Construction and Building Materials 186 (2018) 525–536

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Tensile constitutive behavior of high and ultra-high performance fibre-reinforced-concretes

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HIGHLIGHTS

- A study about the performances of FR concretes is presented.
- Both flexural and tensile strengths are investigated.
- The experimental program encompasses straight and hooked steel fibers.
- The effect of fiber dosage has been assessed in detail.
- The critical dosage of fibers to ensure hardening behavior is assessed.

ARTICLE INFO

Article history:
Received 3 February 2018
Received in revised form 14 May 2018
Accepted 12 July 2018

Keywords:
Metal-matrix composites
Mechanical properties
Damage mechanics
Mechanical testing

ABSTRACT

High Performance Fibre-Reinforced-Cement-Composites and Ultra-High Performance Fibre-Reinforced-Concretes, also named HPFRCCs and UHPFRCs respectively, are today widely used as repair and strengthening existing structures, such as bridge decks, pavements, piers etc. Simple test methods to characterize its mechanical behavior are requested, in order to ensure that the product meets the designer's requirements, especially in term of tensile behavior. Various test methods are available, even though a proper correlation between direct and indirect tensile (e.g. flexural) tests is needed. In this paper a model based on the "Composite Material Theory" (CMT) was developed to predict the flexural behavior of three commercialized SFRCs once the direct tensile strength is measured. A good agreement was found between experimental results and the values predicted by the model.

1. Introduction

The technology of Steel-Fiber-Reinforced-Concrete (SFRC) has much evolved in the past years thanks to a great number of researches performed on the fiber-based materials [6,12,24,26,13,28,23,25,32] and on their applications in field [14,1,3,20,2]. On the hand, new shapes and types of steels have been developed to improve the fibers performances [4,5,11,27][1], on the other hand, new optimized gradation of granular skeleton have permitted to obtain the high packing density typical of HPFRCC/UHPFRC matrix. These new SFRCs are today largely used to repair and strengthen existing structures. Their success has promoted the development of a number of commercial products manufactured according to technical data sheets. When SFRC is used as repair or strengthening materials, its mechanical behavior must be known a priori by the designer. Due to the heterogeneity of the composite material itself, several parameters affect its mechanical performances, such as fiber properties. Factors such as the aspect ratio of fibers [56], their shape, [53], their dosage [55,55], orientation and distribution [56] within the concrete, proved to strongly affect the mechanical response of the composite material, to the point that these parameters are used to develop predictive models [31,42,43] et al.

It should be noted that a number of standard test methods are available to characterize the tensile behavior of this new generation of SFRCs, by direct and indirect tests. Direct uniaxial tensile tests are preferred to indirect ones (e.g. splitting tension tests),

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[1] Recent studies about FRCs based on synthetic fibers can be found in [15,18,21], whereas time effects in concrete and steel structures have been accounted for in [7–9].

https://doi.org/10.1016/j.conbuildmat.2018.07.099
0950-0618/

whose estimated strength could be affected by the size effect [45–46] and by test set-up. For instance, in [48,48] splitting tension tests were carried out revealing that first tensile cracks opened approximately at a third of the height of the specimen in the loading plane, in conjunction with a wedge rupture below the load bearing strips, and not in the center of the specimen cross section – according to the theory of elasticity, which forms the basis of the calculation formula for the splitting tensile strength applied today –. Any standards propose other indirect tensile tests such as four-point bending flexural test (e.g. [51,49,33]) and three-point bending test set up (e.g. [52,52,49]). Although similar, these two tests yield different results: the three point bending test shows values for modulus of rupture 10% higher than the four-point bending flexural test,[22]. Further investigations pointed out the problem of unexpected crack formation in the vicinity area of the notch of SFRC beams tested with the three point bending technique [51]. The notch area is a disturbed stress region also because the load is applied in this point and because of the influence of shear stresses. As consequence, the SFRC characteristics obtained by three-point bending tests according to [51], are not generally representative for notched SFRC beams, [10]. Four-point tests on un-notched SFRC beams [50] have shown that the deflection is influenced also by the formations of shear cracks appearing outside the pure bending region [10] and therefore the results of the tests are not accurate. A solution to this problem has been proposed by a recent Italian standard [33], that requests notched SFRC beams also for four-point bending tests. Results showed the formation of a limited number of cracks due to the presence of the notch. This condition is preferable for characterizing softening SFRCs for which a single crack is often observed. In addition shear cracks did not occur, thanks to the fact that the section notched was more slender limiting the influence of shear.

