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Steady-state dynamic method: An efficient and effective way to predict dynamic modulus of asphalt concrete

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HIGHLIGHTS

- Transient and steady-state dynamic methods were used to obtain asphalt concrete E^*.
- The steady-state dynamic method is more efficient in calculating asphalt concrete E^*.
- The steady-state dynamic method is proved effective to predict asphalt concrete E^*.

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ABSTRACT

This study presents two meso-mechanical methods of analyzing the asphalt concrete's dynamic modulus, including the transient dynamic method (implicit dynamic method) based on the modified Newmark numerical differential algorithm and the steady-state dynamic method based on the perturbation theory. The results indicate that compared to the transient dynamic method based on the modified Newmark numerical differential algorithm, the steady-state dynamic method based on the perturbation theory is much more efficient in calculating dynamic modulus of asphalt concrete while maintaining similar accuracy. Furthermore, the random aggregate model of asphalt concrete coupled with the steady-state dynamic method is also employed to obtain the asphalt concrete's dynamic modulus. The numerical solution was found in a good agreement with the corresponding experiment results, which indicates the proposed steady-state dynamic method an efficient and effective way to predict the dynamic modulus of asphalt concrete.

1. Introduction

Asphalt layers on asphalt pavements sustain traffic loading and various environmental conditions. The serviceability of asphalt pavements is highly related to the properties of asphalt concrete. Therefore, a better understanding of asphalt concrete properties is essential to the evaluation of pavement performance. Asphalt concrete, characterized as elastic-visco-plastic materials, has creep and relaxation behavior under the static and dynamic loading from vehicles and natural environments [1–4]. The response of asphalt concrete is highly dependent on the loading frequencies and temperature. Thus dynamic modulus was introduced to describe the dynamic properties of the asphalt and asphalt concrete [5,6]. The dynamic modulus is defined as the ratio between the stress amplitude and strain amplitude when the material is undertaking the dynamic loading. It is well acknowledged that the dynamic modulus of asphalt concrete is a reliable parameter to investigate the dynamic response of asphalt pavements [7].

Numerous studies have been conducted on predicting and evaluating dynamic modulus of asphalt concrete based on the inclusion theory in composite material mechanics. Hirsh and Zimmerman [8–10] are the pioneers to research the mechanics characteristics of concrete material based on meso-mechanics of composite materials. Hirsh proposed an empirical model to predict the modulus of material, especially for cement concrete material. Christensen et al. [11] modified the Hirsh's model and considered the aggregate gradation in the calculation of dynamic modulus of asphalt concrete material. Buttlar et al. [12,13] and Lytton [14] also proposed meso-mechanical models to evaluate the dynamic modulus of asphalt concrete based on its in-situ performances and dynamic response data. It is noteworthy that Buttlar's and Lytton's models were still semi-empirical and semi-theoretical models. Li et al. [15] and Li and Metcalf [16] developed a classic analytical

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model based on Hashion's multi-layer inclusion model, which was initially developed to investigate the relationship between macro-mechanical properties and micro-structure of composite materials [17]. They also integrated the difference method from composite meso-mechanics into the model to consider aggregate gradation. Li and Li's studies made the multi-layer inclusion theory a powerful tool of predicting the dynamic modulus of asphalt concrete. The traditional generalized self-consistent theory assumes the inclusion is set in an infinite matrix region [18,19]. The key point for Hashion's model is that the infinite matrix region around the inclusion medium has been altered from case to case. Christensen and Lo [20] modified Hashion's model in which the tension and compression effects are considered while the shear effect is ignored. Other analytical models were developed, such as Huang and Shu [21–23], Zhu [24,25]. The three-layer model shown in Fig. 1 is the widely used multi-layer model for predicting the dynamic modulus of asphalt concrete. This model can reasonably predict the dynamic modulus of asphalt concrete. However, all these models mentioned above are based on the assumption that aggregates have regular shapes, such as circle, cylinder, or sphere, corresponding to plane strain condition, cylindrical coordinate condition and spherical condition respectively. This simplification does not always conform to reality.

