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Field and laboratory stress-wave measurements of asphalt concrete

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HIGHLIGHTS

- A 48 MEMS sensor array, providing clear surface wave data, is presented.
- Good fit between laboratory and non-contact field measurement regarding stiffness.
- Non-contact field measurements showing high repeatability.

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ABSTRACT

Non-contact surface wave measurements are performed on a new asphalt concrete (AC) pavement using 48 micro-electro-mechanical system (MEMS) sensors as receivers to estimate the real part of the dynamic moduli of the AC top layer. Laboratory measurements of core samples, extracted from the field measurement positions, are used to construct master curves for comparison with the field measurements. The real parts of the dynamic moduli from the two test methods are consistent at the field measurement temperatures, and the non-contact field measurements are highly repeatable. These results indicate a possible application for quality assurance of AC based on mechanical properties.

1. Introduction

Material stiffness is one of the most important parameters in pavement design. The dynamic modulus is directly linked to structural capacity [1] and it strongly affects the pavement's lifespan and deterioration. The modulus for asphalt concrete (AC) is highly dependent on both frequency and temperature; the stiffness of AC decreases with increasing temperatures and/or longer loading times (lower loading frequencies). It is therefore essential to characterize and account for the time and temperature dependency of asphalt in stiffness-based methods used for quality assurance/quality control (QA/QC).

The dynamic modulus in the field can be estimated using a falling weight deflectometer (FWD) that measures the deflection at various offsets from an impact. These measurements can be used to study the deflection from a complete (multi-layered) pavement structure. However, backcalculation of the mechanical properties from the deflection data is subject to uncertainties. Additionally, results have indicated that this approach is more sensitive to the moduli in the base and subgrade layers and less sensitive to that of the thinner AC layers [2]. It also can be difficult to link a representative frequency to this type of measurement. In a recent study, Varma and Kutay [3] evaluated a frequency- and temperature-dependent dynamic modulus from repeated FWD tests at different temperatures. They presented a dynamic modulus master curve that was backcalculated from the deflection time history. The linear viscoelastic behavior of the AC layer and the nonlinear elastic behavior of the unbound subgrade were introduced in the same model to more accurately characterize the master curve of the AC layer and the material parameters of the unbound underlying layer.

In recent years, seismic field measurements on pavement were compared to data from seismic laboratory tests in order to conduct material characterization. Nazarian et al. [4] applied the spectral analysis of surface waves (SASW) method to collect in situ surface

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wave data and construct a continuous dispersion curve. They successfully compared the in situ measurements to laboratory seismic test results on core samples and showed small differences between the two. Ryden and Park [5] used a method similar to SASW, called the multichannel analysis of surface waves (MASW) method [6], to construct a multichannel data record used to calculate multimodal dispersion curves and subsequently estimate the material properties and layer thickness. Recently, Lin et al. [7] determined the in situ moduli through surface wave measurements and compared them to laboratory moduli from indirect tension testing. However, all previous measurements on AC layers were performed using contact receivers (accelerometers), which present several difficulties. There must be sufficient coupling between the surface and the contact receiver, and this can be difficult to achieve on rough surfaces or for multiple measurements in various locations. Stationary measurements are also costly and labor intensive for large-scale scanning, since a new setup is needed for each individual measuring position. Thus, there is a need for a faster test method for measuring the dynamic field modulus that can cover larger areas.

Non-contact sensors (microphones) hold great potential for faster data acquisition when performing large-scale testing, since it is not necessary to set up each individual measurement. Several papers over the past decades have described the use of non-contact receivers for data acquisition in seismic wave testing. Uses include material characterization [8–10], detection of bridge deck delamination [11], and determination of surface crack depths [12]. Bjurström et al. [13] presented measurements obtained using air-coupled microphones that were rolled over a concrete surface. This method provided reliable results for the Rayleigh wave velocity that were comparable to stationary accelerometer measurements.

The dynamic modulus can be measured in the laboratory by applying cyclic loading to AC specimens. This conventional laboratory testing for the dynamic modulus is usually performed at $\sim$50 micro-strains over a narrow and limited number of loading frequencies, and it is repeated at several different temperatures [14] to capture the viscoelasticity of AC. However, these tests are time consuming and have high costs. Furthermore, there are no in situ test methods that link the results to these conventional laboratory measurements. New, rapid non-destructive testing (NDT) methods are needed that can link results from the field with those from the laboratory. These test methods need to be performed at well-defined temperatures and frequencies and could ideally lead to QA/QC based on the measured mechanical properties of the materials instead of using bulk density and/or void ratio data.

