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Effect of hybrid fiber reinforcement on the cracking process in fiber reinforced cementitious composites

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ABSTRACT

The simultaneous use of different types of fibers as reinforcement in cementitious matrix composites is typically motivated by the underlying principle of a multi-scale nature of the cracking processes in fiber reinforced cementitious composites. It has been hypothesized that while undergoing tensile deformations in the composite, the fibers with different geometrical and mechanical properties restrain the propagation and further development of cracking at different scales from the micro- to the macro-scale. The optimized design of the fiber reinforcing systems requires the objective assessment of the contribution of each type of fiber to the overall tensile response. Possible synergistic effects resulting from particular combinations of fibers need to be clearly identified. In the present study, the evaluation of the response of different fiber reinforced cementitious composite materials is carried out by assessing directly their tensile stress-crack opening behavior. The efficiency of hybrid fiber reinforcements and the multi-scale nature of cracking processes are discussed based on the experimental results obtained, as well as the micro-mechanisms underlying the contribution of different fibers to bridge cracks resulting from tensile loading.

1. Introduction

The performance of concrete at the serviceability and ultimate limit states is governed by its susceptibility to cracking due to its quasi-brittle nature. Damage tolerant concretes have been investigated since the appearance of the first structural applications of fiber reinforced concretes. Pseudo-strain hardening behavior in tension has particular relevance in the development of these materials. The Strain Hardening Cementitious Composites (SHCCs) with pseudo-strain hardening ability in tension improve the durability and lead to a more efficient preservation of functional properties of structures [1]. Over the past few years, significant research efforts have been dedicated to the development of SHCC [2], adopting different strategies and technological approaches [3]. High toughness, tensile strength, tensile strain hardening ability with the development of diffuse crack patterns in tension are some of the most important properties, which have guided the optimization and design of these materials. Engineered Cementitious Composites (ECCs), a class of cement based materials typically reinforced with Polyvinyl Alcohol (PVA) fibers, is one of the examples of SHCC showing high ultimate tensile stain (between 3% and 7%) at an ultimate tensile strength of about 5 MPa [2].

The recent technological development of a wide variety of fibers has been creating new opportunities to the improvement of fiber reinforced cementitious composite materials. The strategy often adopted in the design of these materials is based on the utilization of fibers of different natures in the same composite. This strategy aims at designing composites with improved tensile response by taking advantage of the combined contribution of all types of fibers to the overall tensile response of the composite. The use of fibers of different natures and with distinct geometrical and material properties in hybrid fiber reinforced cementitious composites has been reported to improve the material properties of fiber reinforced cementitious composites [4–8].

The main advantage often attributed to the utilization of hybrid fiber reinforcement in fiber reinforced cementitious composites is the ability to restrain cracking at different scales of the cracking process [3,9]. It is generally recognized that the micro-mechanics of the cementitious composites is determined by the multi-scale nature of these materials, which in turn is reflected in a multi-scale structure of the cracking processes [10]. In a simplistic perspective, it is assumed that the micro-cracks generated during cracking process are bridged by smaller fibers, while the propagation of macro-cracks is restrained by the larger fibers [11]. A visible crack can be assumed as the result of the coalescence of randomly oriented and diffusely distributed micro-cracks previously formed. In this context, it is believed that the design of the fiber reinforcement is

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optimal when the multi-scale nature of the cracking process is taken into account. Further research concerning this mechanism is required though, as the explicit evidence of the true crack restraining micro-mechanics in multiple fiber-type reinforced cementitious composites is not fully established. The relation between the hierarchized cracking process in a composite, the different material scales and the mechanics of crack restraining by the different fiber reinforcements at different scales is not clearly understood.

It is the objective of the work presented in this paper to investigate in detail how fibers of different types are affecting the bridging behavior, and if a synergy between these bridging mechanisms in the composite can be established. Therefore the strategy adopted in the assessment of the tensile performance of fiber reinforced cementitious composites needs to appraise explicitly the importance and role of the micro-mechanisms of each composite phase in the overall composite response. In particular, when multiple fiber-type reinforcements are used, the contribution of each type of fiber and the interaction between different fiber reinforcements and different matrices in the overall composite mechanics needs to be clearly identified.

