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Observed deviations from isotropic linear viscoelastic behavior of asphalt concrete through modal testing

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HIGHLIGHTS

- Material properties of asphalt concrete were determined through modal testing.
- Isotropic linear relation between E^*, υ^* and G^* was observed above ~10 kHz at 0 °C.
- Discrepancies were found from isotropic linear behavior below ~10 kHz at 0 °C.
- G^* calculated from E^* and υ^* are overestimated at key frequencies and temperatures.

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ABSTRACT

The complex Young's moduli, complex shear moduli and complex Poisson's ratio of a beam shaped asphalt concrete specimen have been characterized through low strain ($\sim 10^{-7}$) frequency response function measurements. The assumption of isotropic linear viscoelastic behavior has been applied and investigated. The results indicate that the asphalt concrete specimen agree with the isotropic linear viscoelastic assumption at low temperatures and high frequencies (>10 kHz at 0 °C), but at higher temperatures and lower frequencies, discrepancies from isotropic linear behavior are shown. The dynamic shear moduli calculated from the estimated Young's moduli and Poisson's ratio of the asphalt concrete specimen are overestimated for frequencies and temperatures often applied to pavements.

1. Introduction

The viscoelastic complex modulus of asphalt concrete is fundamental to modern pavement design due to the time and temperature dependency of bituminous materials. Methods to determine the complex modulus over a wide frequency and temperature range (i.e. master curve) are today based on predictive equations or mechanical laboratory testing [1–5]. The conventional cyclic loading tests of bituminous mixtures are expensive and complicated to perform while the predictive models are more economic but not as accurate as actual testing. New methods to measure the complex modulus of asphalt concrete through stress wave measurements are economic, accurate and open up the possibility of future nondestructive quality control of pavement materials [6–9].

In the field of pavement engineering, the complex Young's modulus (E^*) is often related to the complex shear modulus (G^*) and complex Poisson's ratio (υ^*) according to isotropic linear viscoelastic theory. However, it has been shown in several papers that the relations of E^*, G^* and υ^* according to isotropic linear viscoelastic theory are not at all accurate for asphalt concrete [10–15]. It has instead been recommended to apply empirical formulations to relate E^*, G^* and υ^* [3,13]. The reason for the discrepancy from isotropic linear viscoelastic theory is not fully understood, even if anisotropy of the asphalt concrete has been believed to be one important reason [13,14,16]. At the same time, anisotropy has shown to have a minor influence to the small strain behavior as e.g. the dynamic modulus [2,17]. Di Benedetto et al. [16] concluded that the relation between E^* and G^* remains unknown for asphalt concrete and needs further studying.

In the field of geophysics it is well known that compression and shear waves exhibit different attenuation in saturated rocks and soils [18,19]. For these porous materials it has been necessary to apply the theory of linear poroelasticity to be able to predict the dynamic response. Different damping properties of compression and shear waves may also be the case of asphalt concrete, especially at higher temperatures, but this has not been thoroughly

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examined. On the other hand, it has been theoretically shown that the complex bulk moduli have a lower damping than the complex shear moduli for viscoelastic materials [20,21]. Furthermore, Pritz [22] showed that the bulk and shear loss factors are related through the dynamic Poisson's ratio for viscoelastic materials if the shear loss factor is lower than 0.3. It was also pointed out by Pritz [22,23] that the relation may be accurate enough for a higher shear loss factor. Measurements of asphalt concrete often results in loss factors above 0.3 for both E^* and G^* at high temperatures [5,9,24]. Possible differences between the loss factors of E^* and G^* of asphalt concrete could be a reason to discrepancies from isotropic linear viscoelastic theory [10,25].

Despite the uncertainties of the relation between the isotropic linear viscoelastic properties, there are few papers reporting measurements of E^* and G^* that have been performed on the same asphalt concrete specimens [10,11]. More common are measurements of E^* and G^* that have been performed to the same asphalt mixture but not on the same specimens cf. e.g. [13,14,26]. A probable reason for this are limitations of most of the conventional test methods to measure both E^* and G^* for the same specimen. In addition, the conventional test methods often introduces different boundary conditions and different types of set-up of the E^* and G^* measurements. Therefore, it is of high interest to further investigate the low strain E^* and G^* of asphalt concrete using nondestructive testing. Nondestructive stress wave measurements may enable the characterization of both E^* and G^* by measuring different modes of vibration of an asphalt concrete specimen.

