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# Inverse identification of the bond behavior for jute fibers in cementitious matrix

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ABSTRACT

This paper analyzes the bond behavior of natural fibers in cement-based matrix. First, it presents the results of pull-out tests carried out on jute fibers embedded in a cementitious mortar. Then, the experimental results are employed in identifying the bond-slip relationship which describes the interaction between fiber and matrix. A theoretical model, capable of simulating the various stages of a pull-out test, is formulated and applied for an inverse identification of the bond-slip law. Finally, the obtained results demonstrate the soundness of the proposed theoretical interpretation for the bond behavior of jute fibers embedded in a cementitious matrix.



## 1. Introduction

The use of fiber reinforcement in cement-based materials attracts more and more interest as a solution for enhancing the intrinsic weaknesses of mortars and obtaining materials generally referred to as Fiber-Reinforced Cementitious Composites (FRCCs). As it is well known, the presence of fibers within the cement matrix promotes a “bridging effect” across the cracks and, consequently, the post-cracking behavior of FRCC is significantly improved [1]. Therefore, FRCCs are generally characterized by higher tensile and flexural strength [2,3], tougher and more ductile post-cracking behavior [4] and superior durability properties resulting by a reduction in crack widths [5–7].

The design of FRCC members is mainly based on the post-cracking response provided by the fiber reinforcement, which, in principle, are controlled by several parameters, such as fiber geometry and shape [8], fibers dosage, orientation and distribution in the matrix [9,10], mechanical properties of the fibers and the chemical adhesion between fiber and cementitious matrix [11].

Plenty of researches were carried out in the last two decades mainly investigating the mechanical performance of cementitious composites reinforced with industrial steel fibers, as they are characterized by excellent performance in terms of tensile strength, stiffness and bond adhesion with the cement matrix. Despite this, several researchers have recently investigated the feasibility of using alternative fibers for the design and the production of FRCCs for instance, synthetic, recycled [12] or natural fibers [13]. Moreover, the use of natural fibers could lead to produce High Performance FRCCs [14] which represent a viable solution for enhancing sustainability of construction materials.

In fact, due to their wide availability, especially in tropical countries, these fibers have a low economic impact (with respect to “ordinary” steel fibers) and present the great advantage of being renewable. The natural fibers are obtained from vegetable raw materials and, among them the most common include sisal, jute, coir etc. [15–17]. All the natural fibers present a complex microstructure, composed of hundreds of microcells with a characteristic length ranging between 2 and 5 mm, and nominal diameter less than 0.2 mm, composed by lignin and natural adhesive. In terms of mechanical properties, natural fibers can be defined as high performance fibers being characterized by a tensile strength, generally, higher than 200 MPa [14].

On the other hand, being an organic material, the natural fibers are vulnerable to biological attacks, affected by the moisture

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condition and sensitive to alkali attack which can decompose lignin and the other constituents. For these reasons, several solutions were proposed in literature in order to prevent degradation phenomena in natural fibers [18–20]. However, the bond behavior between natural fibers and cement matrix should be guaranteed and more deeply investigated [21].

This paper analyzes the bond behavior between jute fibers and cement-based matrix. More specifically, it presents the results of 22 pull-out tests carried out on jute fibers in a cementitious matrix by considering two embedded lengths, namely 5 mm and 10 mm.

The experimental results in terms of applied force vs. maximum interface slip were, then, employed for identifying a local bond-slip relationship intended at describing the interaction between fiber and matrix. To this end, a theoretical model capable of describing the various stages of the pull-out test on fibers embedded within an homogeneous matrix is formulated in Section 4. As a matter of fact, this model is a generalization of a fully analytical solution recently proposed in the literature for describing the bond behavior of FRP strips subjected to a pull-out force [22]. Due to the clear mechanical similarities, this model can be also employed in simulating the pull-out out behavior of fibers [23]: in principle, it is capable to simulate the global force-slip response of fibers under pull-out forces, only considering a given bond-slip law and the key geometric properties of the fiber, such as its embedment length and the area-to-perimeter ratio of their transverse section. Therefore, the proposed model, assuming a bond-slip law more general than in the previously cited works, can be employed, along with the presented experimental results, for obtaining an inverse identification [24] of the local bond-slip law describing the interaction between the jute fibers and the cementitious matrix under consideration.