When irregular shapes of aggregates are considered, it is difficult to obtain the analytical solutions of asphalt concrete's dynamic modulus. Instead, numerical methods have advantages in calculating the dynamic modulus of asphalt concrete with irregular-shaped aggregates. Numerical simulation is an innovative way to study the mechanical characteristics of asphalt concrete in meso-view. Conventionally, dynamic modulus is merely an input in numerical simulation procedure. However, when the structure form of asphalt concrete is examined in meso-view, it can be found that asphalt concrete is made of aggregates, mastic, voids, and interface between the mastic and aggregates. Thanks to the development of computational mechanics and computer science, the discrete element method (DEM) has been widely used to simulate the dynamic behavior of asphalt concrete [26–29]. Due to the numerical integration algorithm of the central difference numerical method which inherited from DEM [30], the initial investigations using finite element method for simulating the dynamic modulus of asphalt concrete is with respect to the same central difference numerical method [31]. This numerical method is conditionally convergent. The time increment step should typically be small enough to avoid wave passing through a single time increment step. In order to obtain the steady solution for dynamic modulus of asphalt concrete, a huge amount of calculation costs will be consumed. The computational costs will dramatically increase with the decrease of loading frequencies. To overcome the low computational efficiency, Masad and Somadevan [32] proposed a modified implicit Newmark numerical difference algorithm, which can employ a larger increment step in numerical simulation. However, there is no study found using this numerical difference method to simulate the dynamic modulus of asphalt concrete. So far, it is still a challenging task to simulate dynamic modulus of asphalt concrete accurately and efficiently.

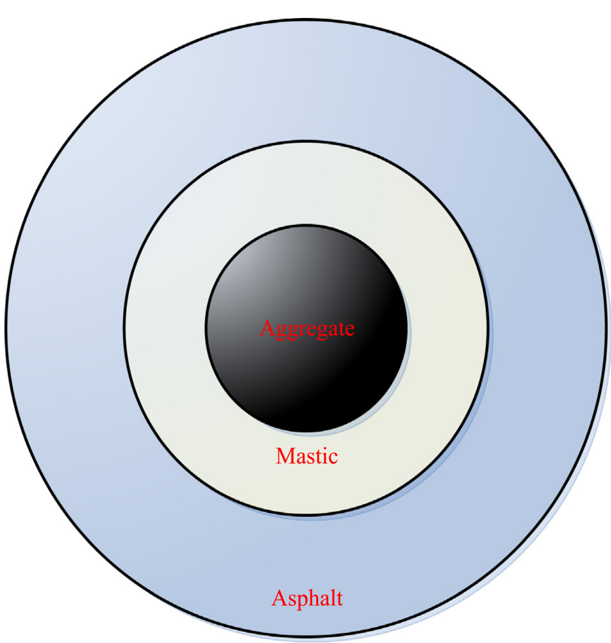

Fig. 1. The 2-dimensional physics structure of GSC method.

2. Definition of dynamic modulus

Asphalt concrete is a typical visco-elastic material on asphalt pavement. When the environmental temperature is under the glass transition temperature, the asphalt and asphalt concrete material behaves elastically just like Portland cement concrete. When the temperature rises above the rubber transition temperature, the visco-plastic behavior plays a leading role in characterizing the constitutive behavior of asphalt and asphalt concrete. In practice, the visco-elastic constitutive model is commonly used in the ambient temperature. Therefore, the stress–strain curve is usually different from traditional elastic curves due to the time-dependent properties.

For asphalt concrete, dynamic modulus is suitable to accurately characterize its visco-elastic behavior. The visco-elastic behavior can be mathematically simplified with a series of mechanical components such as spring, dashpot, and so on. Based on the Kelvin model (Fig. 2), the dynamic modulus definition is introduced as follows. When the Kelvin material is under the simple harmonic loading (Fig. 3), its stress response is decomposed into the real part and imaginary part using the Euler formation:

$$\sigma = \sigma_0 \cos(\omega t) + i\sigma_0 \sin(\omega t) = \sigma_0 e^{i\omega t} \tag{1}$$

where σ_0, ω and f are the stress amplitude, circular frequency and loading frequency, respectively. The units are MPa, rad/s and Hz, respectively.

When the material is under the sinusoidal forced vibration, the initial dynamic excitation due to the transient loading will be eliminated by the viscosity from the material and air. When the sinusoidal forced loading has continued for an extended period, the material will enter the steady-loading status, and the steady dynamic response of the material will manifest the period behavior with the inertia effort dissipation. The steady-status dynamic equation is written as:

$$\lambda_1 \frac{\partial \varepsilon}{\partial t} + E_1 \varepsilon = \sigma_0 \exp(i\omega t) \tag{2}$$

And the solution is written as follows:

$$\varepsilon(t) = \varepsilon_0 \exp i(\omega t - \phi) \tag{3}$$

where ε_0 is the magnitude of the harmonic strain, ϕ is the phase angle between the strain and stress.

Substitute Eq. (3) into Eq. (2) and get

$$i\lambda_1 \varepsilon_0 \omega \exp i(\omega t - \phi) + E_1 \varepsilon_0 \exp i(\omega t - \phi) = \sigma_0 \exp i\omega t \tag{4}$$

Then Eq. (4) can be written as follows based on the equivalence of the real part and imaginary part: