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Small and large strain rheological characterizations of polymer- and crumb rubber-modified asphalt binders

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HIGHLIGHTS

- The rheology of polymer- and crumb rubber-modified binders was studied.
- The linear viscoelastic properties can predict the performance to some extent.
- The large strain rheology is important to help understand the behavior.
- Lissajous-Bowditch plots and non-linear measures could help rank the performance.

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ABSTRACT

Nowadays, polymers and crumb rubber (CR) are extensively used modifiers in bituminous pavements. The objective of this paper is for characterizing the response of polymer- and CR-modified asphalt binders under small and large deformations to fully understand the behavior of such blends under various possible conditions. Under small strains, the complex modulus was measured and analyzed; while the large amplitude oscillatory shear (LAOS) test was carried out to characterize the non-linear behavior at strains beyond the linear viscoelastic region (LVER) of these materials. Styrene-butadiene-styrene (SBS) and ethylene vinyl acetate (EVA) as elastomeric and plastomeric polymers, respectively, and CR, at different concentrations were used to prepare the modified asphalt binders. For the large strain analysis, the waveforms for each material were collected for strain amplitudes of 0.5%, 10%, 20%, 30%, and 40% at 30 °C and 1 Hz. The small strain rheology was applied to discuss the linear properties, while the viscoelastic non-linearities of the studied asphalt binders were analyzed as a function of strain through the use of Lissajous-Bowditch plots and elastic and viscous non-linearities of an oscillatory shear cycle. The rheological measurements at small strain showed distinctive properties can be attained by the addition of polymers over CR, especially the EVA-modified binder. The analysis of Lissajous-Bowditch plots showed that higher deformations can dramatically change the behavior of the binder and it is worth be studied in conjunction with the small strain properties to capture the overall performance. Moreover, the polymer-modified binder showed higher ability to resist high strains and exhibited strong strain stiffening compared to the CR-modified binders. A continuous shear thinning was registered for the polymer- and CR-modified binders with the increase in strain amplitude.

1. Introduction

Recently, increased traffic levels and new axles' designs with heavier loads and different configurations as well as harsh climates conditions spur the deterioration of the pavements [1,2]. In most cases, the unmodified pavements cannot perform satisfactorily in these conditions; therefore, using modifiers is the most attractive option and of a continuous interest by many researchers. Of the available asphalt modifiers, the polymers and crumb rubber (CR) have been used widely by many highway agencies to surpass the characteristics of the unmodified binder [2–5]. The polymer-modified asphalt binder in bituminous pavements decreases the temperature susceptibility and fatigue cracking as well as increase the rutting resistance [6]. Polymeric additives including elastomers (rubbers or elastics) and plastomers (plastics) are the general categories for the asphalt modification. Styrene-butadiene rubber (SBR) and styrene-butadienestyrene (SBS) are the most frequently used elastomeric additives mainly to increase the resistance to rutting, fatigue, and thermal cracking of the asphalt pavements [7].

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The plastomeric additives including among others, low density polyethylene (LDPE) and ethylene vinyl acetate (EVA) are generally used to decrease the rutting of the bituminous pavement [8,9]. Upon blending polymers of any chemical nature with bitumen, the polymer starts to emulsify then swell partially or completely dissolve in the bitumen medium. However, this process depends on the content of polymer and chemical composition of bitumen and polymer [10]. The polymeric additives are usually added at concentrations range of 2–6% by the weight of asphalt binder [11]. Due to the limited resources as well as the escalating costs of polymers and bitumen, researchers are exploring alternative materials such as CR for the road construction [12]. Generally speaking, the relatively similar characteristics to some polymers that can be imparted, increased the interest in using the CR in asphalt pavements [13,14]. Basically, in addition to the enhanced engineering properties, the usage of CR in asphalt pavements decreases the environmental burden through make use of a large amount of waste tires that is disposed of every year [3,13]. The CR is a reduced size of rubber and can be incorporated at different concentrations in the bituminous pavements either in the dry or wet processes. In the dry process, the CR is mixed with the aggregates before feeding the asphalt binder into the mixture. While in the wet process, the CR is blended with the asphalt binder first before mixing with the aggregates [15]. When the CR is blended with asphalt binder, the light fractions of bitumen or aromatic oils get absorbed by the rubber which causes the particles swell in a non-chemical mechanism [16–18]. This mechanism depletes the light fractions, making the residual bitumen stiffer and more brittle [19]. The mixing of rubber with the asphalt binder for long periods of time would degrade the rubber particles in the form of devulcanization and depolymerization [20]. By the addition of CR in asphalt, it imparts many positive characteristics to the constructed pavement, such as increased service life, reduced maintenance costs, and decreased traffic noise [21]. In addition, it is effective in open-graded friction courses, chip seals, and stress absorbing membranes [22]. Several research works have studied the polymer- and CR-modified blends to fully understand the rheological properties of these composites; however, there is no too much attention to the responses of these materials under both small and large strains of shearing to better understand their linear and non-linear behaviors. The rheological properties of asphalt binder significantly influence the performance of the asphalt mixture [23]; excessive flow and deformation of the asphalt binder may increase the susceptibility to rutting and bleeding of the pavement, while too stiff binders are more prone to fatigue or thermal cracking [24]. Various failure mechanisms of the pavements occur at different strain or stress levels, therefore, the rheological behaviors should be understood for a wide range of strain levels to characterize the linear and non-linear regimes of the bituminous material. To compare the benefits of different asphalt modifiers, it is not enough to judge the behavior under a linear viscoelastic regime, the mechanical behavior of such materials under large strains is also important. From this point, the behavior of polymer- and CR-modified binders under different amplitudes of strains was analyzed using the dynamic shear rheometry. First, the viscoelastic properties were analyzed, then the viscoelastic non-linearities were discussed through the Lissajous-Bowditch plots and through non-linear elastic and viscous measures of non-linearities of an oscillatory cycle.

