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Pull-out behavior of straight steel fibers from asphalt binder

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HIGHLIGHTS

- Single steel fiber pull-out tests from asphalt binder are conducted.
- Matrix, interface, and mixed failure modes are observed during the fiber pull-out.
- Stress distribution along the fiber-binder interface is investigated by FE analysis.
- The fiber-binder bond strength is independent of temperature and loading rate.

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ABSTRACT

The interaction between a straight steel fiber and the surrounding asphalt matrix is investigated through single fiber pull-out tests and numerical simulations. Based on experimental observations from 240 pull-out tests for various temperatures, displacement rates, and fiber dimensions, pull-out failure modes are classified into three types: matrix, interface, and mixed failure modes. The experimental data suggests that there is a critical shear stress beyond which fiber-binder interface debonding will occur. Detailed finite element analyses employing a nonlinear viscoelastic constitutive model for asphalt are carried out to explain the observed test results. The numerical simulations show that the stress distribution along the fiber surface varies substantially with temperature and fiber dimensions. At −20 °C, the concentration of interfacial shear stress becomes significant as the embedded aspect ratio of fibers becomes higher, and causes a decrease in the value of average interfacial shear stress at the onset of the interface debonding. The simulations also showed that this stress concentration decreases at 0 °C as the contribution of viscous behavior becomes more significant. The simulation results confirm that the shear bond strength between steel fiber and asphalt binder is 6.9 MPa, and it is independent of temperature, loading rate, and fiber dimensions within the ranges used in the study.

1. Introduction

1.1. Background

The most common way for improving the mechanical performance of asphalt concrete is through the use of polymer modifiers [1,2]. While fiber additives have been generally viewed as a stabilizer that enriches adhesion between binder and aggregates during construction [3,4], some laboratory investigations have shown that they can also enhance resistance to rutting and fatigue [5–8]. These investigations have fueled growing interest in investigating other beneficial effects of fiber additives, e.g., increasing mechanical strength [9–15], and enabling multifunctional applications [16–22]. NCHRP Synthesis 475 [23] provides a comprehensive literature review, survey results, and case examples of using fibers in asphalt mixtures.

The use of fibers for the purpose of reinforcing asphalt concrete was tried in the field without a thorough understanding of the mechanisms responsible for improving composite behavior. Field studies by Maurer and Malasheskie [24], Huang and White [25], and Serfass and Samanos [26] showed that fibers can improve [SPS]code="HY" instruction="Hyphenation"[/SPS] resistance to reflective cracking, fatigue, moisture damage, thermal cracking, and raveling. Kutay et al. [27] observed that even though many micro cracks developed on the surface of on-site fiber reinforced

Abbreviations: FRAC, fiber reinforced asphalt concrete; LVDT, linear variable differential transducer; MaF, matrix failure; InF, interface failure; MMF, mixed mode failure.

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asphalt concrete (FRAC), they did not localize into large cracks. In fiber reinforced cement concrete, the development of micro cracks is considered to be a positive sign of proper fiber reinforcement [28]. However, the positive field experience achieved was not consistent with laboratory experimental evidence, and in some cases actually conflicted with it.

Laboratory tests by Kim et al. [5], Lee et al. [9], Tapkin et al. [10], Anurag et al. [29], Ye et al. [30], Brovelli et al. [31], and Mansourian et al. [32] have shown that some improvements can be achieved in the resistance to rutting, fatigue, and moisture damage by adding fibers. Stronger evidence of the reinforcing effect of fiber additives can be found in experimental investigations of asphalt mastic, which is a mixture of asphalt binder and fibers. Significant improvements in tensile strength [33–35] and resistance to rutting and fatigue [36–38] have been reported in fiber reinforced asphalt mastics. However, the tensile strength of FRAC as measured by direct tension, indirect tension, or Marshall stability tests have been generally shown to either be unaffected [2,5,12,39–42] or degraded [9,43–45] by the presence of fibers. These negative test results have hindered the widespread use of fibers for strength improvement. More recently, studies have reported that the indirect tensile strength and Marshall stability of FRAC can be improved using specific fiber types, fiber contents, and mixture design [14,15,46,47].

