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Nondestructive quality assessment of asphalt pavements based on dynamic modulus

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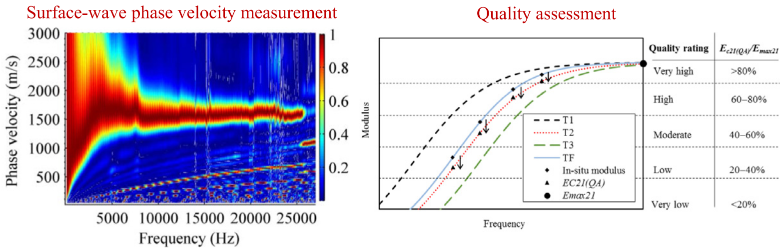
HIGHLIGHTS

- A novel nondestructive QC/QA procedure is proposed based on in situ dynamic modulus.
- A method is proposed to correct in situ moduli to a reference asphalt temperature.
- In situ shear-wave velocity is very sensitive to pavement type and temperature.
- In situ density is much less sensitive than velocity to pavement type and temperature.
- Modulus is a critical, objective, and sensitive property of asphalt pavement systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Dynamic modulus has been recognized as an objective and sensitive material property for designing and evaluating pavement systems. To accurately measure the in situ elastic modulus ($E = 2(1 + \nu)\rho V_s^2$) for nondestructive quality assessment of asphalt pavements, field measurements of density (ρ) via an electromagnetic gauge and shear-wave velocity (V_s) via surface-wave testing were examined for four paving projects covering a range of mixes and traffic loads. A quality control/quality assurance (QC/QA) procedure was developed to correct the in situ moduli at different field temperatures to a common reference temperature using a fitting function from experimental data for QC and using master curves from laboratory dynamic modulus tests for QA. The corrected in situ moduli can then be compared against the maximum moduli for an assessment of the actual pavement performance.

1. Introduction

Asphalt pavements suffer various modes of failure after construction, and commonly require rehabilitation to enable them to reach their design life-spans. The empirical design of asphalt pavements has been identified as one of the major reasons for cases of inadequate performance. The mechanistic-empirical pavement design guide (MEPDG) was therefore developed to enable quantitative performance prediction for the design of new and rehabilitated pavement structures [1]. In addition to traffic and climate data as inputs, mechanistic-empirical (M-E) design procedures require measurement of fundamental pavement material properties rather than use of empirical relationships. Quality control and quality assurance (QC/QA) procedures based on measured fundamental properties are thus necessary for enabling quantitative evaluations of pavement condition and performance.

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Traditional QC/QA procedures are based on properties of asphalt mixtures (e.g., density, air voids, permeability) measured in one of two ways: (1) using in situ measurements taken on the surface of an asphalt layer (e.g. [2–5]), or (2) using laboratory tests on field cores (e.g. [5–7]). Although these traditional QC/QA procedures play an important role in ensuring high-quality pavements, they employ only the volumetric properties, thickness, and roughness (i.e., present serviceability index), but not actual mechanical properties such as modulus. However, the mechanical properties are more sensitive than volumetric properties to variations in quality, and are also required for performance-based M-E pavement design. Additionally, the quality and remaining life of a pavement can be evaluated based on modeling it as an elastic and/or viscoelastic multilayered system, and predicting the strains and stresses at interfaces of different layers [8]. The modulus of an asphalt layer is also of critical importance for estimating fatigue cracking [9].

The use of modulus for QC/QA has been examined by Celaya et al. [8], Li and Nazarian [10], Nazarian et al. [11], Celaya and Nazarian [12], Jiang [13], Barnes and Trottier [14,15], and Icenogle and Kabir [16]. A variety of nondestructive surface-wave testing equipment for in situ modulus measurement has been developed by Nazarian [17], Stokoe et al. [18], Park et al. [19], Ryden [20], and Lin and Ashlock [21,22], among others. Overall, good correlations have been demonstrated between in situ modulus and laboratory modulus (e.g. [23,24]). Additionally, QC/QA methods based on measured moduli have been demonstrated to be more objective for characterization of asphalt layers by accounting for effects of temperature and loading frequency [8,11,25]. The advancement of QC/QA from methods based on volumetric and geometrical properties to those based on mechanical properties has been driven by the evolution from empirical to M-E design procedures [24].

