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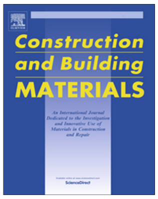

Dynamic simulation analysis of the tire-pavement system considering temperature fields

Ding Han [a,*], Guodong Zhu [b], Huimin Hu [a], Linglin Li [b]

[a] *School of Civil Engineering, Hefei University of Technology, Anhui, China*
[b] *School of Automobile and Transportation Engineering, Hefei University of Technology, Anhui, China*

HIGHLIGHTS

- A viscoelastic model considering temperature dependence was proposed and verified.
- A tire-pavement coupling system was founded to analyze tire footprints.
- Dynamic analyses of asphalt pavement were implemented with vehicle braking.

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ABSTRACT

In order to analyze tire footprints in different conditions and calculate dynamic responses of asphalt pavement with vehicle braking, a tire-pavement coupling simulation system, which can use a viscoelastic constitutive model of asphalt concrete considering temperature dependence, is established. The user subroutine of the material model was programmed by the FORTRAN language, and viscoelastic parameters of the material model were recognized based on dynamic strain data of dynamic impact tests, whose validity was verified by using test data in the literature. The tire-pavement coupling simulation system was established to analyze tire footprints in static and dynamic conditions at different temperatures of asphalt concrete layer, whose calculation accuracy of the numerical simulation was verified. Based on measured temperature data at different depths of an actual pavement structure and the corresponding simulation model, thermal parameters of each layer in the pavement structure were recognized. Field distributions of the viscoelastic parameters in the asphalt concrete layer of the coupling simulation system were obtained by using the heat transfer analysis and the user subroutine. Average braking decelerations of trucks at a chosen intersection were calculated according to the investigation data. Based on the tire-pavement coupling simulation system, peak values of dynamic shear strain in the asphalt concrete layer at the intersection were calculated, which considered the coupling effect between axle loads and temperature fields.

1. Introduction

Asphalt concrete is one of predominant materials for building pavement structures. Material properties, vehicle loads and climate characteristics are important factors to influence dynamic responses of asphalt pavement.

Different constitutive equations have been proposed to describe the temperature dependence of asphalt concrete. A nonlinear viscoelastic model based on the Schapery's nonlinear viscoelastic model was proposed by Darabi et al. [1], which can simulate the temperature-dependent response of asphalt concrete. Costanzi et al. [2] presented a mathematical model considering temperature dependency for the viscoelastic behavior of idealized bituminous mixtures, which can be represented as a special nonlinear form of the Burgers model. The generalized modified Kuhn model was proposed for asphalt concrete, whose temperature effect was considered using time-temperature superposition principle [3]. Nivedya et al. [4] proposed the viscoelastic fluid model and viscoelastic solid model to predict the mechanical response of asphalt mixture at different temperatures. Zhu et al. [5] proposed a two-stage viscoelastic-viscoplastic damage constitutive model for predicting the mechanical response of asphalt mixture at high temperatures, where the generalized Maxwell model was adopted as the viscoelastic component.

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[*] Corresponding author.
E-mail address: handing@hfut.edu.cn (D. Han).

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The viscoelastic constitutive equations are commonly used in the dynamic analysis of asphalt pavement. Varma et al. [6] developed a computationally efficient model to analyze flexible pavements, which considered the top layer of linear viscoelastic asphalt concrete. A new asphalt pavement dynamic model was established by Dong et al. [7], where the material of asphalt concrete was visco-elastic which was simulated with 3D constitutive relations. Xu et al. [8] evaluated the effects of static versus viscoelastic wave propagation simulation approaches on pavement responses using finite element method, where the generalized Maxwell model was used to describe the viscoelastic behaviour of the HMA material. Coleri et al. [9] built full-scale micromechanical finite element models of asphalt concrete samples that were sawn from the accelerated pavement test sections to evaluate the accuracy of layered elastic theory, where the generalized Maxwell-type viscoelastic model was used for asphalt concrete. Khavassefat et al. [10] studied the non-stationary response of flexible pavements to moving loads, and the viscoelastic behaviour of asphalt layer was modelled with Prony series. In order to study the structure-induced rolling resistance of pavements, Shakiba [11] built a 3D five-layer pavement structure considering viscoelastic behaviour of asphalt concrete layers. Ulloa et al. [12] presented a predominant frequency to predict critical pavement responses in asphalt layers by analyzing 3D-Move Pavement Responses, where the asphalt layer was treated as a viscoelastic material.

