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Thermo-plastic fiber's reinforcing effect on hot-mix asphalt concrete mixture

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HIGHLIGHTS

- Average interfacial bond strength resulted in the value of $\tau = 0.12\ \mathrm{N/mm^2}$.
- Fiber's contribution to resisting the failure is approximately 25.5%.
- The maximum tensile stress at the peak of $0.47\ \mathrm{N/mm^2}$.

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ABSTRACT

We propose a method for predicting the direct tensile bond strength of plastic fiber-reinforced hot-mix asphalt (HMA) mixtures. The toughening effects of the plastic fiber-reinforced HMA mixtures are characterized using the direct tensile loading test. A method for calculating the effective fiber volume fraction along the failure plane is proposed to estimate the interfacial bond strength along the failure plane. The average interfacial bond strength resulted in the value of $\tau = 0.12\ \mathrm{N/mm^2}$. Comparing to the maximum tensile stress at the peak of $0.47\ \mathrm{N/mm^2}$, the fiber's contribution to resisting the failure is approximately 25.5%. The generality of the direct tensile loading approach was confirmed by the experimental data from the direct tensile tests and three-point bending beam tests.

1. Introduction

In recent years, increasing attention has been given to the possibility of improving the mechanical properties of hot-mix asphalt (HMA) by incorporating fibrous reinforcement HMA mixtures with some types of plastic fibers, such as polyester, polypropylene, or nylon, have been reported to be superior to plain HMA in terms of toughness, indirect tensile strength, shear strength, and fracture energy [1–3].

The improved toughness and fracture energy, which may increase the fatigue life of HMA, were the representative effects in the use of fibers with HMA [4–7]. In addition to HMA, steel fibers, polyesters, or nylon fibers in a short, discontinuous dimension were utilized to implement the enhanced toughness and fracture energy to concrete material by the fiber-bridging effect [8–10].

The toughening effects of the fiber composite are typically characterized using direct tensile tests associated with force–displacement curves; however, the fiber's random distribution and orientation features require the use of assumptions regarding the probability density functions for calculating the effective composite stresses along the failure plane by accounting for the fiber's bridging forces. The mechanical behavior of the fiber reinforced composite typically depends on the fiber geometry, fiber contents, the relative stiffness of the matrix and fiber, and the fiber–matrix interfacial bond strength. However, the probabilistic approach to calculate the composite stress considers the bonding effect through an indirect parameter, such as the snubbing coefficient, that depends on the fiber geometry instead of through the interfacial shear stress or strength term [11,12].

Not all fibers mixed in the composite are equally effective in their toughening effect because of the randomness in fiber's orientation or dispersion; however, if sufficient strength improvement can be obtained, the practical advantages of fibers in HMA will be confirmed. A promising cause of toughening may be that the fibers in HMA enhance the shear strength at the interface between the HMA matrix and fibers, and the enhanced property can delay the initiation and propagation of damages [11,12].

This study addresses the three-dimensional reinforcement of a HMA mixture using recycled plastic fibers to enhance the

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interfacial bond strength and proposed a method to calculate the effective fiber volume fraction along the failure plane. The effective fiber volume fraction confirmed the enhanced interfacial bond strength along the failure plane. The reinforcing effect by the fibers may occur through the fiber and matrix interfacial shear strength, and a law of mixture considering the matrix and fiber's contributions to enhance the composite strength separately was adopted, and the interfacial bond strength, which depends on the various fiber contents, was also obtained using direct loading tests.

In addition, the generality of the direct tension test was confirmed by the experimental data from direct tensile tests and three-point bending beam tests.

2. Plastic fiber-reinforced HMA

Plastic fiber-reinforced HMA is comprised of a fiber phase and a HMA matrix phase. In addition to the HMA matrix, the fiber phase is also supposed to enhance the tensile or shear strength of the composite. Polyethylene terephthalate (PET) plastic fibers that are randomly oriented in the matrix were used in this study; the fibers were manufactured through an extrusion process and have embossments on the surface of the fiber and a unique shape and dimensions depending on the extrusion nozzle, as shown in Fig. 1a–d.

The plastic fibers, shown in Fig. 1a, are made of recycled PET resin. Fig. 1b illustrates the embossments of the rectangular shape of Fig. 1a with a width of 1.5 mm. The colorless fiber, shown in Fig. 1c, has one longitudinal groove for expecting the additional separation of the fiber's end during a dry mixing process with aggregates in a plant. The nozzle in this case has a sharp tip inside the extrusion nozzle to make the groove. Fig. 1d shows the fiber for the surface mixture with an aggregate size (13 mm) smaller than the base layer size (19 mm); the circular nozzle that made this fiber is 0.5 mm wide and 15–30 mm long.