The tensile performance of fiber reinforced cementitious composites is typically characterized by the fracture parameters and the load-deformation behavior derived with different standard test setups [12–14]. For conventional types of fiber reinforcement, the three point bending test and the wedge splitting test setups are the most frequently used, mainly because the experimental procedure is considered simple and allows the characterization of the composite post-cracking behavior in a replicable fashion [15–18]. Inverse analysis is often utilized to derive the tensile stress-crack opening behavior from these experimental load-deformation results. Although satisfactory correlations are typically obtained, the uniqueness and universality of the solution independent of the test setup, of the boundary conditions and of the generated stress fields are not fully established [19]. In addition, when SHCC materials are considered, the potential formation of an unknown number of cracks during testing compromises the explicit characterization of the tensile material constitutive behavior. The direct assessment of the tensile stress-crack opening behavior, while experimentally more demanding, may be regarded as the most effective approach to access objectively the tensile performance of SHCC. In particular, when multiple types of fibers are used as reinforcement, this procedure may also allow the clear distinction of the contribution of each type of fiber to the overall composite behavior.

The assessment of the constitutive tensile stress-crack opening behavior has clear benefits in the structural design with SHCC. The numerical modeling of the mechanical behavior of SHCC at the meso-scale level may be based on micro-mechanical parameters like the mechanical properties of the fibers and of the matrix, and the properties of the fiber–matrix interface [20,21]. However, the explicit characterization of the material behavior in terms of the stress-crack width is important to the consistent constitutive modeling [22–24]. The material design process also becomes more efficient when the direct assessment of the tensile stress-crack opening behavior is made possible. In this study, the single crack tension test (SCTT) setup is used to directly assess the tensile stress-crack opening behavior of single fiber and multiple fiber SHCC. As shown in previous research, this procedure allows the direct assessment of the tensile stress-crack opening behavior of SHCC [25–28]. The tensile responses obtained with the SCTT were also analyzed and compared with the behavior of a single crack in multiply-cracked dogbone-shaped specimens under direct tension [28]. In this study the contribution of the single crack tension test to understand the fracture micro-mechanisms and their influence in the tensile performance of fiber reinforced cementitious composites is analyzed, as well as its importance to support the design process of cementitious composites reinforced with multiple types of fibers.

2. Materials and methods

2.1. Materials

The present study is focused on investigating the influence of each type of fiber on the tensile behavior of SHCC, when single or multiple types of fibers are used as reinforcement. Therefore, a similar composition of the cementitious matrix was used in all the tested composites. The cementitious matrix was mainly composed of cement (CEM 52.5 N type I), fly ash (type S), fine sand (0.17 mm), quartz powder and water, with the weight proportions presented in Table 1.

Fibers of three different natures were used: PVA (polyvinyl alcohol), PAN (polyacrylnitrile) and PP (polypropylene). The main geometrical and mechanical properties of these fibers are presented in Table 2.

Considering the extensive experience available with PVA fibers in the design of SHCC (Li2003), a composite formulation containing 2% of PVA fibers was studied. This composite represents a performance reference, when the objective of accomplishing strain hardening ability in tension is considered. As reported in a previous study [28], the composite reinforced with 2% of PVA fibers may be classified as a SHCC. For reference, a composite with 1% of PVA fiber reinforcement was also investigated. The volumetric percentages of the six composites tested are presented in Table 3.

The experimental characterization of the multiple cracking behavior of SHCC is typically carried out using the direct tension tests of dogbone-shaped specimens. The SCTT approaches the problematic of the tensile behavior of these composites from a different perspective, that is, by investigating the tensile behavior of the composite at the level of a single crack. The requirements for the attainment of a single crack with the SCTT were discussed in a previous research study [28]. The SCTT results of the 2% PVA fiber reinforced SHCC were analyzed and compared with the direct tension test results of dogbone-shaped specimens. In particular, the behavior of a single crack in the multiply-cracked dogbone shaped specimen was described during tensile testing and compared with the SCTT results of the same composite [28].

Table 1
Weight of the materials used for 1 dm^3 of cementitious matrix.

Cement	Fly ash	Fine sand (0.17 mm)	Quartz powder	Water
428 g	856 g	150 g	150 g	320 cm^3

Table 2
Main properties of the fibers used.

Fiber	Tensile strength (MPa)	Length (mm)	Diameter (μm)
PVA 15	1600	8	40.0
PP	900	12	40.0
PAN 1.5	826	6	12.7

Table 3
Fiber reinforcement volumetric percentages of the developed fiber reinforced cementitious composites.

Composite	PVA 15% vol.	PAN 1.5% vol.	PP% vol.
1PVA	1	0	0
2PVA	2	0	0
HybPAN	1	1	0
2PAN	0	2	0
HybPP	1	0	1.25
2.5PP	0	0	2.5