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Characterization of the three-dimensional linear viscoelastic behavior of asphalt concrete mixtures

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HIGHLIGHTS

- Measurement of the complex bulk modulus K^* and shear modulus G^* of asphalt mixture.
- Time–temperature superposition principle is applicable to complex moduli K^* and G^*.
- The bulk response of asphalt mixtures cannot be considered elastic.
- Strain level effect on bulk and shear response is related to the loading mode.
- Poisson's ratio master curve described by the Kramers–Kronig relations.

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ABSTRACT

Mechanistic-empirical pavement design methods typically require the identification of the complex Young's modulus and Poisson's ratio for the characterization of bituminous layers. However, since in small deformation the frequency-dependent shear and bulk responses of an isotropic body are decoupled, the complex shear and bulk moduli are generally considered fundamental response functions. The objective of this study was to perform the experimental characterization of the three-dimensional response of asphalt mixtures in the linear viscoelastic domain, through the simultaneous measurement of the complex moduli E^*, K^* and G^* and the complex Poisson's ratio ν^*. The testing program consisted of cyclic compression and cyclic tension–compression uniaxial tests on cylindrical specimen, with the measurement of both axial and transverse strain. In particular, frequency sweeps were carried out at temperatures between 0, and 40 °C and at axial strain levels between 15 and 60 με. Experimental results highlighted that, for the tested mixture, the time–temperature superposition principle was applicable to both the bulk and shear response, and consequently to the axial response. E^* and G^* showed very similar trends in terms of both stiffness moduli and loss angle, whereas K^* values highlighted smaller frequency dependence. The time–temperature superposition principle was also applicable to ν^* whose master curves can be qualitatively described using the local approximation to the Kramers–Kronig relations. Results suggest that the simultaneous assessment of bulk and shear response may be a useful tool for the performance characterization of asphalt mixtures.

1. Introduction

The mechanical characterization of asphalt concrete (AC) in small deformation is based on the linear viscoelastic theory [1] and on the time–temperature superposition principle [2]. In particular, mechanistic-empirical pavement design methods also assume that AC exhibits an isotropic three-dimensional response to traffic loads and temperature variations and therefore the identification of Young's modulus E and Poisson's ratio ν is generally required [3].

Huge research efforts have been devoted to the measurement and modeling of the one-dimensional linear viscoelastic (LVE) response of AC, with particular emphasis on the complex Young's modulus E^*, whereas less attention has been paid to the characterization of the viscoelastic Poisson's ratio [1].

Recent studies [4–8] confirmed that, similar to E^*, the complex Poisson's ratio ν^* of AC mixtures is temperature- and frequency-dependent. In particular, at high frequencies or low temperatures the absolute value ν_0 generally varies from 0.15 to 0.25, whereas at low frequencies or high temperatures it approaches 0.5 [9,10]. The phase angle δ_ν is also variable, but generally is lower than 10°. Moreover, applying the time–temperature superposition

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principle (TTSP), master curves can be obtained for ν^*, and consequently for both ν_0 and δ_ν. Typical experimental data show that master curves of ν_0 generally have a sigmoidal trend [4,6] characterized by glassy and equilibrium asymptotes, similar to the master curves of the absolute value of Young's modulus E_0. However, results from other studies [5,11,12] apparently indicate that, at low reduced frequencies the presence of an equilibrium asymptote is not clear and, instead, the master curves of ν_0 show a maximum value. Similarly, Hilton and Yi [13], Lakes and Wineman [14] and Hilton [15] highlighted that the viscoelastic Poisson's ratio need not be monotonic with time.

Starting from 2012, Task Group 3 (TG3) "Mechanical Testing of Mixtures" of RILEM Technical Committee 237-SIB "Testing and characterization of sustainable innovative bituminous materials and systems" decided to study the complex Poisson's ratio of bituminous mixtures. To this aim a Round Robin Test (RRT) was organized in order to compare different measurement techniques and evaluate the possible effect of compaction-induced mixture anisotropy on the tested specimens. Results of the RRT showed that ν_0 was not monotonic and δ_ν showed a change in sign [16].

