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Dynamic responses of asphalt concrete slab under cyclic wheel loading using acceleration spectrum analysis

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HIGHLIGHTS

- MMLS test and FE simulations were performed to investigate dynamic responses.
- The energy of vibration was greater when the wheels travel at higher speed.
- Vibration information can be utilized for irregularities detection.
- The energy of vibration was greater as the temperature increases.
- Thickness of slab significantly influenced the amplitude of vertical acceleration.

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ABSTRACT

The dynamic response of pavement, especially in term of vibration, provides information on pavement damage prediction, noise control and so forth. The vibration of pavement is also a potential energy which can be collected by energy harvester and utilized by sensing technology to obtain information of traffic and pavement conditions. In this research, both laboratory Model Mobile Load Simulator (MMLS) tests and Finite Element (FE) simulation were performed to assess the effects of several factors influencing the dynamic response of Hot Mix Asphalt (HMA) slabs that include material properties, wheel loading speed, top-down cracking and thickness of the slab. The parametric analysis was performed using the validated finite element model based on laboratory MMLS test results to investigate the effects of each parameter. Frequency spectrums of vertical acceleration for the HMA slabs under different loading scenarios were obtained through Fast Fourier Transform (FFT), and analyzed to help formulate recommendations for an actual pavement structure from dynamic responses in the field.

1. Background

As a major component of the transportation infrastructure system, pavements are constructed to provide a smooth riding surface and basic load-bearing capacity for vehicles to travel on. However, pavement surface may become deteriorated by environmental factors under cyclic traffic loading, thus unevenness caused from cracking, rutting and potholes is induced to the pavement surface. Due to this uneven surface and the moving vehicles which also act as the external force on the pavement structure, pavements are subject to dynamic periodic pulses from traffic. Under such periodic traffic pulses, pavement structure will vibrate accordingly, bringing influences to itself and its surroundings. For instance, the traffic-induced pavement and ground vibration may cause damage to pavement and even noises that disturb people living in the area; the vibration can also affect buildings and sensitive equipment located nearby. On the other hand, the vibration of pavement provides an energy which can be collected and utilized through embedding vibration-based harvesters into the pavement structure [1]. Moreover, current sensing technologies for traffic information collection and pavement distress detection also rely on different vibration patterns of pavements and vehicles [2,3]. Therefore, by detecting the acceleration of pavement under specific wheel loadings and analyzing the vibration modes, it is possible to distinguish between deteriorated or cracked pavement section from the intact ones.

The dynamic response of flexible or rigid pavement provides essential information to engineers because they are helpful in damage prediction [4]. With the increased computational capabil-

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ities, the dynamic Finite Element (FE) analysis of a pavement structure is a technique of considerable reduction in computation cost than before. The dynamic analyses considering the vibration of pavement structure under cyclic traffic loading are widely adopted by many studies for various research purposes. However, for pavement analysis the major applications are still distress-related performance predictions, such as predictions on strain at critical locations, or permanent deflections. A comprehensive literature review by Beskou and Theodorakopoulos [4] summarized that the existing studies (analytical or numerical) typically consider the pavements as beams or plates with linear elastic material behavior, subject to concentrated or distributed moving traffic loading. FE simulation is recommended to be the best method for solving such problem due to its efficiency, versatility and availability.

The factors that would influence the dynamic responses of asphalt concrete pavement under cyclic traffic loading are typically related with material properties, geometric properties of pavement, and the external excitation from vibration/traffic loading characteristics. Especially in front of not only the regional climate differences, but also the current global climate changes, the climate-related factors such as temperature-dependent material properties and top-down cracking, as well as their influences on pavement dynamic responses should be carefully considered. The frequently occurred top-down cracking in flexible pavements is reported to be closely related with the cyclic diurnal or annual changes of temperature [5], which also results in roughness of the pavement surface. Material-wise, it has been well established that the increasing in stiffness and damping factor of surface or base materials would reduce the vibration [6]. Saad et al. [8] investigated how the base and subgrade layers would influence on dynamic pavement responses by 3D FE analyses. There are also many studies providing different forms of pavement temperature adjustment factors to consider the influence of temperature on the pavement deflection in the past [7]. Saad et al. [8] investigated the effects of base and subgrade layers on dynamic pavement responses including rutting and fatigue cracking assessed by 3D FE analyses. The speed of vehicles which travel on pavement surface also has a significant effect on pavement dynamic responses [9,10]; the deflection of runway concrete slab is found to increase with an increasing airplane velocity [11]. Uddin et al. [12] investigated the influence of surface longitudinal cracks on the dynamic deflection of pavement using FE analysis. Dynamic pavement responses with different thicknesses of asphalt isolating layer within concrete pavement were investigated by Wu et al. [13]. The maximum center deflections were found to be decreasing with increasing slab thickness for airport concrete pavement by dynamic pavement analysis [11]. Parametric study was performed by Patil et al. [14] to investigate the influence of pavement thickness, and soil parameters on the dynamic response of pavement. The factors such as thickness and elastoplastic behavior of the pavement base and subgrade were investigated to reveal their influences on pavement dynamic performances.

