convenient due to reduction in number of variables [6]. If two asphalt binders behave similarly in the linear region, it cannot be guaranteed to behave in a similar way in the non-linear region. Thus, it is important to determine non-linear properties and measure some related characteristics of asphalt binders especially in presence of additives when asphalt binder's behavior is more unpredictable.

Several researches devoted to evaluation of linear and non-linear viscoelastic characteristics of asphalt binders and also finding more accurate and reliable methods to do so. Schapery developed a robust framework to quantify non-linear viscoelastic properties of a viscoelastic material and used it for modeling fracture and strength of such materials [7,8]. During NCHRP Project 9–10 (superpave protocols for modified asphalt binders), preliminary experimental tests for examining the non-linear behavior of asphalt binders were performed and results indicated that several factors should be considered to characterize non-linear properties of neat or modified asphalt binders including asphalt binder type, strain level, temperature, frequency of loading, number of cycles and etc [9].

Polacco et al. [10] studied the correlation of nonlinear viscoelastic behavior of modified asphalt binders with polymer modifiers architecture which are blended with them. They emphasized that nonlinear properties is the most promising and prone to describe rheological and mechanical behavior of modified asphalt binders.

Implementing Schapery equations, Masad and his co-workers presented a framework for analyzing the nonlinear viscoelastic behavior of unaged and aged asphalt binders at different temperatures and stress levels. Their research was limited to only one asphalt source and they suggested to extend this research to chemically modified asphalt binders [11]. Using temperature and frequency sweep tests, Underwood and Kim [12] studied linear and nonlinear viscoelastic behavior of asphalt binder and asphalt mastic at different volumetric conditions. Based on experimental results, it was concluded that the main source of nonlinear viscoelastic behavior of asphalt mastic is nonlinear properties of asphalt binder due to heterogeneous and complex structure of asphalt binder. They successfully used the Schapery's single integral model in the case of shear loading for both asphalt binder and asphalt mastic and mentioned that it is required to extend this model for other mechanisms which occur at high strain levels such as fracture, damage and thixotropy.

Narayan et al. [13] introduced a three-dimensional nonlinear viscoelastic model for asphalt binder and showed that this model can well predict experimental data and primary characteristics of the experimental data such as relaxation behavior and development of normal forces in torsion. However, they mentioned that some nonlinear viscoelastic features such as shear thickening/shear thinning behavior or stress overshoots in steady shear flows cannot be captured implementing the presented model and it should be extended for modeling such complexities. Sadeq et al. [14] used nonlinear plasto-viscoelastic method to determine the total irrecoverable strain and investigate the nonlinear response of unmodified and warm-mix modified asphalt binders by using strain-controlled oscillation and multiple stress creep recovery (MSCR) tests. They also compared nonlinear plasto-viscoelastic method with nonlinear viscoelastic approach and showed that while nonlinear plasto-viscoelastic method can calculate the actual percent of permanent deformation and recovery after load removal, there is no significant difference between results of these two methods.

In this research, three types of well-known asphalt modifiers including crumb rubber, styrene–butadiene-styrene (SBS) and polyphosphoric acid (PPA) were used to investigate the effect of modification on non-linear viscoelastic characteristics of neat asphalt binder. These modifiers were added with three different percentages to neat asphalt binder and then by using the dynamic shear rheometer (DSR) a simple creep recovery test was performed to determine the strain after applying different amount of stress levels. Furthermore, the generalized fractional nonlinear viscoelastic model is presented to explain non-linear viscoelastic behavior of neat and modified asphalt binders by inspiring Delgadillo and Bahia's [5] research work for constructing a nonlinear constitutive relationship for asphalt binders and based on the previous research work in which the simple fractional viscoelastic element was successfully implemented to determine linear viscoelastic properties of modified asphalt binders [15,16].

In this paper, a comprehensive theoretical background is presented to develop fractional viscoelastic model and its generalization as a new simple model for simulating linear and non-linear viscoelastic behavior of neat and modified asphalt binders. Materials and test methods are explained in detail. Then, results and discussion are presented and analyzed based on three primary approaches: 1) rough experimental test results interpretation for explaining the effect of modification on non-linear viscoelastic characteristics of neat asphalt binders using some simple indices, 2) implementing the generalized fractional viscoelastic model to demonstrate creep and recovery behavior of neat and modified asphalt binders and 3) investigating recovery characteristics of modified asphalt binders by using permanent and recovered strain in the form of generalized fractional viscoelastic model. Finally, summary and concluding remarks are presented.

2. Theoretical background

Two types of relaxation functions may be defined for viscoelastic materials, a stretched exponential (Kohlrausch-Williams-Watts) decay ($\Phi(t) \propto exp((-t/\tau)^{\alpha})$) or a power law behavior sometimes called scaling decay ()) [17]. Assuming power law behavior for a linear viscoelastic material, the relaxation modulus can be derived as:

$$E(t) = \frac{E}{\Gamma(1-\beta)}\left(\frac{t}{\tau}\right)^{-\beta} \tag{1}$$

with $0 \leq \beta < 1$. In this equation, $\Gamma(x)$ denotes the Gamma function [18], t is time and E and τ are constant parameters. Considering Gamma function and power law properties, it is evident that for $\beta = 0$, $E(t) = E$ (time independent) leads to pure elastic behavior and increasing β highlights viscous part of material behavior and $\beta = 1$ denotes Newtonian fluid which shows a pure linear viscous behavior.

There are two constitutive equations for time-dependent stress and strain of viscoelastic materials which are characterized by using Boltzmann's superposition integrals [19]:

$$\sigma(t) = \int_{-\infty}^{t} E(t-\xi)\frac{d\varepsilon(\xi)}{d\xi}d\xi \tag{2}$$

$$\varepsilon(t) = \int_{-\infty}^{t} D(t-\xi)\frac{d\sigma(\xi)}{d\xi}d\xi \tag{3}$$