Due to the susceptibility to sustain tensile loads, flexural and splitting tests, discussed above, are widely used to characterize the tensile strength for ordinary concretes. Even if the values obtained are not so representative of the true tensile strength, they are interesting in order to compare different batches of concrete or different concretes. Nevertheless for characterize SFRCs a better precision is requested since their major interest and selling point is in their higher tensile strength.

The main purpose of this work is to characterize the tensile behavior of several SFRCs, estimating the relationship between direct and indirect tensile (flexural) tests, according to the "Composite Material Theory" (CMT). Furthermore, a CMT-based model is used to predict the flexural behavior, once the direct tensile strength is measured. A description about the materials and test methods adopted for characterizing their mechanical performances is provided in Section 2. In Section 3, the CMT-based model is presented and results are compared to experimental data. Conclusions are drawn in Section 4.

2. Materials and methods

Three commercially available SFRCs (labeled hereafter A, B and C) with different mix design and fiber dosage, were investigated through compressive, direct dog-bone tensile and four-point flexural bending tests. Compressive tests were performed also to define the strength class of each SFRC investigated. According to [34], A, B and C are HPFRCC, UHPFRC and UHPFRC, respectively. Direct tensile and flexural bending data tests were used also to define the ductility indexes and tensile strength classes, according to [38] (Table 1). The mix design of investigated SFRCs is provided by the manufacturer, see Table 2. Each "premix" – that represents the solid part of each SFRC – contains cement, aggregates (<6 mm) and pozzolans, usually silica fume, even though the amount and type of each compound was not provided by manufacturers.

In each premix a specific superplasticizer is used at high dosage to increase the strength, enhance the durability and give high workability [35]. Because of the presence of superplasticizer the water/cement ratio is very low (< 0.2 for B and C). The manufacturer advises to add in B mixture a set of hardening accelerator to shorten the dormant period and to speed up the hydration process. Specific dosages of steel fibers with a given geometry were suggested by manufactures for each SFRC investigated (Fig. 1). Fibers were carefully dispersed in the fresh mixture.

Mixing HPFRCCs and UHPRFCs requires the use of high intensity mixers, due to their high packing density and the presence of steel fibers as well. In this work a 1.5 kW high shear Zyklos rotating pan mixer was used. The casting of specimens took several working days. Making and curing of specimens for strength tests were made in standard conditions [36].

Standard tests have been performed in order to assess the compressive strength on cubic specimens [37], the direct tensile strength on dog-bone shaped specimens [33], and the flexural strength, by four-point bending flexural tests, on notched [33] and un-notched beam specimens [39]. The geometry of specimens

Table 2
Mix design of SFRCs.

	kg in 1 m^3 of composite		
Material	A: HPFRCC	B: UHPFRC-1	C: UHPFRC-2
Premix	2226	2296	1970
Superplasticizer	22.3	43.13	39
Accelerator	–	10	–
Water	231	184	195
Hooked steel fibers 30/0.35 mm	130 (1.7 %)	–	–
Straight steel fibers 20/0.3 mm	–	195 (2.5 %)	–
Straight steel fibers 13/0.175 mm	–	–	296 (3.8 %)

Table 1
Classification of the investigated SFRCs according to standards.

Class F	F2.0	F2.5	F3.0	F3.7	F4.5	F5.5	F6.5	F7.7	F9.0
$f_{1lk,min}$ (MPa)	2	2.5	3	3.7	4.5	5.5	6.5	7.7	9
Index of ductility		Softening			Plastic			Hardening	
	D_{S0}	D_{S1}	D_{S2}		D_P		D_{H0}	D_{H1}	D_{H2}
$D_{0\ k,min}$	≤ 0.5	$\geqslant 0.5$	$\geqslant 0.7$		$\geqslant 0.9$		$\geqslant 1.1$	$\geqslant 1.3$	$\geqslant 1.55$
Classification							A	B	C
Class							C60/75	C120/140	C110/130
SFRC							HPFRCC	UHPFRC	UHPFRC
Class F							F6.5	>F9.0	F7.7
Class D_0							D_{S1}	D_{S1}	D_{S1}
Class D_1							D_{S0}	D_{S2}	D_{S2}