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3D numerical model to investigate the rheological properties of basalt fiber reinforced asphalt-like materials

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ABSTRACT

This paper presents a new three-dimensional (3D) numerical model to investigate the viscoelastic response and reinforcement mechanism of asphalt-like materials, including asphalt mastic and mortar mixed with basalt fibers at high temperature. For the 3D numerical model, basalt fiber reinforced asphalt-like materials (BFRA) are assumed to consist of two components: the homogeneous asphalt-like matrix with the Burgers viscoelastic model and the basalt fibers with the elastic model. The straight round basalt fibers are considered to be dispersed to random locations and orientations in the matrix, and a 3D algorithm is introduced to generate the numerical model in MATLAB software. The numerical model is then employed in a series simulations of the shear rheological and uniaxial compressive tests in ABAQUS software to study the rheological behavior and reinforcement effect of different fiber contents under constant loading. Results indicate that the rheological behaviors of the BFRA numerical model are in excellent agreement with the test results, and the reinforcement effect increases with the fiber contents within a certain range. Further numerical simulations are performed to analyze the effect of fiber aspect ratios, L_D. Simulated results show that the decrease of L_D has a positive effect on rheological behavior under a constant fiber diameter.

1. Introduction

The behavior of asphalt concrete composite materials can be significantly improved by adding fiber reinforcement [1]. Fibers are extensively applied in construction and building materials, including mineral, carbon, steel, glass, and synthetic fibers [2–4,17–20]. Basalt fiber is one of the four major high-tech fibers used in China [7]. It has a reinforcing role and greatly enhances the properties of composite materials. The properties include natural compatibility, superior mechanical performance, stable chemical characteristics, and outstanding high temperature performance [5,6].

The application of basalt fiber in asphalt concrete has triggered significant research interest. The effect of basalt fiber on the performance improvement of asphalt mixtures has been investigated in previous studies. Xu et al. [8] investigated the performance and mechanical properties of basalt fiber-reinforced asphalt concrete and found that the fiber has a positive effect on the performance of asphalt mixture in terms of high temperature deformation resistance, low temperature cracking resistance, and fatigue behavior. Gao [9] also showed that basalt fiber could improve the low-temperature damage strength and failure strain and reduce the failure stiffness for asphalt concrete; in particular, the maximum failure strain increased by 43.72%, the maximum failure stiffness was reduced by 25.86%, and the low-temperature cracking resistance of asphalt concrete was significantly enhanced. Furthermore, Morova [10] investigated the usability of basalt fibers in hot mix asphalt (HMA) concrete using the Marshall stability test and obtained the optimum fiber content, which indicated that the addition of basalt fiber to the hot-mix asphalt concrete had a positive effect on stability.

The performance of asphalt concrete as a composite material is largely dependent on its components. In particular, binding materials (including asphalt binder, asphalt mastic, and asphalt mortar at nanoscale, microscale, and mesoscale, respectively) play an important role [11]. Research on the stabilizing and reinforcing effects of different fibers on the performance of components in an asphalt mixture has become an issue [12–14]. Asphalt mastic and mortar as asphalt-like materials belong to a level below fiber asphalt concrete. Asphalt mastic, which consists of asphalt binder and filler, and asphalt mortar, which is composed of asphalt mastic and fine aggregate, exhibit a complex thermo–rheological behavior that affects the high-temperature stability of asphalt concrete.

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Adding fiber to asphalt mastic and mortar can improve the advantages of the asphalt-like material and fiber, particularly the stability, reinforcement, crack resistance, and toughening effects of the fiber. Gu and Wang [15,16] indicated that the basalt fiber utilized in asphalt mastic exhibits excellent performance in terms of strength, durability, and suitability for a wide range of temperatures. Zhu [26] investigated the mechanical behaviors of the fiber-reinforced asphalt-like materials by numerical simulation, where the distribution and orientation of the fiber in the composite materials was considered as directional.

However, the actual distribution and orientation of fibers in the asphalt-like materials is random. Moreover, most of the studies focused on the performance of the fiber-reinforced asphalt mixture or asphalt-like materials by experiments. Limited work investigated the effects of the basalt fibers in composite materials on the reinforcement rheological mechanism of asphalt-like materials by numerical simulations. Therefore, developing a 3D model of fibers with random distribution and orientation that can reflect the rheological property and mechanism of the basalt fiber reinforced asphalt-like matrix is necessary.