Some recent investigations provide explanations for the conflicting laboratory and field observations regarding strength improvement. Chen et al. [11] showed that fiber additives require a slight increase in the optimum binder content in order to adequately coat the surface of the fibers and that, when the proper binder content is used, the FRAC specimens will have higher strength than the specimens without fibers. Another observation is that the improvement in strength is dependent upon temperature. Kaloush et al. [13] showed that the strength improvement in FRAC due to fiber addition increases with decrease in test temperature. Since cracking of asphalt pavements occurs at cold temperature, the evaluation of strength at room temperature (indirect tension test at 25 °C) or higher temperatures (Marshall stability test at 60 °C) can underestimate the fiber reinforcing effect on cracking. Poor mixing due to the clumping or balling of fibers is another reason of the reduced strength of FRAC [23,48]. Garcia et al. [49] reported that the longer and thinner fibers (high aspect ratio) tend to have more clumping than the shorter and thicker fibers (low aspect ratio). Synthesizing the results in Chen et al. [11], Kaloush et al. [13], Garcia et al. [49], and Kutay et al. [27], it can be concluded that the use of fibers as reinforcement is promising, but that a proper optimization of the composite is necessary to maximize the benefits of adding fibers. Such optimization requires a thorough understanding on the interactions between fiber, aggregate, and binder.

The highest reinforcing effect of adding fibers is reported by the previous work done by the authors of this paper [15]. Through indirect tension tests conducted at −20 °C for dense graded asphalt concrete containing various steel fibers, Park et al. [15] observed up to 62.5% increase in the indirect tensile strength and 370% increase in cracking energy. The experimental data for various fiber dimensions indicated that the reinforcing effect was significantly influenced by the fiber length and thickness. Based on these observations, Park et al. [15] suggested a hypothesis that the fiber pull-out in asphalt concrete is resisted by two mechanisms – the fiber-binder adhesion and fiber-aggregate interlocking. Yoo and Kim [50] and Yoo and Al-Qadi [51] also noted that the reinforcing effect in tensile strength of FRAC originates from the bond strength at the fiber-mixture interface. Therefore, understanding the interfacial behavior during the pull-out of a fiber from the temperature dependent and viscoelastic asphalt binder is one of the fundamental steps to understand the microstructural reinforcing mechanism that enables an optimum design of FRAC.

A single fiber pull-out test is a useful experimental method to understand the fiber-matrix interface behavior of fiber reinforced composites, and has been used for fiber reinforced cement concrete [52–57]. A bond-slip model, based on the relationship between shear stress at the fiber-matrix interface and the relative displacement between the fiber surface and surrounding matrix, has been commonly used for describing the interfacial bond characteristics of the fiber-matrix system including cement concrete [52,53]. However, the bond-slip model for cement concrete assuming the matrix as an elastic-brittle material cannot be generally extrapolated to FRAC because the asphalt matrix is a viscoelastic material and the matrix may remain attached to the fiber or part of it, as discussed later on in the paper.

To date, fiber pull-out tests from asphalt binder have been conducted only by Lee et al. [9] and Shunzhi et al. [58]. Lee et al. [9] conducted a single fiber pull-out tests from asphalt binder to determine the critical embedded length of Nylon fibers (15 denier), at which the fiber breaks instead of being pulled-out. The pull-out test is conducted only at 20 °C with a constant displacement rate. Shunzhi et al. [58] conducted multiple fiber pull-out tests from asphalt mastic using direct tension test configuration. Polyester (diameter = 20 μm) and aramid (diameter = 14 μm) fibers were tested to determine the critical embedded length at −18 °C. The focus of these two tests was to determine the critical embedded length, at which the fiber-binder adhesion exceeds the strength of fibers at a specific temperature, and hence, a detailed fiber-matrix interfacial response was not described in their papers. To the best of the authors' knowledge, the study described herein is the first to investigate the comprehensive interfacial characteristics between a fiber and a viscoelastic asphalt matrix over wide range of temperature and loading rate. The pull-out load versus displacement responses and the stress distribution at the interface provide fundamental and unique insight into the fiber reinforcing mechanisms that occur within a temperature dependent viscoelastic matrix.

1.2. Main objective

The objective of this study is to employ experimental and computational methods to develop a fundamental understanding of the interaction between a single steel fiber and asphalt binder. The specific goals of the study are: 1) to characterize the interfacial behavior between a steel fiber and asphalt binder over wide temperature and loading rate ranges, and 2) to investigate the effects of fiber dimension on the interfacial behavior. Focusing on straight steel fibers, a set of single fiber pull-out tests from asphalt binder were conducted under various test conditions to obtain the pull-out stress versus displacement relationship. In addition, nonlinear viscoelastic finite element analyses were carried out to investigate the interfacial stress distribution that occurs under various test conditions.

2. Single fiber pull-out test

2.1. Test setup and scope

The parameters for the pull-out experiments are summarized in Table 1, the key variables being: temperature (T), pull-out displacement rate ($\dot{\Delta}$), fiber diameter (D) and embedded depth of fiber (L_{em}). Each test is repeated at least three times for each test condition leading to a minimum of 240 pull-out tests. While the stiffness, shape, and surface roughness of the fiber can play an important role, they are not included in this part of the study to keep the main focus on the interface behavior for a smooth steel fiber. Also, since the matrix is pure asphalt, the effect of aggregate