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Impact of aggregate packing on dynamic modulus of hot mix asphalt mixtures using three-dimensional discrete element method

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ABSTRACT

Aggregates are the major component of hot mix asphalt (HMA) mixtures. The properties of aggregates and the way of aggregate packing have important influence on the performance of HMA mixtures. Because the dynamic modulus is considered as the most important HMA property influencing the field fatigue and rutting performance of a flexible pavement and are used in the mechanistic-empirical pavement design guide for determining the stress–strain responses of the pavements, a study of the impact of aggregate packing on dynamic modulus will provide insight on the HMA mix design and the material performance evaluation. This paper studies the effect of aggregate size distribution and angularity distribution on dynamic modulus using a 3D discrete element method (DEM). Angular particles are generated using an image-based ball-clumping approach which requires significantly reduced number of balls and is capable of capturing the particle shape and angularity effect. These particles are assigned to the DEM dynamic modulus specimen based on the angularity distributions of the actual experimental specimen. A 3D DEM dynamic modulus model is thus established and calibrated using experimental data. This calibrated model is further used to evaluate how the different aggregate packing due to the change of the proportions of aggregate particles and the change of aggregate angularities can result in the change of dynamic modulus.

1. Introduction

Pavement design is now moving toward more mechanistic based design methodologies for the purpose of producing long lasting and high performance pavements in a cost-effective manner. The recent mechanistic-empirical pavement design guide (MEPDG), introduced by the NCHRP 1-37A project, is a product under such direction and is making progress in improving current design methods. Dynamic modulus (E^*) is proposed by the MEPDG as an important material characterization property and a key input parameter which determines the stress and strain responses in hot mix asphalt (HMA) pavements, and correlates the time–temperature dependant properties of asphalt mixtures to field fatigue cracking and rutting performance [1]. Gabriel and Thompson [2] pointed out that dynamic modulus is the most important hot mix asphalt (HMA) property influencing the structural response of a flexible pavement.

The dynamic modulus of asphalt mixtures is based upon the properties of individual constituents including asphalt and aggregates and the physicochemical interactions between the two. Particularly, because aggregates are the major component and occupy 85% by volume and 95% by weight in typical dense-graded HMA mixtures [3], the properties of aggregates and the way they are packed play a significant role in determining the dynamic modulus of asphalt mixtures.

However, the effect of aggregates on dynamic modulus is also less understood due to the complexity of the aggregate structure. The properties of aggregates (shape, angularity, surface texture) and the nature of aggregate packing as a whole can all influence dynamic modulus. Therefore, it is the objective of this paper to investigate how the specific packing characteristics of aggregates including gradations, aggregate shape and angularities are influencing the dynamic modulus. A comprehensive evaluation of the impact of aggregate packing on dynamic modulus will be beneficial for:

- Developing or improving dynamic modulus prediction models to be used in the Level II and III MEPDG analysis for a better pavement performance prediction.
- Helping the designer to realize cost-effective asphalt mixtures with maximized usage of local materials and optimized binder content through a balanced aggregate structure design.
- Assisting with the pavement structural design by providing insight to optimizing the dynamic modulus based on local materials and specific loading and temperature conditions.

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2. Background

There are mainly three approaches to determine dynamic modulus of an HMA mixture, by experimental testing [4], by empirical regression equations [5,6], or by combined experiments and numerical simulations [7,8]. Experimental testing is the most straightforward method which gives the dynamic modulus properties of a specific mixture over a wide temperature–frequency domain with reasonable accuracy. It is yet a costly and time-consuming method which cannot provide a full assessment of the effect of individual material properties on dynamic modulus. The availability of experimental equipments can also limit the possibility of obtaining direct dynamic modulus testing results. Existing regression equations [5,6] have related some material properties to the dynamic modulus. However, due to the limitation of the regression equations which have to be based on a large representative database, current prediction equations did not clarify how the aggregate packing can affect the dynamic modulus. They mainly focus on the impact from a few sieve sizes while not considering the shape and angularity impact, both of which have been found to play significant roles in achieving a stable aggregate structure [9]. Numerical simulations, when calibrated by experimental results, are found to be promising, especially for assessing the impact of individual properties on dynamic modulus. Buttlar and Roque [10] proposed that micromechanical models can be used to predict the viscoelastic properties of asphalt mixtures. Uddin [11] studied the creep compliance of asphalt mixtures considering both the viscoelastic properties of asphalt binder and the elastic properties of aggregates. Zhu and Nodes [12] studied 2-D normal force–displacement compliance relation based on an elastic or visco-elastic binder, and the effects of aggregate angularity is incorporated in the stress–strain relations. The results showed that a higher degree of aggregate angularity results in higher structural stiffness.

