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Effect of fiber shape and morphology on interfacial bond and cracking behaviors of sisal fiber cement based composites

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ABSTRACT

An experimental investigation was performed to understand the pull-out behavior of sisal fibers from a cement matrix. The effect of curing age and fiber embedment length on the fiber–matrix interface was studied. Sisal fiber presents irregular cross-section with different shapes that may be beneficial for the bond strength. A scanning electron microscope coupled with image analysis was used to measure the cross-section area of individual tested fibers and to determine and classify their morphology. The results were correlated to the fiber morphology. Direct tension tests were performed on composites reinforced by 10% in volume of continuous aligned sisal fiber. A finite difference model developed earlier by authors was used to determine the bond strength versus slip constitutive relation from experimental data and to predict the composite tensile behavior and crack spacing. It was found that the sisal fiber morphology plays an important role in the bond strength. Average adhesional bond strength as high as 0.92 MPa were reported for the fiber shape that promoted the best interfacial performance.

1. Introduction

Cement based composites reinforced with continuous aligned sisal fibers demonstrate a tension-hardening with multiple cracking behavior [1] with high tolerance to fatigue loading [2] and high energy absorption capacity under dynamic loading [3]. This type of composite system is reinforced with up to five layers of fibers resulting in a total volume fraction of 10%. In humid environments the sisal fiber cement composites produced with ordinary Portland cement matrices undergo an aging process during which they may suffer a reduction in post-cracking strength and toughness. This process is a result of migration of hydration products (mainly $Ca(OH)_2$) to the fiber structure. To mitigate this effect a special matrix that has 50% of cement replaced by calcined clays has been recently developed and optimized for use with sisal fiber systems [4]. This matrix lowers the calcium hydroxide production resulting in enhanced durability against fiber degradation and also providing adequate rheology in the fresh state for the fiber volume fractions proposed. The multiple cracking behavior achieved is governed by interfacial bond characteristics between fiber and matrix.

A significant amount of experimental and analytical investigations have been dedicated to the mechanical characterization of interface in man-made-fiber cement matrix systems. Tests for bond adhesion of cementitious composites have been performed by many researchers; however, limited data has been presented for natural fibers. Most of the interface characterization work has been performed on steel, glass and polymeric fibers. Naaman and Najm [5] state that there are four main factors that influence the bond between fiber and matrix: (i) physical and chemical adhesion, (ii) mechanical component of bond such as deformed, crimped and hooked end fibers, (iii) fiber-to-fiber interlock, and (iv) friction. Peled and Bentur [6] investigated the pull-out behavior of straight and crimped polyethylene yarns. They found that increasing the crimp density enhances the mechanical anchoring and the equivalent adhesion bond strength increases from 1 to 1.84 MPa (10 mm fiber embedded length). Markovich et al. [7] studied the pull-out behavior of hooked end steel fibers for different types of matrices and reported an average frictional stress between 2.76 and 4.97 MPa depending on the mixture. Kim et al. [8] investigated steel hooked ended and torroidal shaped fibers. Equivalent bond stresses calculated from experimental pull-out of hooked end and torroidal fibers were 4.7 and 14.5 MPa, respectively.

Several models have been used for prediction and characterization of pull-out behavior in fiber reinforced cement composites. Naaman et al. [9] proposed an analytical model for smooth fibers or bars with an idealized bond–stress–slip relationship of the interface. The solution led to the prediction of the bond shear stress-versus slip curve assuming that one can employ a back-calculation procedure to use the pull-out load versus slip in

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parameter estimation. Sueki et al. [10] modified Naaman's model to analyze pull-out test results and quantified the equivalent bond properties of several fabrics. In their analysis, the role of fill yarns in providing anchorage points along the length were modeled in a discrete approach. Banholzer et al. [11] proposed another analytical model to simulate the pull-out response of a fiber–matrix system in which an N-piecewise linear bond stress versus slip relation is adopted.

In the present research single fiber pull-out tests were performed on sisal fibers for curing ages ranging from 3 to 28 days. Embedment lengths of 10, 20, 30 and 40 mm were tested for samples after 3 days of curing. Microstructure characterization was coupled with image analysis in order to compute the sisal fiber area of each test and to investigate the effect of the fiber shape on the bond strength. A non-linear finite difference model developed by Soranakom and Mobasher [12–14] for a regularly anchored, and aligned fiber composite was used to simulate the pull-out response. The pull-out results were then used in predicting direct tensile and crack spacing of sisal fiber reinforced composites based on the interface properties. The numerical analysis is compared to experiments, and it is shown that small modifications to the model are necessary in order to fit the response of unidirectional aligned fibers.

2. Experimental program

2.1. Materials and processing

The sisal fibers used in this investigation were extracted from the sisal plant farm located in the city of Valente, state of Bahia – Brazil. Their mechanical properties consisted of a mean elastic modulus and tensile strength of 19 GPa and 400 MPa, respectively as characterized by Silva et al. [15]. More information on the mechanical properties of the used sisal fiber can be obtained elsewhere [16,17].