Though the Young's modulus and the Poisson's ratio are the most commonly used material parameters in pavement engineering, their definition and measurement comprises the realization of simultaneous changes in shape (shear) and size (bulk) [17]. Since in small deformation the frequency-dependent shear and bulk responses of a LVE isotropic body are neatly separated, the complex shear modulus G^* and the complex bulk modulus K^* are generally considered fundamental response functions [18], whereas E^* and ν^* may be regarded as derived response functions.

A recent study presented a methodology for the complete (i.e. bulk and shear) experimental characterization of asphalt mixtures in the LVE domain, by means of cyclic tension–compression tests [19]. Results highlighted the importance of measuring the axial/transverse or the shear/bulk responses simultaneously, on the same specimen. For the analyzed test conditions, the absolute value of K^* was found to vary at least by a factor of 10 and the complex moduli E^*, G^* and K^* were found to satisfy the interconversion relations derived from the Hooke's law.

The objective of the present study was to perform the experimental characterization of the three-dimensional response of asphalt mixtures in the LVE domain. To this end, cyclic axial tests were carried out at various strain levels, both in compression and tension–compression. Results were analyzed to determine the complex response functions E^*, K^*, G^* and ν^* and check their interrelations, under the hypothesis of isotropy.

2. Experimental approach

The experimental approach is based on the analysis of cyclic uniaxial tests carried out on cylindrical AC specimens. In such tests, though the stress state is uniaxial, the strain field is multi-axial. With the additional hypothesis of isotropy, the strain field is also axisymmetric and therefore it is characterized by only two degrees of deformation freedom. As a consequence, the simultaneous measurement of axial and transverse strain allows the complete three-dimensional viscoelastic characterization [15,20].

The well-established elastic–viscoelastic correspondence principle (EVCP) [21] was applied to define complex moduli E^*, K^* and G^* and verify their interrelations. However, the EVCP is not applicable in a straightforward way to Poisson's ratio because of the interdependency of the axial and transverse strain [22]. In addition, its application requires identical initial and boundary conditions [14] and therefore, when dealing with experimental measurements, the source functions must be measured simultaneously on the same specimen [23].

A linear and isotropic behavior is normally assumed to model AC for pavement applications [1,3]. In particular, the linearity limit for the evaluation of E^* is generally lower than $100 \cdot 10^{-6}$ mm/mm [24]. Moreover, several researchers showed that, within this deformation range, the hypothesis of material isotropy is valid [29,30].

For the present study, tests were performed at strain levels from 15 με to 60 με in both compression and tension–compression. Since the objective was to evaluate complex-valued response functions, only the harmonic (i.e. steady-state) part of the measured stress and strain signals was analyzed.

2.1. Uniaxial tests on LVE material

We restrict our attention to an isotropic cylindrical body (Fig. 1a) subjected to steady-state harmonic uniaxial stress history ($\sigma_2 = \sigma_3 = 0$). Linearity implies that stress and strain (both axial and transverse) have the same frequency, whereas isotropy implies that the transverse response is the same in all directions. Using complex exponentials, stress and strains (Fig. 1b) are written as follows:

$$\sigma_1^*(j\omega) = \sigma_{1,0}\exp[j(\omega t + \delta_1)] \tag{1a}$$

$$\varepsilon_1^*(j\omega) = \varepsilon_{1,0}\exp(j\omega t) \tag{1b}$$

$$\varepsilon_3^*(j\omega) = \varepsilon_2^*(j\omega) = \varepsilon_{2,0}\exp[j(\omega t - \delta_2)] \tag{1c}$$

where j is the imaginary unit, $\sigma_{1,0}$, $\varepsilon_{1,0}$ and $\varepsilon_{2,0}$ are the steady-state amplitudes of the harmonics, ω is the angular frequency and δ_1, δ_2 are the phase angles, with respect to the axial strain $\varepsilon_1(t)$, to which a zero phase is customarily assigned.