The tire-pavement interaction can influence the contact stress distributions between tires and pavement, which have significant effects on dynamic responses of asphalt pavement. Shakiba [13] used Nonlinear Damage Approach (PANDA) user interface to incorporate realistic tire-pavement interface contact areas and stresses into the pavement analysis and confirm the importance of considering realistic three dimensional contact stresses to design and analyse pavements. Li et al. [14] analyzed the viscoelastic response of the instrumented asphalt pavement with a 3D FE model, where the tire-pavement contact model was fitted from the measured data. Al-Qadi et al. [15] used a 3D FE approach to simulate pavement responses to a moving load, and all transverse and longitudinal stresses induced by a rolling tire were discretized into tangential forces according to the contact area of each individual tire rib. Khavassefat et al. [16] developed a numerical framework for quantifying the dynamic response of the viscoelastic flexible pavement to moving loads, where a quarter car model combined with measured road profiles was used. Sarkar [17] analyzed the pavement structural responses under different axle configurations using the 3D FEM, where the approximate contact area of the tire-pavement interaction was simplified as a combination of two semicircles and a rectangle. Wang et al. [18] developed a 3D tire-pavement interaction model to predict the contact stress distributions at static and various rolling conditions, whose results showed that tire braking induced significant longitudinal contact stresses. A 3D finite-element model was proposed to simulate the distribution of contact stresses, which considered different loading levels and conditions of tires, including standstill, free rolling, accelerating rolling, and decelerating rolling conditions [19]. Park et al. [20] established a two-dimensional half-truck finite element model to investigated the effects of vehicle operation properties on vehicle dynamic loads.

As different temperatures can change material properties of asphalt concrete, it is important to analyze temperature changes of asphalt pavement. Arraigada et al. [21] conducted accelerated pavement testing to measure the structural response of asphalt pavement with different loading conditions and temperatures, whose results showed that strain amplitudes of pavement grew with the increase of temperature. Chupin et al. [22] presented a method to derive the structure-induced rolling resistance (SRR) for a vehicle driving along a flat asphalt pavement, and the SRR of asphalt pavements increased with temperature. FE models were developed to simulate flexible pavement behaviour under impulsive FWD loading, which considered temperature gradient, and the result showed that the effect of temperature gradient on tensile strains became more significant at the high temperature case [23]. Wang et al. [24] developed FE model to simulate the pavement responses caused by impulsive dynamic loading and moving vehicular loading, where the temperature profile was used in asphalt layer. A rutting model for asphalt pavement was proposed by Kim et al. [25], which considered pavement temperature.

A dynamic impact test is established in this paper, which can approximately simulate the pressure on the pavement surface induced by truck wheel loads. Based on test data of the dynamic impact test, parameters of the three-dimensional dynamic viscoelastic model were recognized and their validities were subsequently verified. The tire-pavement coupling simulation system was developed, which was consisted of the pavement structure and the full-scale model of radial truck tires with wheel loads. Based on the viscoelastic material properties of asphalt concrete considering temperature dependence and different temperatures of the asphalt concrete layer, tire footprints in static and dynamic conditions and dynamic shear strain of the asphalt concrete layer at the intersection were respectively analyzed. The work can implement the dynamic analysis of asphalt pavement take into account the coupling effect of material properties of asphalt concrete, vehicle loads and climate characteristics.

2. Viscoelastic constitutive model of asphalt concrete considering temperature dependence

Asphalt concrete is a temperature-dependent viscoelastic material. Based on dynamic impact test data of asphalt concrete at different temperatures, a material model using the dynamic viscoelastic constitutive equations, which considered temperature dependence for asphalt concrete, was derived, while a user subroutine to describe dynamic behaviors of the material model was compiled by the FORTRAN language and subsequently verified.

2.1. Dynamic impact tests at different temperatures

The loading system of dynamic impact tests includes a specimen, a drop hammer, a slide bar, a lock lever, a rubber gasket and a bearing plate. The diameter of the steel-made bearing plate placed on the top surface of the specimen is 0.3 m. The bearing plate is impacted by dropping the hammer whose weight and falling height are respectively 10 kg and 0.85 m, then axial deformations of the specimen occur. Dynamic strain data at measuring positions of the specimen were collected by the dynamic strain indicator *INV1861* and related software *DASP-V10*, whose sampling frequency was 48 K.

The impact load $F(t)$, which is induced by the drop hammer, can be approximately expressed by a haversine formula as Eq. (1).

$$F(t) = A\sin(\omega t) \quad 0 \leqslant t \leqslant T/2 \tag{1}$$

where A is an undetermined constant; $\omega = 2\pi/T$, T is the period of the impact load; t is the time variable.

Eq. (2) is obtained based on the impulse theorem. By substituting Eq. (2) into Eq. (1), the calculation formula of A is obtained as Eq. (3).

$$I = mv = m\sqrt{2gh} = \int_0^{t_1} F(t)dt \tag{2}$$

$$A = \frac{m\omega\sqrt{2gh}}{1-\cos(\omega t_1)} \tag{3}$$