Mounier et al. [27] performed ultrasonic testing to cylindrical asphalt concrete specimens where the propagation of compression and shear waves was measured. E^* and υ were determined through simplified approximate formulations for one loading frequency per temperature, but no results of G^* were presented. Other stress wave measurements performed to asphalt concrete has also been focused on only determining E^*, through either ultrasonic wave propagation measurements [25,28–31] or impact resonance testing [32–34]. In common for these tests is that simplified approximate relations have been used to determine one E^* per temperature (cf. e.g. ASTM C215 2008 [35]). Therefore, the frequency dependency of the asphalt concrete cannot be estimated through this approach. To characterize the frequency dependency of E^* through stress wave measurements, numerical methods (resonant acoustic spectroscopy) were applied by Ryden [36] and Gudmarsson et al. [8]. The combination of numerical computations and resonance frequency measurements allows the determination of the full elastic tensor of isotropic and anisotropic elastic materials, since the resonance frequencies of free solids depend on the mass, the dimensions and the elastic constants [6]. The application of resonant acoustic spectroscopy to the frequency dependent asphalt concrete enabled the determination of E^* at more than one resonance frequency. However, in order to determine master curves based only on stress wave measurements, it was also concluded that the measurements should not be limited to the discrete resonance frequencies. Frequency response functions (FRFs), i.e. the acceleration divided by the applied force in frequency domain, provide information of material properties over a wide frequency range including both resonance peaks and valleys in a frequency response curve. This allows material properties to be determined over a wide and fine sampled frequency range. Measurements of FRFs have been applied in other fields of engineering to estimate master curves, where properties of materials as e.g. metal polymer sandwich [37], silicone rubber [38] and multi-layer beams of metal and viscoelastic material [39] have been characterized. Measurements of FRFs have also been applied to an asphalt concrete specimen where E^* was characterized over a wide frequency range [9]. This enabled the E^* master curve to be determined for the longitudinal modes of vibration by only applying modal testing to asphalt concrete. However, there have been no studies applying this method to characterize E^*, G^* and υ^* of asphalt concrete specimens.

In this paper, FRF measurements of the longitudinal, flexural and torsional modes of vibration are performed to characterize the low strain $E^*(T, f)$, $\upsilon^*(T, f)$ and $G^*(T, f)$ of a beam shaped asphalt concrete specimen. Theoretical FRFs are calculated numerically by the finite element method and optimized against measured FRFs to estimate the material properties of the asphalt concrete specimen. The results presented in this paper indicate that the calculated $G^*(T, f)$ from the estimated $E^*(T, f)$ and $\upsilon^*(T, f)$ are overestimated for the asphalt concrete specimen at important frequencies and temperatures.

2. Methodology

2.1. Materials and measurements

The asphalt concrete specimen used in these measurements has previously been tested in [8], where resonant acoustic spectroscopy was applied to derive the complex modulus from the discrete resonance frequencies. It has also been tested in [9], where the method of optimizing FRFs of asphalt concrete was developed and applied to characterize the complex modulus for the longitudinal modes of vibration over a wider frequency range. In this study, additional modes of vibration are measured to characterize and investigate the relation between E^*, G^* and υ^* of the beam shaped asphalt concrete specimen. The specimen consists of granite aggregates with the gradation according to Table 1 and Nynas binder with an original penetration grade of 70/100. The beam-shaped specimen has been sawn out from a roller compacted slab with the dimensions of 500 * 560 * 80. The length, width and height of the specimen are 382.00, 58.74 and 58.94 mm, respectively. The specimen has an air void content of 2.7% and the density is 2.359 g/cm^3. The binder content of the asphalt concrete mixture is 6.3% by weight.

The specimen was placed on soft foam to provide free boundary conditions while exciting the flexural, longitudinal and torsional modes of vibration. An instrumented hammer (PCB model 086E80) was used to apply the load impulse and an accelerometer (PCB model 352B10) attached by wax was used to measure the response of the specimen. The light accelerometer (0.7 g) is assumed to not affect the measurements. The measurement devices were connected according the following scheme: hammer and accelerometer → signal conditioner (PCB model 480B21) → data acquisition device (NI USB-6251 M Series) → computer. The data from the hammer and the accelerometer were recorded with a sampling frequency of 500 kHz. Fig. 1 illustrates the locations of the hammer impacts and the placements of the accelerometer when measuring the flexural, longitudinal and torsional modes of vibration of the asphalt concrete beam. The accelerometer was placed on the opposite sides to the locations of the hammer impacts, which are marked in Fig. 1 for each mode of vibration. The strain levels were approximated for the fundamental resonance frequency where the highest strains occur. For the longitudinal modes of vibration the maximum strain have been approximated to the magnitude of 10^{-7} according to Eq. (1), where ε is the strain, $Y(f)$ is the measured acceleration and L is the length of the specimen [40,9]. Note that the highest acceleration at the fundamental resonance frequency (~17.5 m/s^2 at ~5200 Hz) was measured for the longitudinal modes of vibration.

$$\varepsilon = \frac{Y(f)}{4\pi L f^2} \tag{1}$$

The flexural, longitudinal and torsional modes of vibration were excited by five impacts each at seven temperatures between −30 and 30 °C, while the specimen was located inside the temperature chamber. The opening of the door to the temperature chamber is assumed to not affect the temperature of the specimen during the short time of the measurements (~10–20 s). The recorded load impulse and response of the specimen were used to calculate the FRFs according to Eq. (2), where the five measurements ($n = 5$) are averaged at each frequency. The coherence

Table 1
Gradation of the asphalt concrete mixture.

Sieve size (mm)	0.063	0.125	0.25	0.5	1	2	4	5.6	8	11.2	16	22.4
% Passing	8.9	12	16	21	28	39	50	58	70	81	98	100