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Microstructural analysis and mechanical properties of concrete reinforced with polymer short fibers

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ABSTRACT

The paper focuses on the development of a methodology for quantitative characterization of a concrete containing polymer fibers and pores. Computed tomography (CT) characterization technique is used to provide input data for Finite Element Method (FEM) simulations and analytical modeling based on micromechanical homogenization via the compliance contribution tensor formalism. Effective elastic properties of reinforced concrete are obtained experimentally using compression testing, analytically in the framework of Non-Interaction approximation and numerically performing direct FEM simulations on specimen with reconstructed microstructure. It is shown that CT produces results suitable for implementation in numerical and analytical models. The results of analytical and numerical modeling are in a good agreement with experimental measurements providing maximum discrepancy of $\sim$ 2.5%.

1. Introduction

In countries such as Italy, Greece, and Turkey, earthquakes may create large and diffuse damage to existing buildings, depending on the amplitude and frequency content of the earthquake. An innovative technology for vibration control and risk mitigation of reinforced concrete (RC) structures in this area consists in the use of fibre reinforced concrete (FRC) instead of plain concrete. Mechanical performances of FRC are largely improved with special references to dissipative properties under seismic loads (Harajli & Rtei, 2004; Li, 1993). In particular, synthetic fibres are expected to enhance the dynamic properties of concrete by improving the strength, ductility, and toughness of plain concrete, as well as its damping ratio (e.g. Lanzoni, Nobili, & Tarantino, 2012; Yan, Jenkins, & Pendleton, 2000). Since the concrete matrix is generally stiffer than the reinforcing synthetic fibers, their addition to the concrete mix may also reduce the elastic stiffness of FRC structures, thus lowering their fundamental natural frequencies.

The overall properties of FRC strongly depend on the volume fraction of fibres added to the matrix, as well as on their distribution and orientation. To achieve the best FRC performance, the synthetic fibres should also display good chemical compatibility with cement matrix, thus possessing proper bond characteristics. However, due to their chemical inertia, polymeric materials usually display poor adhesion to the cement matrix (Wu, 1982). In order to enhance the adhesion of

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Table 1
Plain concrete composition used to realize the samples.

Cement		Aggregates, kg/m^3		Water	Ratio w/c
type	kg/m^3	0–2,mm	2–4,mm	kg/m^3	
CEM II 42.5 R	315	1080	800	175	0.56

Table 2
Properties of polypropylene fibers.

L, mm	Diameter, mm	ρ, kg/m^3	σ_{TS}, MPa	E,GPa
18	0.28	1000	300	2.2

synthetic fibres to the cement matrix, several approaches have been proposed such as giving a suitable shape to fibres that may increase the grip (Bentur, Peled, & Yankelevsky, 1997; Lanzoni et al., 2012; Won, Lim, & Park, 2006). Recently, an innovative method of chemical nature (based on a nano-Silica surface treatment) has been proposed for improving the bonding of polypropylene (PP) fibres with the hydration products of the cement matrix (Di Maida, Radi, Sciancalepore, & Bondioli, 2015; Payrow, Nokken, Banu, & Feldman, 2011). The proposed treatment has generally a positive effect on the bending strength and other mechanical properties of FRC (Di Maida, Sciancalepore, Radi, & Bondioli, 2018). In particular, the relatively high tensile strength of synthetic fibres contributes to withstanding the crack initiation stress and resisting pull out force. This is due to the strong bond between the fibre and the cementitious matrix (Di Maida et al., 2015; Radi, Lanzoni, & Sorzia, 2015). Moreover, due to the reduced elastic modulus, synthetic fibres may elongate under loading and transfer the load to different parts of the matrix. As a result, the load applied is distributed more evenly along the interface between fiber and matrix (Noushini, Samali, & Vessalas, 2013).

The main objective of the current study is to develop a methodology for quantitative evaluation of the influence of discrete PP fibre addition on the mechanical properties of FRC by using the combined techniques of computed tomography (CT), FEM analysis, and micromechanical modelling, focusing on its effective elastic properties. We validate our methodology on a concrete containing 0.25 wt per cent of PP draw-wired fibres of length of 18 mm and diameter of 0.28 mm. Static mechanical properties of FRC (i.e. stress vs. strain curves, ultimate compressive strength, indirect tensile strength, modulus of rupture and modulus of elasticity) at the age of 28 days were measured and results compared with that of reference concrete.

Laboratory X-ray Computed Tomography (CT) is an increasingly widely used non-destructive testing technique in concrete research. It allows locating and even quantifying internal structures and defects in concrete (e.g., aggregates, pores, reinforcement) in 3D. Especially, in the case of complex structures like FRC, CT is a useful tool for the evaluation of spatial and orientation distribution of fibres (Bordelon & Roesler, 2014; Mishurova et al., 2018; Rifai et al., 2018). Also the damage in concrete after and during (i.e., *in-situ*) mechanical tests can be estimated (Oesch et al., 2016; Ponikiewski, Gołaszewski, Rudzki, & Bugdol, 2015). Additionally, 3D image date from tomography could be used as input for analytical (Qsymah, Sharma, Yang, Margetts, & Mummery, 2017) and numerical models (Yang et al., 2017), improving the prediction of mechanical behaviour of the concrete.

The paper is organized as follows. Samples preparation is described in Section 2, mechanical testing results are summarized in Section 3. CT measurements are reported in Section 4, analytical and numerical modelling procedures are discussed in Section 5. Finally, the main results obtained by the analyses are reported and discussed in Section 7.

2. Specimens preparation and mechanical testing

Fiber reinforced concrete (FRC) beam-like specimens 150 mm deep, 150 mm wide and 600 mm long were cast and cured according to UNI 12,390–1:2002 and UNI EN 12,390–2:2002. The mix design adopted for the concrete mixture is given in Table 1. Cement and aggregates used for realizing samples accomplish regulations UNI EN 197–1:2011 and UNI EN 12,620:2008, respectively. Note that only fine aggregates with size in the range 0÷4 mm have been used in the FRC samples. This avoids significant scale effects on small samples when subjected to mechanical tests (see Section 3).

Polypropylene discrete draw-wired fibers were incorporated in the mixture at the mixing stage at a dosage of 2.5 kg/m^3, that corresponds to a volume fraction of about 0.25%. The aspect ratio of fibers (i.e. the ratio of the length to equivalent diameter ratio) is 65. The main physical and mechanical properties of fibers are reported in Table 2.

After a curing period of 28 days, beam-like 150 mm x 150 mm x 600 mm specimens have been sawed to small ones - $18 \times 18 \times 60$ mm^3 and $18 \times 18 \times 25$ mm^3 suitable for CT using electromechanical blade (see Fig. 1). Specimens were sawed longitudinally, i.e., along the main direction of the beam highlighted in red in Fig. 1.

In order to characterize the mechanical properties of FRC, another group of specimens has been prepared for compressive tests. The mechanical tests were performed according to the standard UNI EN 1015–11:2001 for cementitious mortars. Accordingly, the compression load was applied through a load cell at a load rate of 50 N/s. Four $18 \times 18 \times 25$ mm^3 specimens were subjected to compression until complete failure (Fig. 2). In order to investigate the effect of fibers orientation, two