The matrix used in the present work was based on past research [4,18]. It was produced using the Portland cement CPII F-32, river sand with maximum diameter of 1.18 mm and density of 2.67 g/cm^3, 5% in volume of wollastonite (JG class) as micro reinforcement and a naphthalene superplasticizer Fosroc Reax Conplast SP 430 with content of solids of 44%. The use of micro-fiber reinforcement was directed at increasing the matrix tensile strength and to adjust the matrix rheology. Metakaolin (MK) from Metacaulim do Brasil Industria e Comércio Ltda and calcined waste crushed clay brick (CWCCB) obtained from an industry located in Itaborai – RJ, Brazil, burned at 850 °C, were used as cement replacements. The cement was replaced by 30% of MK and 20% of CWCCB following previous studies [4,18]. The mortar matrix had a mix design of 1:1:0.4 (cementitious material:sand:water) by weight.

The matrix was produced using a bench-mounted mechanical mixer of 5 l capacity. The cementitious materials, sand and wollastonite fibers were dry mixed during 5 min (for homogenization). Water and superplasticizer were slowly added in and the mixture was blended for 5 min. Molds were designed for casting single filament pull-out specimens (see Fig. 1). PVC tubes were used as the formwork while wooden bases were used to guarantee the accuracy of the sisal fiber orientation at the centroidal axis of the mold through a hole drilled at the center of the base plate. The sisal fiber was inserted through the eye of a needle, which was then contrived through the wooden mold. The mix was then poured into the PVC tubes in three layers followed by manual compaction. The specimens were covered in their molds for 24 h and after this time they were demolded and cured in water. Tensile specimens with a volume fraction of 10% continuous aligned sisal fibers were manufactured using the same mixture design [1].

2.2. Testing

2.2.1. Single fiber pull-out tests

An electromechanical MTS (model SINTECH 1/S) was used for the pull-out tests. The test setup is shown in Fig. 2. The PVC mold (diameter of 25 mm) was connected to a 0.44 kN (100 lb) load cell that was attached to the crosshead. The bottom part consisted of a pinch grip where the free end of the fiber was tightened. The test was conducted under constant crosshead displacement control at a rate of 0.1 mm/min. Six specimens of embedment length ranging

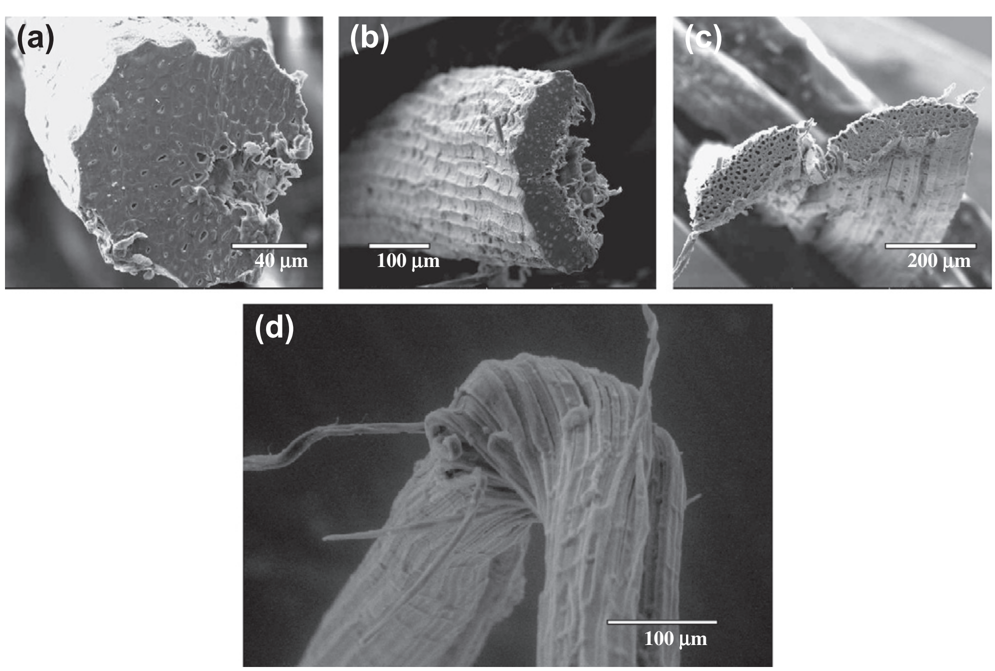

Fig. 1. Different morphologies of the sisal fiber: (a) horse-shoe shape, (b) arch shape, and (c) twisted arch shape. The different type of morphologies affects the fiber–matrix bond strength. The rough surface and flexibility of the fiber is observed in (d).