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Numerical analysis of the rheological behaviors of basalt fiber reinforced asphalt mortar using ABAQUS

Xiaoyuan Zhang [a,*], Xingyu Gu [a], Junxiu Lv [a], Zongkai Zhu [a], Xiaoyong Zou [b]

[a] Southeast University, School of Transportation, Nanjing 210096, China
[b] Jinhua Highway Administration Bureau, Jinhua 321000, China

HIGHLIGHTS

- A 3D model composed of directional fiber and mortar matrix is established and simulated in ABAQUS.
- The additives of fiber into asphalt mortar can cause stress redistribution for mortar matrix.
- Fiber content has a more remarkable influence on the parameters for Burgers model than its modulus.

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ABSTRACT

This study aims to investigate the rheological behaviors of basalt fiber (BF) reinforced in asphalt mortar. The samples of basalt fiber asphalt mortar (BFAM) at various BF contents were prepared and were then submitted for the compressive creep test (CCT) and bending creep test (BCT) at high and low temperatures, respectively. In addition, the numerical simulation in finite element ABAQUS software was performed to model CCT and BCT, where the internal structure of the fiber-reinforced materials was considered to build a two-phase composite material model (fiber and mortar matrix) and further analyze the influence of BF on the rheological behaviors. Testing results indicate that BFAM has an excellent reinforcement performance compared with the control sample (0% fiber content). Moreover, numerical analyses show that the addition of fiber into asphalt mortar causes stress redistribution in BFAM and decreases the average stress value of the mortar matrix. The creep results of the three-dimensional numerical simulation using Burgers constitutive model for BFAM exhibit excellent agreement with those of the testing.

1. Introduction

Fiber asphalt mortar materials, which is a lower level of fiber asphalt mixture, is composed of asphalt mortar (including asphalt binder, filler, and finer aggregate) and fiber, showing a complex thermo-rheological behavior at high temperatures [1]. Adding fiber to the asphalt mortar can fully use the advantages of the asphalt mortar and the fiber, particularly the stability, reinforcement, crack and fatigue resistance, and toughening effects of the fiber, to significantly improve the performances of asphalt mixture [22–25].

The effects of fibers in improving the performances of the asphalt binder and mixture have been investigated in previous works. Serfass and Samanos [2] indicated that the addition of fibers led to rich asphalt contents; thus, the mixture can display high resistance to moisture, aging, and fatigue cracking. Lee et al. [3] evaluated the influence of nylon fibers on the fatigue cracking resistance of asphalt concrete using the pull-out test and the indirect tension strength test, and tests results showed that asphalt concrete samples fabricated with fibers of 1% and 12 mm results in 85% higher fracture energy than non-reinforced specimens. Liu et al. [4] investigated the mechanical properties of carbon fiber modified asphalt concrete through the indirect tensile test, and experimental results indicated that the Marshall stability increased from 12.8 kN to 13.5 kN and residual stability from 91.1% to 92.7%. Wu et al. [5–7] indicated that the addition of polyester fiber can enhance the fatigue property of the asphalt mixture, particularly at lower stress levels. Kumar et al. [8] showed that the addition of waste plastic fibers could improve the properties of asphalt binder such as penetration, softening point, and ductility.

Basalt fiber (BF) is a high-performance fiber made of basalt rocks that are melted at approximately 1500 °C and manufactured into continuous fibers. BF has captured the interest of the research community because of its good performance in terms of strength,

* Corresponding author.
E-mail address: xyzhang_email@163.com (X. Zhang).

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its suitability for a large range of temperatures and its durability [9]. In the recent decade, BFs have been used in asphalt mixture as a strengthening additive [10,11]. Compared with other prevalent strengthening additives of asphalt mixture, polyester fiber, glass fiber, and lignin fiber, BF has a higher tensile strength, an elastic modulus, and a lower elongation rate [1,12]. Research [16] also showed that the absorption rate of BF is high, which allows it to avoid the bleeding and raveling problems of asphalt mixture pavement under high temperatures. BF retains 95% of its strength under 600 °C and is resistant to water, acid, and alkali damage. Its high temperature resistance and good chemical stability makes BF an excellent modifier of asphalt-like materials.

The performance of asphalt mixture as a composite material is largely dependent on its components. In particular, binding materials play an important role, including asphalt binder, asphalt mastic, and a mix of mastic and fine aggregate usually referred to as asphalt mortar in a nanoscale, microscale, and mesoscale, respectively. The study on the stabilizing and reinforcing effects of fibers on the performances of the components in asphalt mixture is becoming a research hotspot [13–17]. However, most studies were focused on the performances of fiber-reinforced binding materials or asphalt mixture based on the macroscopic analysis of laboratory tests, and limited work described the reinforcing mechanism of the fiber on asphalt binding materials or mixture using the numerical simulation. Therefore, developing a numerical model composed of fiber and matrix that can reveal the internal reinforcing mechanism of BF fibers on the asphalt binding materials is necessary.