Significant progress has been made in previous studies on the use of modulus for QC/QA of asphalt pavements (e.g. [8,11,25]), but several challenges remain, such as: (1) statistical variability and uncertainty of in situ shear-wave velocity measurements, (2) a systematic method for correction of in situ moduli measured at different field temperatures to a common reference temperature, and (3) a straightforward and practical QC/QA procedure. To overcome these challenges, the present study is aimed at developing the following: (1) a more robust and less delicate seismic testing system to provide consistent, reliable, and objective in situ velocity measurements, (2) a systematic method to correct in situ moduli measured at different field temperatures to moduli at a common reference temperature based on a fitting function from experimental data for QC and master curves from laboratory dynamic modulus tests for QA, and (3) a straightforward and practical QC/QA procedure to determine quantitative measures of pavement quality from the in situ dynamic modulus measurements.

2. Nondestructive measurement of dynamic modulus

Surface-wave methods (SWM) and falling weight deflectometer (FWD) tests have been widely used for determination of asphalt modulus (e.g. [16,26]). However, it is difficult to accurately determine the modulus of individual pavement layers from FWD tests because of the relatively larger receiver spacing, lack of high-frequency content in the impact load, and lower sampling rates compared to SWM. On the other hand, SWM test equipment can be used with relatively smaller receiver spacing to capture shorter wavelengths for the thin layers of interest, and smaller hammers to generate much greater high-frequency content (typically 10–30 kHz) than FWD tests (typically 1 kHz) [16]. Typical surface wave methods used for pavements include the Spectral Analysis of Surface Waves (SASW, e.g. [17]), Multichannel Analysis of Surface Waves (MASW, e.g. [19,22]), and Multichannel Simulation with One Receiver (MSOR) methods [20]. MSOR and SASW methods involve measurement of surface motion for sequential impacts over an array of source-to-receiver offsets, using a single receiver for (MSOR) or a pair of receivers (SASW). MASW involves simultaneous measurement of surface motion by an array of sensors for a single impact.

Surface wave data are processed to obtain the shear-wave phase-velocity spectra in the form of dispersion images or dispersion curves. Surface wave phase velocities at low frequencies correspond to material properties at greater depths, and high frequencies correspond to shallower depths. To more accurately measure the properties of the pavement surface layer, the measurement depth can be reduced by decreasing the receiver spacing, increasing the high-frequency content of the impact, and increasing the sampling rate. For the small strains involved in surface-wave testing, the asphalt behaves viscoelastically, and the Young's modulus (or stiffness, E) can be obtained from shear wave velocity (V_S) as

$$E = 2(1+\nu)\rho V_S^2 \tag{1}$$

where ν is Poisson's ratio which has a relatively minor influence and can be assumed constant for each layer, and ρ is mass density which can be measured in situ using an electromagnetic gauge.

Because the near-surface velocity (stiffness) decreases with depth for typical pavement profiles consisting of pavement, base, subbase, and subgrade layers, the corresponding phase-velocity spectra from surface-wave tests primarily show an increase in phase velocity with frequency. However, the phase-velocity spectrum of a layered pavement system actually consists of several branches that can be approximated as multiple modes of anti-symmetric and symmetric Lamb waves for a free plate corresponding to the material properties of the pavement layer (Ryden et al. [27]). The correspondence to Lamb waves is approximate, because the pavement layer is not truly free but interacts with the underlying base and subgrade layers to create partial branches of leaky quasi-Lamb waves in the low-frequency regime. At high frequencies (typically above 10 kHz), the experimental phase velocities approach those of the fundamental anti-symmetric (A0) and symmetric (S0) modes of dispersive Lamb waves, which themselves asymptotically approach the pavement layer's Rayleigh-wave velocity [28].

To obtain accurate properties of the base and subgrade layers, inversion of the phase-velocity dispersion data may therefore require matching forward-modeled theoretical dispersion curves to the low-frequency branches generated by interaction of the leaky quasi-Lamb waves. Alternatively, if only the properties (modulus and thickness) of the stiff top pavement layer are desired, inversion can possibly be avoided by using a simplified analysis in which the experimental surface-wave phase velocity is matched to the fundamental A0 Lamb-wave dispersion curve of a free plate (as well as segments of the S0 mode if detected), as described by Ryden et al. ([27,29]). If the experimental dispersion data can be measured to sufficiently high frequencies such that a horizontal asymptote is actually observed, then the Rayleigh-wave velocity of the pavement layer may simply be read as the asymptotic value of the dispersion curve.

For the bandwidth-limited MSOR tests in this study, a more general approach was taken in which a numerical model of the pavement, base, subbase, and soil layers was used in a multilayer inversion procedure to solve for the thickness and phase velocity of each layer. Because the solutions are non-unique, the inversion procedures employ optimization methods to minimize the misfit between the experimental dispersion curves and the theoretical dispersion curves of randomly generated multilayer models [30].