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Tensile behaviour of high performance fibre-reinforced cementitious composites at high strain rates

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A B S T R A C T

The promise of fibre-reinforced cementitious composites for dynamic loading application stems from their observed good response under static loading. An experimental research aimed at contributing to the understanding of the behaviour of advanced fibre-reinforced cementitious composites subjected to low and high strain rates was carried out. The material behaviour was investigated at four strain rates (0.1, 1, 150 and 300 s^{-1}) and the tests results were compared with their static behaviour. Tests at intermediate strain rates (0.1–1 s^{-1}) were carried out by means of a hydro-pneumatic machine (HPM). High strain rates (150–300 s^{-1}) were investigated by exploiting a Modified Hopkinson bar (MHB). Comparison between static and dynamic tests highlighted several relevant aspects. First, with the change in the strain rate, the Dynamic Increase Factor (DIF) of the material appears well predicted by some models proposed in the literature up to a value of 0.1 s^{-1}, while at higher strain rates it increases less than expected from models. Moreover, the post-peak behaviour showed a stress plateau influenced by the fibres and dependent on the strain rate.

1. Introduction

The mechanical behaviour of fibre-reinforced cementitious composites when subjected to impact or blast still has many aspects open to investigation [1], with specific reference to large and socially-sensitive structures, as sheltering structures, high-rise buildings, bridges, off-shore platforms, pipelines, gasification reactors, secondary containment shells for nuclear power plants, and tunnels. For such reasons, the mechanical response of concrete structures exposed to blast and impact loading can only be predicted—and controlled—by formulating proper materials models for cementitious composites, including strain rate effects. As a matter of fact, the scanty information provided so far by specialised equipment such as the Hopkinson bar for very high strain rates shows a significant increase in mechanical properties, but this increase still needs to be related to the main engineering parameters. The current understanding of the dynamic response and impact resistance of cementitious composites, and especially of high strength concrete, is very limited. There are also contradictory results in the literature. With reference to compressive behaviour, Banthia [2], Banthia et al. [3], Bentur et al. [4] and Ross [5] reported a reduced value of the ratio between dynamic and static strength with a growing of static strength of concrete, while in the results reported by Bischoff and Perry [6] that ratio is independent of static strength.

High performance fibre cementitious composites are characterised by high toughness and a hardening behaviour in bending. Fibres enhance the ductility of brittle materials like concrete, and this improvement is strictly related to the process by which the load is transferred from the matrix to the fibres and the bridging effect of fibres across the cracks. Fibre pull-out is the principal mechanism contributing to the high toughness of the material and it is the preferred failure mode, rather than the fracture failure mechanism, because of its ability to redistribute stresses. Gokoz and Naaman [7] carried out tests under static condition (with a velocity v equal to 4.2×10^{-5} m/s) and high displacement rate ($\nu = 3$ m/s) for three types of fibres (smooth steel, glass and polypropylene). They concluded that, while polypropylene fibres were very sensitive to the imposed displacement rate, smooth steel fibres were insensitive to it. They also reported that the post-peak behaviour of steel smooth fibres, whose pull-out behaviour is essentially based on friction, was almost insensitive to displacement rate. Banthia and Trottier [8] investigated the pull-out resistance of deformed fibres (hooked end, crimped and I-shaped fibres) embedded in a cement-

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based matrix. They performed a series of static ($v = 8.46 \times 10^{-6}$ m/s) pull-out tests using a hydraulic testing machine and a series of dynamic ($v = 1.5$ m/s) tests carried out by means a pendulum impact device. The study highlighted that deformed steel fibres embedded in cementitious matrixes generally sustain a higher load under impact than under static pull-out and that the pull-out energy is also greater under impact as long as the fibre pulls out and does not fail. Similar results were found by Kim et al. [9]. The authors studied the pull-out sensitivity to loading rates for two types of high strength steel fibres (hooked and twisted) by applying four displacement rates (v was equal to 0.018, 0.18, 1.8 and 18 mm/s). They concluded that the pull-out response of high strength steel hooked fibres showed no appreciable rate sensitivity, and this result was attributed to the fact that microcracking, from which the rate effects are thought to arise, is localised in a small region in the vicinity of the hooks, and therefore should not affect significantly the rate sensitivity. On the other hand, high strength steel twisted fibres showed rate sensitive pull-out behaviour and they attributed this to the radial and longitudinal interface cracking that takes place along the entire embedded fibre length. Since of fibre behaviour, cement matrix and the bond between them (or the pull-out mechanism) are likely dependent on the strain rate, it is expected that the response of fibre-reinforced cementitious composites is also rate dependent: however, the investigation of the rate dependency of the pull-out mechanism cannot conclusively identify the complete rate sensitivity of the composite.