The sign of the phase angles in Eq. (1) deserves some attention. From a physical point of view, phase angle is the product of angular frequency and time ($\delta = \omega\, t$), which are both positive quantities. In particular, time is added to indicate a lead and subtracted to indicate a lag [25]. Therefore, the "+" sign of δ_1 in Eq. (1a) indicates that axial stress leads axial strain, whereas the "−" sign of δ_2 in Eq. (1c) indicates that transverse strain lags axial strain. It is emphasized that, while the first is a viscous effect, and can be derived analytically from the Boltzmann superposition principle using transform calculus, the second is merely an assumption which is subjected to experimental verification [17]. According to such an assumption, for a conventional material (i.e. a material that stretched/compressed in the axial direction, contracts/expands in the transverse directions), viscous damping implies that $\delta_2 - \pi > 0$, as shown in Fig. 1b.

Uniaxial tests on cylindrical specimens may be regarded as a special case of standard triaxial tests routinely performed in soil mechanics [20]. Because of axial symmetry, bulk and shear strain phasors (phase vectors) are calculated as follows:

$$\varepsilon_p^*(j\omega) = \varepsilon_1^*(j\omega) + 2\varepsilon_2^*(j\omega) = \varepsilon_{p,0}\exp[j(\omega t + \delta_{\varepsilon p})] \tag{2}$$

$$\varepsilon_q^*(j\omega) = \frac{2}{3}[\varepsilon_1^*(j\omega) - \varepsilon_2^*(j\omega)] = \varepsilon_{q,0}\exp[j(\omega t - \delta_{\varepsilon q})] \tag{3}$$

where $\varepsilon_{p,0}$, $\varepsilon_{q,0}$ are the amplitudes and $\delta_{\varepsilon p}$, $\delta_{\varepsilon q}$ are the phase angles for the bulk and shear strain, respectively. The stress phasors are calculated as follows:

$$p^*(j\omega) = \frac{\sigma_1^*(j\omega)}{3} = \frac{\sigma_{1,0}}{3}\exp[j(\omega t + \delta_E)] = p_0\exp[j(\omega t + \delta_p)] \tag{4}$$

$$q^*(j\omega) = \sigma_1^*(j\omega) = \sigma_{1,0}\exp[j(\omega t + \delta_E)] = q_0\exp[j(\omega t + \delta_q)] \tag{5}$$

where $p_0 = q_0/3 = \sigma_{1,0}/3$ are the amplitudes and δ_p, δ_q the phase angles for the bulk and shear stress, respectively, with $\delta_p = \delta_q = \delta_E$.

2.2. Complex moduli

The complex Young's modulus E^*, bulk modulus K^* and shear modulus G^* are defined as follows:

$$E^*(j\omega) = \frac{\sigma_1^*}{\varepsilon_1^*} = \frac{\sigma_{1,0}}{\varepsilon_{1,0}}\exp(j\delta_1) = E_0\exp(j\delta_E) \tag{6}$$

$$K^*(j\omega) = \frac{p^*}{\varepsilon_p^*} = \frac{p_0}{\varepsilon_{p,0}}\exp[j(\delta_E - \delta_{\varepsilon p})] = K_0\exp(j\delta_K) \tag{7}$$

$$G^*(j\omega) = \frac{q^*}{3\varepsilon_q^*} = \frac{q_0}{3\varepsilon_{q,0}}\exp[j(\delta_E + \delta_{\varepsilon q})] = G_0\exp(j\delta_G) \tag{8}$$

where E_0, K_0 and G_0 are the absolute values (norms), and δ_E, δ_K and δ_G are the phase (or loss) angles.

The EVCP indicates that complex moduli E^*, K^* and G^* defined by Eqs. (6)–(8) are the viscoelastic analogs of the elastic moduli E, K and G [28], therefore absolute values K_0 and G_0 may be considered as measure of bulk and shear stiffness, respectively. From Eqs. (6)–(8), it can be observed that, for $\delta_2 > \pi$, the loss angle in axial deformation δ_E is smaller than the loss angle in shear δ_G, but larger than the bulk loss angle δ_K (Fig. 2c) in accordance with [13,17]. Conversely, if $\delta_2 < \pi$, we obtain $\delta_G < \delta_E < \delta_K$ (Fig. 2d).

The complex exponentials described by Eqs. (1)–(8) can be graphically represented in the complex plane (Fig. 2). The advantage of such a representation is that the familiar rules of vector algebra can be readily applied to harmonic quantities.