Finally, Section 5 reports the results of an inverse identification of the bond-slip law resulting from the experimental tests summarized in Section 3 and demonstrates that the theoretical model proposed herein is capable to interpret the bond behavior of natural fibers embedded in the cement matrix.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Jute fibers

The natural fibers employed in this study are made of jute and were derived from Amazon region. Particularly, they were extracted from the steam of the plant *Corchorus capsularis* by a combination of processes comprising various steps, such as cutting, retting, shredding, drying, packing and classification [25].

#### 2.1.2. Cement based matrix

The cement based matrix of the fiber reinforced composite investigated in this work is characterized by the following mixture composition: 1 (binders):0.5 (sand): 0.4 (water-to-cement ratio) by weight. The binder is composed of 30% of Portland cement CP-32 F II [26], 30% of metakaolin and 40% of fly ash. As already demonstrated in previous researches [25], this amount of metakaolin guarantees durability of fibers within the cement matrix. Moreover, the presence of fly ash is mainly aimed at ensuring workability requirements which is a desired property in producing high-performance composites: in fact, the presence of fly ash guarantees a more uniform distribution of the fibers within the composite [18,21]. The sand employed herein was processed in order to obtain a maximum diameter equal to 840 μm. In addition, a superplasticizer (Glenium 51 - type PA) with solids content of 31% was used.

The mixtures, cast at controlled temperature (21 ± 1 °C), were produced by using a mixer with capacity of 5 l. For the matrix production, the following mixing procedure was adopted: all dry components were homogenized in the mixer; water and superplasticizer were added and mixed for 2 min at a rate of 125 revolutions per minute (RPM); the process was stopped during 30 s for removing the material retained in the mixer; mixing continued for 2 min at 220 RPM; and, finally, for a further 5 min at 450 RPM.

### 2.2. Experimental procedures

#### 2.2.1. Morphological and mechanical characterization of the jute fibers

Several test were performed with the aim of characterizing the jute fibers.

First, the morphological characterization of fibers was carried out by analyzing their microstructure through the use of a Hitachi TM3000 Scanning Electron Microscope (SEM). The microscope was operated under an accelerating voltage of 15 kV. Fibers were precoated with a thin layer of gold for approximately 20 nm, with the aim to make them conductive and suitable for the analysis. In order to measure the fiber's cross-sectional area, for each single fiber used in the pull-out and tensile test, an adjacent piece of the fiber (immediately next to the one tested) was kept for future measurement and morphology characterization via SEM. The obtained images were, then, post-processed using ImageJ, a Java-based image processing program.

Then, the mechanical performance of jute fibers was mainly investigated by performing the tensile tests in an electromechanical testing machine Shimadzu AG-X with a load cell of 1 kN. The tests were performed in 15 jute fibers using a displacement rate of 0.1 mm/min. The fibers, with a gage length of 40 mm, were glued to a paper template for better alignment in the machine and for a better griping with the upper and lower jaws in accordance with ASTM C1557 [27]. To calculate the tensile strength of the fibers, their diameters were measured by analyzing the images obtained in the scanning electron microscope.

#### 2.2.2. Physical and mechanical characterization of the matrix

Several parameters were measured for assessing the main physical and mechanical properties of the cement matrix under investigation. More specifically, water absorption, density and void contents, were determined in accordance with ASTM C642 [28]; flow table spread value were measured according to ASTM C1437 [29]; compressive strength at 7 and 28 days was determined in accordance with ASTM C39 [30]; Static Elastic modulus and tensile strength were also determined according to ASTM C496 [31] and RILEM recommendation [32], respectively. Table 1 summarizes the results for the aforementioned measurements.

#### 2.2.3. Single fiber pull-out tests

The bond of a jute fiber with the cement based matrix was evaluated by single fiber pull-out tests. The pull-out tests were performed in an electromechanical testing machine Shimadzu AG-X with a load cell of 1 kN. The tests were carried out using a displacement rate of 0.1 mm/min. A schematic of the single fiber pull-out test is reported in Fig. 1. The samples were fixed in the machine grips through a system with hinged-fixed boundary conditions. The tests were performed at 7 days age. The specimens were cured for six days in the fog room and then, they were dried for a day under the following conditions of temperature and humidity: T = 23° C ± 1 °C and relative humidity of 65% ± 3%.