Discrete element method is one type of numerical simulation method which allows the finite displacement and rotation of discrete particles, making it an excellent tool to simulate the complex micro interactions between aggregate particles within an asphalt mixture [8]. A number of studies have been conducted in the field of asphalt material using the DEM approach. Zeghal [13] presented the results of numerical simulations to characterize the resilient modulus of aggregate base/subbase materials. Lowery and Zeghal [14] applied the DEM approach to study the effects of particle stiffness on the resilient behavior of asphalt mixtures. The result indicated a linear increase of resilient modulus with the increase in particle stiffness. Li and Metcalf [15] proposed a two-step approach to predict the resilient modulus of HMA mixtures, in which the asphalt mixture is represented by a large spherical aggregate particle surrounded by a spherical shell of fine aggregate-filler-binder mixture. You and Buttlar [16] simulated the resilient modulus behavior under indirect tensile loading mode using X-ray tomography and two-dimensional DEM. Spherical balls are clumped together to represent the aggregate and asphalt components obtained from an X-ray image analysis. Chang [17] used the normal contact law to simulate the elastic moduli of granular material with anisotropic random packing structure. Huang et al. [9] applied an image based DEM approach to simulate the effect of particle size, shape, and angularity on the stability of railroad ballast. An aggregate library consisting of particles with specific angularity index (AI) and flat and elongated (F&E) ratio is generated for the simulation. Hossain [18] analyzed the angular ballast breakage behavior under cyclic loading. In this study, an assembly of ballast particles with irregular shapes was considered and the angularity of the particles was modeled in two dimensions by clumping two to nine circular particles together to form single particles of twelve different sizes, as illustrated in Fig. 1. Contact normal stiffness (*kn*) of the disks was set to 5.10E9 N/m, and the contact shear stiffness (*ks*) was set to half of the contact normal stiffness because results are not affected significantly by different ratios of *kn*/*ks*. Matsushima and Saomoto [19] simulated the angularity of aggregates using clump of balls as shown in Fig. 2. The irregular shape of the sand was represented by a set of overlapping circles in 2-D analysis. Their procedures were validated using biaxial simulations and the result indicated higher shear strength for angular particles than circular particles.

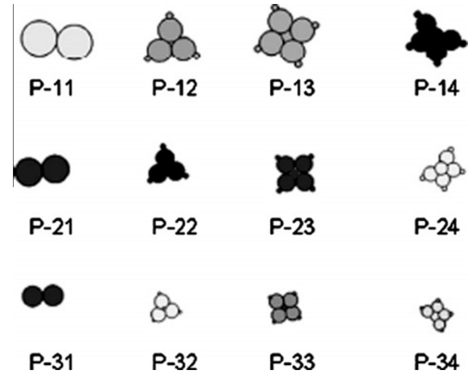

Fig. 1. Angularity of the particles model [18].

In summary, DEM is found to be an effective tool for evaluating the properties of a particulate media like asphalt mixtures and will be applied in this paper to identify the effect of aggregate packing on dynamic modulus. In particular, this paper will extend the 2-D analysis to 3-D analysis using clump of balls in PFC^{3D} program to take into account the effect of aggregate shape and angularity on packing and dynamic modulus.

3. Experimental program

An experimental program was developed to evaluate the effect of aggregate properties on dynamic modulus and validate and calibrate the DEM model. The dynamic modulus test was conducted according to AASHTO TP79-09 [20]. The specimens were compacted with a Superpave gyratory compactor into 150 mm in diameter and approximately 170 mm in height. Then specimens were cored from the center into 100 mm in diameter, and approximately 10 mm were sawed from each end of the test specimen. The bulk specific gravities and air void contents for each test specimen were measured before and after the specimen was cored and cut, prior to dynamic modulus testing. Testing was conducted at four temperatures (40, 70, 100 and 130 °F) and six frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz.).

Four mixtures were included in this testing program. As shown in Table 1, mix C-1 is the base mixture whose mix design has been conducted following the Superpave mix design specification [21] and the Washington State DOT mix design specification [22]. Based on mix C-1, mixes C-2, C-3, and C-4 were developed by varying gradations at three sieve sizes, 9.5 mm, 4.75 mm, and 2.36 mm, highlighted as bold values in Table 1. All four mixes used the same type of aggregates and asphalt binder, and the same asphalt content, 6.2%, which is the optimum asphalt content for mix C-1. For each mixture/gradation, two replicative specimens were prepared and tested for volumetric properties and dynamic modulus.

4. Numerical analysis

This paper applies the *Particle Flow Code in Three Dimensions* (*PFC^{3D}*) commercial DEM program from Itasca Consulting Group, Inc. [23] to conduct dynamic modulus simulation. PFC^{3D} is classified as a *discrete element* code based on the definition in the review by Cundall and Hart [24]. Since it allows finite displacements and rotations of discrete bodies including complete detachment, and recognizes new contacts automatically as the calculation progress, PFC^{3D} has been viewed as a simplified implementation of the DEM because of the restriction to rigid spherical particles. PFC^{3D} uses balls to effectively represent the aggregates with physical