2. Objectives

In this paper, the main objectives of the work presented are as follows:

(1) Dispersing BF fibers into the asphalt mortar as a strengthening additive to prepare fiber-reinforced binding materials at different BF contents, including 0% (the control sample), 0.1% and 0.2%, and then testing the creep performances at a high in-service temperature by compressive creep test (CCT) and at a low in-service temperature by bending creep test (BCT).
(2) Modeling a two-phase composite material model (directional fiber and mortar matrix) to perform the numerical simulations of CCT and BCT in finite element (FE) ABAQUS software, and conducting performance analysis of basalt fiber asphalt mortar (BFAM) under unidirectional and constant loading to evaluate the reinforcement effects of BF to the creep deformation resistance of the mortar materials.

3. Materials

3.1. Raw materials

SBS modified asphalt of PG76-22 grade was used in asphalt mortar [1]. The mineral powder and fine aggregate were limestone and basalt, respectively. The properties of component materials are satisfied according to the standard (JTG E42-2005; JTG E20-2011) [18,19], where the Young's modulus and Passion's ratio of the BF are 100 GPa and 0.15.

3.2. Gradation

Asphalt mortar corresponding to asphalt mixture should be prepared to analyze the effects of BF on asphalt mortar. At present, because fiber added into an asphalt mixture is used in the upper and middle course of the asphalt pavement, the asphalt mortar of AC-13 gradation usually used in the upper surface course of the asphalt pavement is selected in this study. Referring to the corresponding specification (JTG F40-2004) for the AC-13 aggregate gradation [20], the asphalt mortar is composed of fine aggregates less than 4.75 mm in size at a certain proportion. Asphalt mixture and corresponding asphalt mortar gradation are listed in Table 1.

3.3. Basalt fiber content

Fiber content (FC) are usually calculated by weight of asphalt mixture, therefore, the percentage of FC in asphalt mortar can be obtained by the relationship between asphalt mortar and its asphalt mixture in terms of FC in asphalt mixture. In the present study, the basalt FCs are 0.1% and 0.2% in asphalt mixture, and correspondingly, 0.19% and 0.38% in asphalt mortar.

4. Test methods

4.1. Creep tests

For CCT, specimens at different FCs (0%, 0.1%, 0.2% by weight of asphalt mixture) were fabricated by Superpave gyratory compactor (SGC). The diameter and height of the cylindrical specimen are all 100 mm. The CCT is performed using a loading instrument UTM-25 with a loading rate of 2 mm/min at a temperature of 60 °C [19]. In this study, the loading level of specimens is set as 20% and 30% compression strength of the control specimen, that is, 0.28 and 0.42 MPa, respectively.

A compressive stress (0.0056 MPa) with 2% of the loading level was first preloaded by keeping 60 s to avoid gap impact on the results to eliminate the contact gap between the pressure head of the loading instrument and the specimen. Then, the creep loading was performed by keeping 30 min and finally, the creep unloading was conducted approximately 10 min, where the maximum compressive creep deformation is seen as the peak value at the loading process. The elastic and delayed viscoelastic deformation are removed by unloading to obtain the residual creep deformation.

For BCT, the beam samples with dimensions of 40 mm × 40 mm × 160 mm were made by the static pressure method [1]. BCT is commonly used to evaluate the deformation and relaxation behavior of asphalt mixture at low temperatures. According to JTG E20-2011, the deflection of the asphalt mixture beam sample at midspan, loaded by a constant load, presents three stages including migration, stable, and failure stages with time increase. In this study, the performance was further evaluated by the creep rate of the stable stage under a temperature of −10 °C and the loading rate of 50 mm/min [20], where the higher the creep rate is the greater low-temperature deformation of asphalt mortars, resulting to stronger relaxation ability and more excellent performance in low-temperature crack resistance. The tester was

Table 1
Relationship between asphalt mixture and mortar for AC-13 gradation.

Sieve size (mm)	2.36	1.18	0.6	0.3	0.15	0.075	<0.075
Retained percentage of asphalt mixture	16	10.5	7.5	5.5	3.5	4	6
Retained percentage of asphalt mortar	30.2	19.8	14.2	10.4	6.6	7.5	11.3