2. Theoretical background

Oscillatory shear tests have been used extensively to characterize the rheological behavior of various materials. Basically, in the oscillatory tests, the material is subjected to a sinusoidal strain/deformation or stress and the mechanical response is measured. More specifically, the oscillatory shear test applies a shearing force to a thin asphalt sample sandwiched between lower fixed plate and upper plate oscillating back and forth in a sinusoidal pattern, across the material at a prespecified temperature and frequency using the controlled-stress mode or the controlled-strain mode, but the latter is most common. In the case of the strain-controlled test, at small amplitudes of strain, the stress response of the material is maintained sinusoidal by the nature of the viscoelastic properties and the constant complex modulus G* and related moduli G' (storage modulus) and G" (loss modulus) can be estimated as well.

In the oscillatory shear measurements, a sinusoidal strain signal $\varepsilon(t)$ can be formulated as a function of imposed strain ε_0, time t, and the angular frequency of testing ω.

$$\varepsilon(t) = \varepsilon_0 \sin(\omega t) \tag{1}$$

In the case of the linear viscoelastic regime, the stress $\sigma(t)$ also will be sinusoidal by resulting stress amplitude σ_0 and phase shift δ as follows:

$$\sigma(t) = \sigma_0 \sin(\omega t + \delta) \tag{2}$$

From the imposed strain (i.e. strain-controlled mode) and stress response, one can calculate the complex modulus $G^* = \frac{\sigma_0}{\varepsilon_0}$, which is unique in this case. Eq. (2) can be rewritten as a function of in-phase (storage modulus) $G'(\omega)$ and out-of-phase (loss modulus) $G''(\omega)$ components.

$$\sigma(t) = G'(\omega)\varepsilon_0 \sin(\omega t) + G''(\omega)\varepsilon_0 \cos(\omega t) \tag{3}$$

The response of a viscoelastic material can follow the above equations if relatively low amplitudes of strain are applied. At larger strain and/or corresponding stress amplitudes, the non-linear behavior commences and different theories are applicable. Analysis of the non-linear response interplays large deformations, structural changes, and phase transitions, which complicates the resolving and their mathematical representations [25]. The LAOS test is widely used by researchers for quantifying the mechanical characteristics of bituminous materials under a wide range of strain amplitudes [26].

The interpretation of the non-linear data from the LAOS test is still a topic of research [27,28]. When large strain amplitudes are imposed, the stress response is no longer sinusoidal, and the LAOS stress data in the time domain can be analyzed through the Fourier transform rheology [29], as the pioneering technique for analyzing the non-linear viscoelastic behavior under the oscillatory tests. The stress response can be represented as a Fourier series. In the non-linear regime (large strain amplitudes), the response of the material (shear stress) is no longer independent of the strain amplitude and the shear stress response $\sigma(t;\omega,\varepsilon_0)$ is given as the superposition of odd harmonics n of the base frequency:

$$\sigma(t;\omega,\varepsilon_0) = \sum_{n=1}^{N} \sigma_n \sin(n\omega t + \delta_n) \tag{4}$$

The shear stress of the n-th harmonic can also be written as:

$$\sigma(t;\omega,\varepsilon_0) = \varepsilon_0 \sum_{n=1}^{N} [G'_n \sin(n\omega t) + iG'_n \cos(n\omega t)] \tag{5}$$

where N is the number of series terms defined by the desired accuracy of experimental data approximation, and G'_n and G''_n are amplitudes of n harmonics with frequencies (nω).

A convenient way to analyze the material's behavior within this region of non-linearity by presenting the data in the form of Lissajous-Bowditch curves, and multiple non-linearity measures can be derived to be interpreted. The experimental data can be pre-