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Complex modulus and complex Poisson's ratio from cyclic and dynamic modal testing of asphalt concrete

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HIGHLIGHTS

- Linear viscoelastic properties of asphalt concrete from cyclic and modal testing are compared.
- Strains from the modal testing are approximated for the different temperatures.
- Modal testing results in higher absolute value of the complex modulus compared to cyclic tests.
- Cyclic and modal testing resulted in similar complex Poisson's ratio master curves.

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ABSTRACT

The complex moduli and complex Poisson's ratio of two cylindrical asphalt concrete specimens have been determined through modal testing in this paper. These results have been compared to cyclic tension–compression measured complex moduli and complex Poisson's ratio of asphalt concrete specimens with different dimensions. The modal testing has been performed by measuring frequency response functions of the specimens using an impact hammer and an accelerometer. The material properties have been characterized by matching finite element computed frequency response functions to the measurements. The results of the different specimens show that the modal test systematically give a slightly higher absolute value of the complex moduli compared to the cyclic testing. The differences are most likely a result of the different strain levels applied in the two test methods. However, the modal and cyclic tension–compression testing resulted in similar values of the complex Poisson's ratio for the two different asphalt concrete mixtures despite the different applied strain levels.

1. Introduction

There is a need for simple and economic test methods to measure the linear viscoelastic material properties of asphalt concrete. Modal testing is widely known to be economic, accurate and simple to perform which makes it advantageous compared to costly conventional cyclic loading test methods to measure the complex moduli [1]. Nondestructive test methods based on impact modal testing have shown great potential in characterizing the temperature and frequency dependent complex moduli of asphalt concrete [2–6]. In addition, wave-based measurements can be used for nondestructive quality control and quality assurance of pavement materials by e.g. comparing laboratory and field measured complex moduli [7,8].

Alternative test methods to conventional testing have measured fundamental resonance frequencies of asphalt concrete specimens and applied simplified analytical formulations to derive a complex modulus at different temperatures [8–10]. Limitations of this approach are that the analytical approximate formulations are valid only for certain specimen geometries and that the complex modulus can be determined for only one frequency per temperature. Ultrasonic test methods applied to asphalt concrete have also been based on simplified analytical formulations and suffer therefore from the same limitations [11–15]. These alternative test methods to conventional testing have not been able to characterize the frequency dependency of asphalt concrete. However, through measurements of frequency response functions (FRFs) it has been possible to determine master curves of asphalt concrete that describe the viscoelastic material properties as a function of frequency and temperature [4–6]. FRFs are determined by dividing the measured response with the measured applied force in

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frequency domain. The characterization of the frequency dependency of the asphalt concrete through modal testing has been enabled by combining numerical computations with measured FRFs [4]. This approach was developed for a beam shaped asphalt concrete specimen in Gudmarsson et al. [4] and further applied to a cylindrical specimen to compare the method to conventional cyclic tension–compression tests in Gudmarsson et al. [5]. As expected, the comparison between the two test methods showed small differences of the complex moduli due to the known nonlinearity of asphalt concrete and because different strain levels are applied in the two test methods cf. e.g. [16–18]. However, the results showed large differences between the two methods regarding the complex Poisson's ratio. Although, the reasons for the different results of complex Poisson's ratio could not be fully determined, it was seen that the tension–compression measured complex Poisson's ratio did not agree with the measured FRFs. Therefore, further comparisons of complex Poisson's ratio of asphalt concrete determined through modal and tension–compression measurements are needed. It is also of interest to further apply the modal test to specimens with different dimensions and to quantify the applied strain levels at different temperatures.

In this paper, modal testing of two asphalt concrete specimens have been performed to enable further comparisons of the complex moduli and complex Poisson's ratio to cyclic tension–compression test results. The linear viscoelastic properties of specimens with different dimensions are compared. The results presented show that the modal and tension–compression test methods are able to give similar complex Poisson's ratio.