Beginning in the 1980s, various researchers [10–14] studied strain rate effects on the tensile properties of strain-softening fibre-reinforced concrete. They observed a significant increase in tensile strength, strain at maximum stress, and fracture energy due to high strain rates. Moreover, these studies have pointed out that the mechanical properties and rate sensitivity of fibre-reinforced cementitious composites are dependent upon the fibre type, fibre volume fraction and matrix composition, which influences the bond between the fibre and the matrix. Very few studies have investigated on the effect of the strain rate on the tensile behaviour of strain-hardening high performance fibre-reinforced cementitious composites. Kim et al. [15], following the work presented on the fibre pull-out rate sensitivity [9], have investigated the tensile response of High Performance Fibre-Reinforced Cementitious Composites (HPFRCC) to strain rates. The main parameters investigated were the type of high strength steel fibres (hooked and twisted), the fibre volume fraction ($V_f = 1\%$ and $V_f = 2\%$), and the matrix strength using a specimen with a bell-shaped ends geometry. They have investigated four different strain rates from $\dot{\varepsilon} = 10^{-4}$ s^{-1} up to $\dot{\varepsilon} = 10^{-1}$ s^{-1} and between these extremes, the strain rates of $\dot{\varepsilon} = 10^{-3}$ s^{-1} and $\dot{\varepsilon} = 10^{-2}$ s^{-1}. They reported that, in general, the HPFRCC specimens with twisted fibres are generally sensitive to strain rate, whereas their counterparts with hooked fibres are generally not. However, it is important to highlight that the strain rates investigated by Kim et al. [15] are considered as a seismic rate, because they are usually reached during an earthquake, while blast and impact scenarios are characterised by strain rates thousand times greater than seismic ones. Cadoni et al. [16] studied the behaviour of HPFRCC (two different fibres were studied: polyvinyl-alcohol and steel fibres) when subjected to high strain rates ($\dot{\varepsilon} = 50$ s^{-1} and higher) by means of a modified Hopkinson bar (MHB). They observed, after dynamic failure, that steel fibres were pulled-out from the matrix, while the majority of polyvinyl-alcohol fibres experienced tensile failure. The difference in failure could justify the variation in terms of fracture energy as reported by the authors. On the other hand, the tensile strength of the steel fibre composite increases with strain rate while the tensile strength of PVA composites seems to be less sensitive to strain rates, even though it is remarkably increased compared to the static values.

2. Mix design and manufacturing

This research studies a high performance cementitious composite optimised with steel fibres. The mix design of the HPFRCC material is specified in Table 1. The steel fibres were high carbon straight fibres, 13 mm long with a 0.16 mm diameter (aspect ratio l_f/d_f equal to 80); their proportion in the mix was equal to 100 kg/m^3 (volume fraction V_f equal to 1.25%), while the density of the composite material was equal to 2380 kg/m^3. The sand used in the material was sieved up to 2 mm and it can be classified as mixed quartz sand. The mix procedure was composed of several phases. First cement and slag were mixed in dry condition for 2 min, then water and super plasticiser were added and the cement paste was mixed for 5 min. Then the sand was introduced into the cement paste and mixed for 5 min. Finally, fibres were added while the mortar material was mixing. Before casting, its workability was measured by means of a flow test carried out with Abrams cone. A 1.6 m $\times$ 0.60 m in plane slab, 30 mm thick, was manufactured. The slab was cast by applying a unidirectional flow as shown in Fig. 1. In order to guarantee a certain fibre orientation, the properties of the self compacting material were used, taking advantage of the flow direction. Three prismatic beam samples, 40 mm wide and 600 mm long, were sawed from the slab and tested in bending to perform a proper mechanical characterisation of the material according to Italian Guidelines. The high fibre content and the favourable orientation imposed by the casting flow control allow us to guarantee a small dispersion of the response before and after single-crack localisation and a hardening behaviour in uniaxial tension [17–20]. From the bent specimens, several small cylinders 20 mm long, the object of the present work, were cored in the direction of tensile stresses. Their diameter was nominally equal to 20 mm (Fig. 2(a)). Each cylinder cored from each prismatic specimen was notched (notch depth = 1.5 mm), to be tested in uniaxial tension at different loading rates. The specimen identification used in the paper consists in two parts: the first one identifies the strain rate investigated (S0 for the quasi-static tests, S1 for a strain rate equal to 0.1 s^{-1}, S2 for a strain rate equal to 1 s^{-1}, etc.), while the second part is referred to the specimen number. The tests reported are part of a large experimental campaign investigated in Caverzan's PhD thesis. In order to simplify the identification scheme the first part (T20/U-20) was deleted; a reader interested to collect all the data coming from this experimental campaign performed on HPFRCC material and to have a database focused on the HPFRCC mechanical behaviour characterized by different tests type should consider the extended notation (i.e. T20/U-20-S3-1).

3. Experimental procedures

An experimental programme was carried out to properly identify the mechanical properties of high performance steel fibre-reinforced cementitious composites under static and dynamic conditions. In particular, two different mechanical testing machines were used: a hydro-pneumatic machine (HPM) was employed to investigate the strain rate range between 0.1 s^{-1} and 1 s^{-1}, and

Table 1
Mix design.

Constituent	Dosage [kg/m^3]
Cement type I 52.5	600
Slag	500
Water	200
Sand 0–2 mm	983
Fibres ($l_f = 13$ mm; $d_f = 0.16$ mm)	100
Super plasticizer	33 l/m^3