Recently, a new and cost-efficient laboratory modal test method, based on the backcalculation of simple frequency response measurements, was developed by Gudmarsson et al. [15]. The assumption of a thermo-rheologically simple material and the time-temperature superposition principle allowed the complex modulus to be expressed over a wide range of frequencies and temperatures (i.e., a master curve) [15]. Then, laboratory measurements of the complex modulus performed by modal testing at the same strain levels ($\sim 10^{-7}$) as the field measurements can enable a direct comparison between laboratory and field testing.

This paper presents a study that evaluates the surface wave velocity of the top AC layer using acoustic non-contact field measurements. The dynamic modulus is then determined using the surface wave velocity through fundamentally correct elastic relationships. An air-coupled receiver array, consisting of 48 micro-electro-mechanical system (MEMS) sensors, is constructed and employed for in situ data acquisition to enable fast and effective measurements. The tests are performed in five different sections of a newly built pavement, and each section is constructed using a unique set of layers and mixtures. Once the in situ tests are completed, core samples are extracted from the five test locations to perform modal testing on the same material volumes in a controlled laboratory environment. The laboratory measurements are performed over a range of temperatures and frequencies in order to characterize the master curves, allowing the dynamic moduli to be shifted and presented over a wider range of temperatures and frequencies. Using this approach, the dynamic modulus can be expressed at an arbitrary reference temperature and frequency. Comparisons with field measurements at the measurement temperatures show good agreement between the laboratory and field test results. These results indicate that the presented method can be used for asphalt concrete QA/QC based on the seismic dynamic modulus.

2. Methodology

2.1. Test site

The field testing in this study was performed on a newly built highway (riksväg 40) close to the town of Ulricehamn, Sweden. A 2 km portion of highway was built for research purposes and was divided into five sections that were constructed using different designs (see Table 1). The five different test sections were examined during this investigation. The road was not opened to traffic during the in situ measurements. The width of the road is 10.75 m (two driving lanes in one direction) and the lengths of each section are 500 m for the reference section and 375 m for the four sections P1-P4. All tests were performed in the central part of the respective section in order to avoid errors due to the boundaries.

The reference section was constructed with four layers of conventional hot mix asphalt (HMA) at a total thickness of 19 cm with unmodified bitumen (penetration grade of 70/100 in examined top layer), according to Swedish specifications of bituminous layers [16]. Section P1 was constructed with the same asphalt mixtures but with three layers of HMA, resulting in a total thickness of 14 cm. Sections P2, P3, and P4 were constructed using the same layer thicknesses as used in P1, but they all contain different bitumen in the asphalt mixtures. Section P2 has a stiffer unmodified bitumen (penetration grade of 50/70 in top layer), Section P3 has a 4% SBS-polymer modified bitumen (PMB), and Section P4 has a 7.5% SBS-polymer modified bitumen (penetration grades of 45/80 and 25/55 respectively).

Although all sections were constructed using multiple AC layers, this study was limited to estimates of the dynamic moduli of the top layer (4 cm, highlighted in Table 1) for each respective test section using a wavelength filter (described in Section 2.3).

Asphalt concrete is at small strains considered as a linear viscoelastic material. In this study, the field data are presented in terms of wave propagation velocity, thus linear elastic theory. In order to fully characterize the material, the attenuation of surface waves can be analyzed to determine the viscous properties of the AC mixture [17]. The collected data contain information about the viscous properties; however, it is in practice difficult to quantify from in situ measurements. The laboratory measurements also showed that the imaginary parts of the moduli are small compared to the real parts. The attenuation is therefore omitted from this study. Future studies can possibly include attenuation analyses to fully characterize the viscoelastic behavior.

In the presented study, all AC mixtures are considered to be isotropic. It cannot be excluded that anisotropy could affect the results to some degree. Prior authors have presented laboratory test results showing anisotropy in AC specimen [18]. Both field (Rayleigh waves) and laboratory measurements used in this study are influenced by both vertical and horizontal stiffness, and can