This study only used PET fibers, shown in Fig. 1a, to investigate the effect of various fiber contents on the HMA toughness. To make the fibers, the recycled PET chips were first reproduced out of discarded PET bottles. A local recycling manufacturer provided the recycled PET chips. PET fibers having a unique dimension were produced through an extrusion process with a rectangular nozzle. The dimensions of the recycled PET fibers for a coarse aggregate mixture are shown in Fig. 1a and are 30 mm (length) × 1–1.5 mm (width) × 0.2–0.3 mm (thickness) in this study.

The mechanical properties of the recycled PET fibers are as follows: the specific gravity of the recycled PET fiber is approximately 1.32, the tensile strength is 300–305 MPa, the elastic modulus at room temperature is approximately 13 GPa, and the elongation is 7.5%. All of the mechanical properties of a recycled PET fiber are equivalent to the typical values of a new PET fiber.

The asphalt binders for all of the mixtures used in this study were of Superpave PG 64-22 grade with a penetration of 65 and a softening point of 49 °C. The characteristics of the HMA mixtures are provided in Table 1, and the aggregate gradation of the mixtures is provided in Table 2. All HMA mixtures, both with and without fibers, were mixed with the optimum asphalt content according to the Marshall mix design process with a fixed course aggregate gradation. This study attempted to avoid the binder content's dependency on the mixture's behavior, and aimed to observe only variations due to the fiber contents. The fiber contents for the coarse aggregate gradation varied, with values of 0.2, 0.4, 0.6, 0.8, and 1.0 wt%, based on the specimen's weight. The aggregate gradation for the maximum aggregate size of 19 mm was in coarse gradation, as shown in Table 2. The lower G_{mm} of the fiber-reinforced mixes may be due to the additional fiber volume in the HMA.

Without any balling of the fibers in the mixture, all of the specimens were compacted in a 150-mm-diameter mold at approximately 160 °C using a gyratory compacter, with 100–120 gyrations applied to each specimen until the target height for each specimen (i.e., 120 mm) was achieved. The relatively higher air void content of the fiber-reinforced mixture required additional gyrations. The mass of each specimen was calculated as a function of the target air void content, such as 5%, the volume of the gyratory mold, and the theoretical specific gravity, G_{mm}. Two specimens with dimensions of approximately 100 mm (height) × 100 mm (width) × 50 or 70 mm (thickness), shown in Fig. 2, were cut from each compacted specimen for direct tensile testing, as described in the following section.

3. Laboratory tests and analysis

3.1. Direct tensile loading test

A new fixture with two clamping grips for a direct tensile test on HMA was presented. The new fixture makes it possible to use a rectangular specimen, as shown in Fig. 2, by imposing uniform tensile loading at the central area of the specimen. Using the new direct tensile test fixture, it was possible to determine the tensile force vs. displacement curves of the various fiber contents.

The toughening effect of PET fiber-reinforced HMA is characterized by considering specimens subjected to uniaxial tension. Fig. 3a–c illustrates the direct tensile loading test set-up, including the specimen mounting device, the plates that hold the test specimens, and the upper and lower loading jigs with two clamping grips. The specimen mounting device, shown in Fig. 3a, holds the rectangular specimens and ensures identical test dimensions, such as the 1-mm gap between the plates and central point of the specimen, as shown in Fig. 3b. The upper and lower end of the mounted specimen is glued, whereas the middle of the specimen is not glued, as shown in Fig. 3b; this schematic is used to induce a uniform uniaxial tension and a failure plane in the middle of the specimen. The glued portion of the specimen should not slip during the direct tensile loading test if a realistic force–displacement curve is to be obtained. In addition to the specimen being glued to the plates, a uniform torque is applied at the end of a

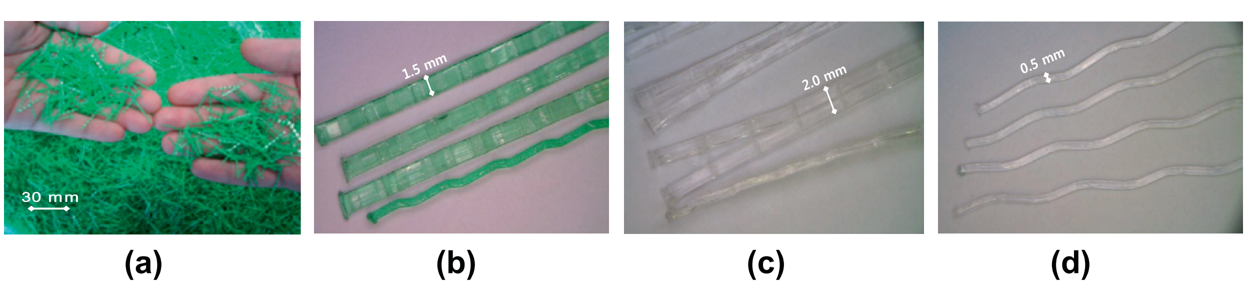

Fig. 1. (a) PET fibers, (b) magnified PET fibers, (c) grooved PET fibers, and (d) fibers for the wearing course.