2. Methodology

The applied methodology to determine the material properties of the asphalt concrete specimens includes modal testing to measure FRFs and numerical computations of FRFs that are optimized to match the measurements. The modal testing has been performed to two cylindrical specimens from two different asphalt mixes called GB3 and GB5® [19]. These measurements have been compared to results of conventional cyclic tension–compression testing performed to cylindrical specimens of the same mixes but with different dimensions. The modal and tension–compression measurements have been performed at the University of Lyon, Ecole Nationale des Travaux Publics de l'Etat (ENTPE), Laboratorie Génie Civil et Bâtiment. Results from a total of eight different specimens are presented here, where two specimens have been tested through modal testing, five specimens through tension–compression measurements and one specimen have been tested by both modal and cyclic tension–compression measurements [5]. The specimens have been produced at the same time at Eiffage Travaux Publics in France but tested at different times. Therefore, there may be small differences in the material properties of the specimens due to aging of the binder. However, research has shown that even if aged binders show significant physical hardening effects, the asphalt mixtures are less affected by the aged binder [20]. The mixes have been part of a round robin test (RILEM technical committee 237-SIB: testing and characterization of sustainable innovative bituminous materials and systems), where the three-dimensional linear viscoelastic behavior of the specimens have been characterized. The tension–compression test method is thoroughly described in work by e.g. Di Benedetto et al. [21], Nguyen et al. [22] and Nguyen et al. [23].

2.1. Materials

Table 1 presents details of the eight different specimens from which results are reported. Note that the modal and tension–compression measurements have been performed to different specimens except for the specimen GB3 (s.3). To this specimen, both modal and tension–compression testing have been performed and reported in Gudmarsson et al. [5]. Results of the tension–compression tested specimens have previously been presented by e.g. Nguyen et al. [24]. The GB5® mix has a higher content of large aggregates than the GB3 mix as shown by the gradation curves in Fig. 1 and presented by Tables 2 and 3. Otherwise, the two mixes contain the same binder with the penetration grade of 35/50 and a binder content of 4.5% by weight.

2.2. Impact hammer modal testing

Waves in a solid generated from an external input can interfere and create standing waves if the input provides energy to the frequencies that corresponds to the solids natural frequencies. The condition of when the input frequencies equal the natural frequencies of a solid is known as resonance. Any system or solid in which standing waves can form have a large number of natural frequencies which depend on the elastic constants, the geometry, the boundary conditions and the density. The elastic constants can therefore be determined with great accuracy by measuring a complete set of resonance frequencies below some upper limit [25]. Since a large number of resonance frequencies of different mode types can be measured by one single excitation, all elastic constants of a solid with free boundary conditions can be determined by one single measurement of an isotropic or anisotropic elastic material if the solids dimensions and density are known [26]. This is a great advantage compared to methods measuring the velocity of propagating waves, where measurements needs to be performed in several directions to obtain the same information. Furthermore, no assumptions of idealized states of stress and strain are needed since the numerical methods to derive elastic constants from resonance frequency measurements account for the complex vibrations of a solid [27]. In the case of viscoelastic

Table 1
Details of the specimens from which results are reported.

Specimen	Test date	Test method	Test ID	Mass (g)	Height (mm)	Diameter (mm)	Density (kg/m^3)
GB3 (s.1)	Aug. 2012	Tension–compression	TC – GB3 (s.1)	1572	140.9	73.8	2609.7
GB3 (s.2)	Aug. 2012	Tension–compression	TC – GB3 (s.2)	1564	140.1	73.7	2613.6
GB3 (s.3)	May 2013	Tension–compression and FRFs	TC – GB3 (s.3) FRF flex. – GB3 (s.3) FRF long. – GB3 (s.3)	1378	122.6	74.1	2606.8
GB3 (s.4)	Feb. 2014	FRFs	FRF flex. – GB3 (s.4) FRF long. – GB3 (s.4)	1198	140.7	64.6	2586.0
GB5 (s.1)	Sep. 2012	Tension–compression	TC – GB5 (s.1)	1616	142.3	74.1	2635.9
GB5 (s.2)	Aug. 2012	Tension–compression	TC – GB5 (s.2)	1595	140.4	73.9	2647.7
GB5 (s.3)	Aug. 2012	Tension–compression	TC – GB5 (s.3)	1596	140.7	73.9	2641.3
GB5 (s.4)	Feb. 2014	FRFs	FRF flex. – GB5 (s.4) FRF long. – GB5 (s.4)	1209	140.2	64.6	2630.9