The Model Mobile Load Simulator (MMLS) is a scaled down simulator for accelerated trafficking of model pavements. It is an effective tool capable of simulating the cyclic moving traffic loading on HMA slabs and evaluating the performance of the slabs under different temperature and loading conditions. This laboratory testing system has been successfully adopted to evaluate both structural and functional (polishing/wear) performance of specific asphalt concrete materials under repeated wheel loading [15]. In this research, in order to investigate the traffic-induced pavement vibrations influenced by several different factors, and to further investigate whether such vibration information could be utilized for pavement deterioration/cracking detection purposes, both laboratory test and FE analysis were performed. The frequency spectrum of an asphalt concrete slab under MMLS loading obtained under the laboratory test conditions was used to validate the simulation results and the FE model. The validated FE model was adopted for various simulations to provide additional information on dynamic pavement performance, which might prove costly via laboratory tests only.

2. Scope of study

In this study, both laboratory tests and numerical simulation were performed to investigate the effects of several critical factors on the dynamic response of HMA slabs. These factors included temperature-dependent material properties, wheel loading speed/excitation of vibration, and geometric properties such as thickness and discontinuities of the slab. HMA slabs Instrumented with a 3-axis accelerometer were tested under MMLS in the laboratory while the vertical accelerations of the slabs were measured and recorded to validate FE analysis model, and also to help formulate recommendations for a real pavement structure in dynamic responses.

Based on the laboratory-validated FE model, a finite element analysis considering different traffic, material, and pavement geometric conditions was also performed to determine the dynamic responses of HMA slabs subjected to cyclic wheel loadings. The parametric analysis conducted to evaluate the effects of these factors, has demonstrated the benefits of the FE simulation in saving large amount of laboratory efforts and time. The additional information about the HMA slab under dynamic wheel loading obtained from both the MMLS test and FE analysis was used to formulate recommendations for real-world pavement performance.

3. Laboratory MMLS test

In this study, laboratory tests using the third-scale model mobile load simulator (MMLS3) system were conducted to investigate the effects of temperature, material, and geometric properties on the vibration characteristics of HMA slabs. MMLS3 is a specially designed testing machine that can be utilized to assess the performance of scaled model pavement structures through mimicking full-size wheel loading condition in both laboratory and field. The MMLS3 has four 80 mm-width rubber tires mounted on 4 bogies, covering a loading area of 34.0 cm^2 during normal operation. The maximum tyre pressure is 800 kPa (about 115 psi) which provides maximum 2.7 kN of loads by self-adjusting springs. The testing wheel speed is adjustable from 0 to 2.5 m/s (about 0 to 5.5 mph) with a load application rate of 7200 per hour [16]. Square specimens were prepared to 1:3 scale of the real pavement in width and length for the MMLS3 testing. Temperature during testing was controlled constant using air flow through thermal ducts, and the Micro Electro-Mechanical Systems (MEMS) wireless accelerometer was mounted on the HMA slabs at 10 cm off the wheel path for acceleration measurements, as shown in Fig. 3. The MEMS accelerometer has a measurement range up to ±250 g for acceleration measurement, and the sampling rate was set up to be 64 Hz (one data point every 0.016 s) during the test. Fig. 1 illustrates the side view of the MMLS3 equipment and the base plate on which HMA slabs were mounted for testing.

Based on the findings that most of the vibration waves propagate near surface [17], only HMA surface layer is investigated in this research. The HMA slabs made from the typical surface layer mixture SM 9.5D was investigated in this study. During the MMLS test, The HMA slab was fixed inside the MMLS base frame which is mounted on in-situ concrete floor to resemble base/subbase stiffness, which results in test results comparable to the actual pavement structure. Therefore, it is assumed that the MMLS test and