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Effect of basalt fiber distribution on the flexural–tensile rheological performance of asphalt mortar

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HIGHLIGHTS

- A modified 3D model of fiber distribution is generated in a cuboid using MATLAB code.
- Models of three are selected to analyze the distribution effect.
- Flexural–tensile rheological value under the horizontal oriented fiber is minimum.

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ABSTRACT

This paper proposes a new three-dimensional (3D) fiber distribution model to investigate the effect of basalt fiber (BF) distribution on the flexural–tensile rheological performance of asphalt mortar. BF-reinforced asphalt mortar (BFRAM) is assumed to consist of the asphalt mortar matrix and the BF. An algorithm of random BF distribution is introduced to generate a 3D numerical model using MATLAB code. The 3D numerical models of the three kinds of directional BF distribution, including vertical, 45° oblique, and horizontal orientation, are selected to analyze the fiber distribution effect and reinforcement mechanism. The BFRAM model is employed in a series of simulations of the bending beam creep test in ABAQUS to study the flexural–tensile rheological behavior. Results indicate that the flexural–tensile rheological deformation of the BFRAM model under different fiber distribution types is ranked in a decreasing order as follows: vertical, 45° oblique, random, and horizontal orientation fiber. The result of random distribution fiber is in excellent agreement with the testing value. The flexural–tensile strain for the vertical, 45° oblique, and horizontal orientation fiber models is reduced by approximately 26.7%, 33.6%, and 63.7% at 3600 s, respectively, compared with that of the control sample.

1. Introduction

The performance of asphalt concrete composite materials can be greatly enhanced by adding fiber reinforcement [1,2]. Fibers are extensively applied in construction and building materials, including carbon, mineral, steel, and glass fibers [3–9]. Basalt fiber (BF), one of the four major high-tech fibers used in China, plays a reinforcing role and enhances the properties of composite materials [10]. These properties include natural compatibility, superior mechanical performance, stable chemical characteristics, and outstanding high temperature performance [11]. Compared with other commonly used fiber modifiers of asphalt-like materials such as lignin fiber, polyester fiber and glass fiber, BF has a higher elastic modulus, tensile strength, and a lower elongation rate [28,29]. Moreover, some research [10,19] also indicated that the absorption rate of BF is high, which allows it to avoid the bleeding and raveling problems of asphalt pavement under high temperatures. BF retains 95% of its strength under 600 °C and is resistant to water, acid, and alkali damage. Therefore, the application of BF in asphalt concrete has gained significant research interest.

Previous studies investigated the effect of BF on improving the performance of asphalt concrete through laboratory experiments. Xu and Gu [12] researched the performance of BF-reinforced asphalt concrete using laboratory test and indicated that the BF can enhance the high-temperature deformation resistance, low-temperature cracking resistance, and fatigue behavior of the asphalt mixture. Gao [13] also showed that BF can improve the low-temperature damage strength and failure strain and reduce the failure stiffness of asphalt concrete. In particular, the maximum failure strain increased by approximately 43.72%, the maximum failure stiffness decreased by approximately 25.86%, and the low-temperature cracking resistance of asphalt concrete was significantly enhanced.

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Furthermore, Morova [14] investigated the usability of BF in hot-mix asphalt (HMA) concrete by using the Marshall stability test and determined the optimum fiber content; results indicated that the addition of BF to the HMA concrete can positively affect its stability.

The performances of asphalt concrete, as a composite material, depend on its components, particularly binding materials (including asphalt binder, asphalt mastic, and asphalt mortar at nanoscale, microscale, and mesoscale levels, respectively) [15]. The effects of stabilizing and reinforcing different fibers on the performance of components in an asphalt concrete have been widely investigated [16–18]. Asphalt mortar, as an asphalt-like binding material, belongs to the category below asphalt concrete and consists of asphalt mastic (include asphalt binder and filler) and fine aggregates, which exhibit a complex rheological behavior affecting the stability of asphalt concrete. Adding fibers into asphalt mortar can maximize the advantages of asphalt mortar and fibers, particularly in terms of the stability, reinforcement, crack resistance, and toughening effects of the fiber. Laboratory tests and numerical simulation [10,19] indicate that asphalt-like binding material containing BF exhibits excellent performances in terms of strength, durability, and suitability for a wide range of temperatures. Zhu [20] investigated the mechanical behavior and reinforcement mechanism of BF in asphalt-like binding materials at high temperatures through numerical simulations, where the orientation and distribution of fibers in the binding materials were considered as directional. Zhang et al. [21] further investigated the three-dimensional (3D) numerical modeling of random BF distribution in the cylindrical binding material matrix to determine the effect of fiber content and aspect ratio on the shear and compressive rheological behavior of matrix at high temperatures.

