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Modelling and evaluation of aggregate morphology on asphalt compression behavior

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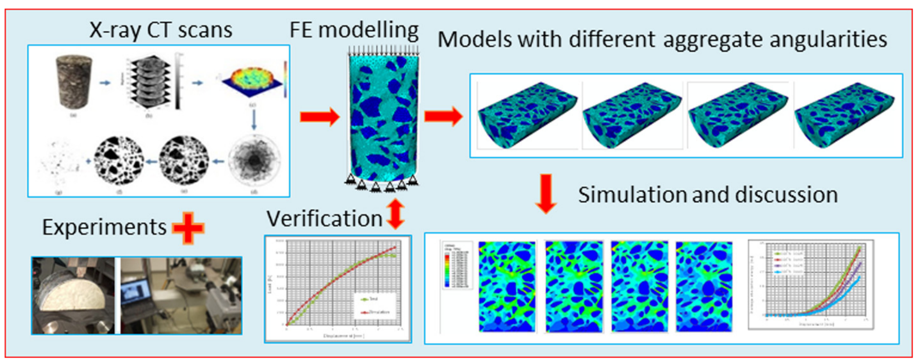
HIGHLIGHTS

- FE models with different aggregate angularities are created.
- Adhesive fracture at mastic-aggregate interfaces is simulated well by surface-based cohesive behavior.
- Relationships between aggregate angularity and the mechanical responses are derived.

GRAPHICAL ABSTRACT



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ABSTRACT

Asphalt mixtures are widely used in the construction of high-grade highways and airport pavements. With regard to numerical simulations it was considered as homogeneous due to limitations of low computational capacity. In fact, it is a typical heterogeneous composite material consisting of aggregate with irregular shape and random distribution, asphalt binder and air voids. The heterogeneous numerical model is more consistent with reality and thus yields more reliable results. Experimental investigations have implied that morphological properties of aggregate have a great impact on the performance of asphalt mixtures. Unfortunately, it is extremely difficult to suppress the interferences from other features of the asphalt mixture in experiments, such as aggregate orientations, the spatial distribution of aggregates and air voids. In this study, the microstructural model of asphalt mixture used for uniaxial compression test was reconstructed based on X-ray CT scans, thus maintaining the original morphology of the aggregate. Then the angularity of the aggregate was decreased artificially while the other features of the asphalt mixture remained constant. Based on these microstructures three dimensional finite element models with different aggregate angularities were created followed by a simulation of a uniaxial compression test. The relationship between aggregate angularity and mechanical responses of the asphalt mixture, such as load-carrying capacity, creep deformation of the asphalt mastic, damage behavior and energy dissipation were investigated. The computational results indicate that the aggregate angularity significantly affects the mechanical

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responses of the asphalt mixture; some initial relationships were set up with high degrees of determination. The quantitative correlation is suggested to be analyzed based on extensive experimental and numerical studies in future research.

1. Introduction

1.1. Background

Asphalt mixtures are widely used in the constructions of high-grade highways and airport pavements due to major advantages, including low noise emissions, high strength, easy construction and maintenance. In order to improve the design, construction and maintenance of asphalt pavement, numerical simulations have been made use of increasingly when investigating the mechanical performance of asphalt mixtures [1]. In early stages, the asphalt mixture was considered as homogeneous due to the limitation of low computational capacity. However, it is a typical heterogeneous composite material consisting of aggregate with an irregular shape and random distribution, asphalt binder and air voids at the micro-scale [2–4]. During the last two decades numerous research projects have been carried out to reconstruct the internal structure of the asphalt mixture at the microscale for numerical simulation. Two popular types of heterogeneous models, an image based model and a computer generated model, were developed to explicitly model the different material phases [5]. Compared to the homogeneous model, the heterogeneous model is more consistent with the reality and thus yields more reliable results [5].