This study presents a new 3D numerical model to investigate the rheological behaviors of basalt fiber reinforced asphalt-like material (BFRA) under constant loadings. The proposed model is assumed to consist of two components: the asphalt-like matrix and the round straight basalt fibers. The asphalt-like matrix is perceived as homogeneous with a viscoelastic behavior. Fibers with higher strength are supposed to be dispersed at random positions and orientations in the matrix using the MATLAB software. The rheological properties of the BFRA specimen under different fiber contents are simulated in the ABAQUS software using the developed numerical model. A comparison between the simulated results and the test data is provided, and the reinforced mechanism of fiber in asphalt-like material at high in-service temperature is further analyzed. In addition, the influence of the fiber aspect ratio on the rheological property is discussed under a constant content.

2. Generation of 3D numerical model

Fiber-reinforced composite is widely used in civil engineering and has been proven an excellent kind of construction material. Several research [21,22] investigated the modeling of steel fiber distribution within a fine aggregate concrete and the steel fiber-reinforced concrete materials under static or dynamic loadings using numerical methods. Based on previous investigations [21,22], a generation algorithm of 3D random distributions of straight round basalt fibers in cylindrical asphalt-like matrix is proposed. Moreover, a numerical program is developed using the MATLAB software to create a 3D finite element analysis model in ABAQUS.

2.1. Generation of random number

Generally, the recursive formula $X_{n+1} = R(X_1, X_2, \ldots X_n)$ is adopted to generate random numbers, where R indicates a recursive function, and the new random number X_{n+1} can be derived from the initial parameter value $(X_1, X_2, \ldots, X_n)$. The feature of this algorithm is that the random number list $\{X_{n+1}\}$ is determined by the initial value $(X_1, X_2, \ldots X_n)$ and the recursive function R. Consequently, the random number list $\{X_{n+1}\}$ cannot completely satisfy the requirement of randomness and independence. Another feature of the algorithm is the ability to obtain the same random number list $\{X_{n+1}\}$ when the amount of random number is large enough. Thus, $\{X_{n+1}\}$ is called a pseudo-random number list. When the random number is small, the pseudo-random number list can satisfy the randomness completely. In this paper, based on the generation principle of pseudo-random number, the internal function *Rand* () in MATLAB is called directly to generate the pseudo-random number list.

2.2. Algorithm and generation of 3D random distribution model for basalt fiber

Basalt fiber is considered straight and round, in which l and d are the length and diameter of the fibers, respectively. The fibers are randomly distributed in the asphalt-like matrix using a numerical program in MATLAB software. The location and orientation of the fibers are random. The total number of fibers can be determined by the volume content, length l, and diameter d of the basalt fiber in the BFRA specimen. The generation and algorithm of the 3D random model for BFRA may be described as follows:

(1) The *Rand* () function mentioned above is used to generate a random number.
(2) The total number of basalt fibers in the BFRA sample is counted.

First, the volume V_ρ of a single fiber is calculated according to the dimensions of the fibers using the formula $\pi d^2 l/4$. Then, the total volume of all fibers is calculated according to the total fiber volume content ρ_v in the sample. Finally, the total number of the fiber in the sample can be derived from the formula $V\cdot\rho_v/V_\rho$, where V is the volume of the sample. If the total number of fibers is between N and $(N+1)$ (N is a positive integer), N is adopted.

(3) The random location and orientation of all basalt fibers in the domain of the cylindrical sample are generated.

First, the random orientations of fibers in the cylindrical sample are calculated. BF_original and BF_final are set as the original and final orientations of the fiber, respectively. a, b, and c are the angles rotating around the X, Y, Z coordinate axis, respectively. The algorithm of random rotation is as follows [22]:

$$\mathrm{BF\_final} = \mathrm{BF\_original}\begin{bmatrix} \cos b\cos c & \cos b\sin c & -\sin b \\ \sin a\sin b\cos c - \cos a\sin c & \sin a\sin b\sin c + \cos a\cos c & \sin a\cos b \\ \cos a\sin b\cos c + \sin a\sin c & \cos a\sin b\sin c - \sin a\cos c & \cos a\cos b \end{bmatrix} \tag{1}$$

Subsequently, the random locations of the fibers in the sample are calculated. BF_Random (X_r, Y_r, Z_r) is a random point in the sample. BF_New (X_n, Y_n, Z_n) is the new random location of the fiber in the sample. BF_Origin (X_o, Y_o, Z_o) is the initial location of the basalt fiber. Then, the fiber is positioned into the sample according to the following algorithm:

$$X_n = X_o + X_r;\quad Y_n = Y_o + Y_r;\quad Z_n = Z_o + Z_r \tag{2}$$