Most studies employed experiments to assess the performances of fiber-reinforced asphalt concrete and investigate the compressive or shear rheological behavior of BF-reinforced asphalt-like binding materials at high temperatures. Limited work utilized numerical simulation to investigate the effects of BF distribution in composite space on the flexural–tensile rheological performance and reinforcement mechanism of asphalt-like binding materials. Therefore, scholars must develop a 3D numerical model that can reflect the distribution and orientation of BF in asphalt-like matrix spatially to elucidate the mechanical behavior of the resulting asphalt concrete.

2. Objectives

This paper presents a new 3D random distribution model to investigate the effect of BF and its distribution on the flexural–tensile rheological behavior of asphalt mortar under constant loadings at 15 °C. The proposed model is assumed to consist of two components, namely, the asphalt mortar matrix and the round straight BFs. The asphalt mortar matrix is perceived as homogeneous with a viscoelastic behavior. Fibers with higher strength are randomly dispersed into the matrix by using MATLAB code. Three kinds of directional distribution of BF are considered to analyze the effect of the orientation and distribution of fibers. The bending creep tests of BF-reinforced asphalt mortar (BFRAM) beam specimen under the random and directional distribution fibers are simulated in ABAQUS software by using the developed 3D finite element (FE) model. The simulated results and the test data are compared, and the distribution effect and reinforced mechanism of BF in asphalt mortar material at room temperature are analyzed.

3. Generation of 3D random distribution model for fiber

Fiber-reinforced composite is widely used in civil engineering as an excellent kind of construction material. Several studies [22,23] investigated the modeling of steel fiber distribution within a fine aggregate cement concrete and the steel fiber-reinforced cement concrete materials under static or dynamic loading through numerical methods. A generation algorithm of 3D random distributions of straight round BF in cuboid asphalt mortar matrix is proposed based on previous investigations [21,22]. Moreover, a numerical program is developed using the MATLAB code to build a 3D FE analysis model in ABAQUS.

3.1. 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 the recursive function, and the new random number X_{n+1} can be derived from the initial parameter value $(X_1, X_2, \ldots, X_n)$. In this algorithm, 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. Moreover, the algorithm can obtain the same random number list $\{X_{n+1}\}$ when the amount of random number is sufficiently large. 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, the internal function *Rand* () in MATLAB is called directly to generate the pseudo-random number list based on the generation principle of pseudo-random number.

3.2. Algorithm and generation of 3D model for fiber

BF can be considered straight and round, and l and d are the length and diameter of the fibers, respectively. The fibers are randomly distributed in the asphalt-like matrix by 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 BF in the beam specimen. The generation and algorithm of the 3D random model for fiber can be described as follows [21]:

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

First, the volume V_ρ of a single fiber is calculated according to the dimensions of the fibers using the formula $\pi d^2 l/4$. 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), then N is adopted.

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

First, the random orientations of fibers in the beam 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, and Z coordinate axes, respectively. The algorithm of random rotation is as follows [23]:

$$\mathrm{BF}_{\mathrm{final}=\mathrm{BF}}\mathrm{original}\begin{bmatrix} cosbcosc & cosbsinc & -sinb \\ sinasinbcosc - cosasinc & sinasinbsinc + cosacosc & sinacosb \\ cosasinbcosc + sinasinc & cosasinbsinc - sinacosc & cosacosb \end{bmatrix} \quad (1)$$

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 fiber. The fiber is positioned into the sample according to the following modified algorithm [21]:

$$X_n = X_o + X_r;\ Y_n = Y_o + Y_r;\ Z_n = Z_o + Z_r \quad (2)$$