In the image based model, an X-ray computed tomography (X-ray CT) scanner or high-resolution camera is used to capture cross sectional or surface images of the asphalt mixture; then the images are transferred into a geometrical model involving numerical aggregate, asphalt mastic and air voids with the help of digital image processing (DIP) techniques [5,6]. This method was initially used to simulate indirect tensile test of asphalt mixture in two dimensions (2D) combined with the discrete element (DE) method by Buttlar and You [7] in the early 2000s. In the same year, Masad et al. reconstructed a 2D finite element (FE) model for asphalt mixture to analyse its strain distribution [8]. With the development of DIP techniques, three dimensional (3D) numerical models based on X-ray CT imagines were reported. Wang [9] reconstructed a 3D FE model by stacking slices of 2D numerical models to investigate the stress distributions and stress concentration factor. You et al. [10] reconstructed 2D and 3D DE models for dynamic modulus tests and compared the results from both models. In their study, only two phases (aggregate and asphalt mastic) were detected by the X-ray CT images and reconstructed in the original numerical model. In the following year You et al. [11] reported that three phases (aggregate, asphalt mastic, and air voids) could be identified and reconstructed in the similar models proposed by them in the former study. Recently, a 3D FE model was developed by Hu et al. [12] to determine the effect of different types of aggregates on the internal structure in the asphalt mixture. Binary images of real microstructures were obtained by applying the Otsu thresholding method, to efficiently and precisely identify the different phases in the asphalt mixture [12,13].

Although the image based model provides an effective way to characterise the internal microstructure of the asphalt mixture, the laboratory dependency is a major limitation considering that it is time-consuming and very expensive to prepare specimens and then to process the scanned images [6]. Besides, this method is not able to provide an absolute virtual environment for a simulation without preparing physical specimens. Furthermore, it may not be suitable to analyse the sensitivity of factors which are not possible to be exactly controlled in the scope of the specimen preparation process, such as aggregate orientations and spatial distribution of aggregates and air voids [14].

Differing from the image based model, the computer generated model constructs the asphalt mixture by generating numerical aggregates, as well as air voids which are placed in the asphalt mastic [1]. In the early stages, idealized aggregate models, such as circles and ellipses for 2D modelling and spheres and ellipsoids for 3D modelling, were widely used. Kristiansen et al. [15] used random ellipses to evaluate mechanical properties of concrete. Subsequently aggregate models with ordinary or special angularities were proposed to improve the description of the morphological characterization of the aggregate. Kim et al. [16,17] developed a generator to reconstruct an asphalt mixture for FE modelling using aggregate models with predefined morphological properties. Recently, the method yielded realistic aggregate models; first the geometries of real aggregates need to be acquired by means of X-ray CT images which are stored and reused to reconstruct the asphalt mixture composed of numerical aggregates with a realistic aggregate morphology [18–20].

1.2. Motivation and objective

The conversion from the image based model to the computer generated model, the aggregate morphology is simplified significantly in the early stages. With the development of the computer generated model, the aggregate morphology has become increasingly complex and realistic. Experimental investigations have implied that morphological aggregate properties have a great impact on the performance of asphalt mixtures, such as load-carrying capacity, skid-resistance and rutting resistance [21–24]. Several numerical simulations also suggested that the geometry and distribution of aggregates have a great influence on the computational results of asphalt mixtures [25–27]. However, few numerical simulations have been conducted on the influence of aggregates with a pre-defined morphology on the mechanistic performance or damage behavior of asphalt mixture, especially in the 3D case. If the influence of the aggregate morphology is to be determined quantitatively, the computer generated model with a rather simplified aggregate morphology is of great practical use in engineering applications due to its much lower requirement of computational resources and a decreased computational time. In another word, if the behavior of different aggregate shapes is known, the mechanistic performance of asphalt mixtures can be simulated with simpler aggregate models more effectively due to computational reasons and afterwards the prediction can be referred to more complex aggregate shapes.

The objective of this study is to investigate the effect of aggregate morphology (focus on aggregate angularity) on the mechanical response and damage behavior of the asphalt mixture. A viscoelastic constitutive model was determined by means of the dynamic modulus test and the adhesive fracture behavior was determined by three-point semi-cylinder bending test to obtain the required material parameters for the numerical simulation. The X-ray CT tomographic data of the asphalt mixture was processed by self-developed codes, and a triangular element model of aggregates was developed from binary images. Thereafter the