Cement & Concrete Composites 37 (2013) 246–248

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

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

Influence of fibre geometry and matrix maturity on the mechanical performance of ultra high-performance cement-based composites

Pierre Rossi *

Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR, previously LCPC), Université Paris-Est, France

ARTICLE INFO

Article history:
Received 19 September 2011
Received in revised form 31 July 2012
Accepted 8 August 2012
Available online 24 August 2012

Keywords:
Ultra high-performance cement-based composite
Multi-scale fibre reinforcement
Fibre geometry
Matrix maturity

ABSTRACT

This paper concerns an experimental study of the influence of the geometry of the longest steel fibre and of the matrix maturity on the mechanical behaviour of an ultra high-performance multi-scale fibre reinforced cement-based composite. The following conclusions can be drawn:

- Ultra high-performance cement matrix with a very low water/binder ratio continues to mature and undergoes additional densification over time. This tendency leads to a significant increase of the material modulus of rupture as the age of the material advances.
- In a very dense matrix, the total number of fibres in the matrix and the specific surface of the fibre are more important parameters than the existence or not of hooks at the fibre ends.
- Twisted steel fibres lead to a better material mechanical performance than steel fibres with hooks at their ends.

1. Introduction

For the past several years, IFSTTAR (previously LCPC) has been working on the development of new cementitious composites with the aim of deriving sufficiently resistant and ductile materials that enable designing structures or structural elements without any reinforcements other than steel fibres. These materials constitute a direct implementation of the "Multi-Scale Concept" developed by Rossi et al. [1]. The underlying notion consists of mixing short fibres with longer fibres in order to affect both the material scale (increase in tensile strength) and the structural scale (load-bearing capacity and ductility), which yields a Multi-Scale Cement-based composite (MSCC).

The material considered by the present study lies within the family of MSCC. It contains three distinct steel fibre geometries, i.e. three reinforcement dimensions, all of which constitute a total fibre volume percentage equal to 11% by volume:

- First dimension: fibre length less than 2 mm.
- Second dimension: fibre length between 2 and 6 mm.
- Third dimension: fibre length of 20 mm or more.

The IFSTTAR research program, devoted to this material, comprised mechanical tests to study its mechanical behaviour under different types of loading (static behaviour, behaviour in fatigue, at high loading rates, etc.) and durability tests [2–6]. In the frame of this vast research, quasi-static bending tests have been conducted to study, more especially, the influence of the material age and the geometry of the longest fibre on the mechanical behaviour of this cement-based composite.

2. Mixture designs

Three mixture designs, differentiated solely by the geometry of the longest fibre, have been studied herein, with all other fibres remaining identical and the volume percentage relative to each fibre dimension also identical. The reference mixture design of the material is described in Table 1.

In all three mixtures, the longest fibre is composed of a drawn steel fibre with a high elastic limit ($f_e > 1500$ MPa) and a high strength ($f_t > 2500$ MPa). The geometric characteristics of the three types of fibres used during this experimental campaign are as follows:

- Fibre 1: fibre with hooks at its ends – 25 mm long and 0.3 mm in diameter.
- Fibre 2: twisted fibre – 25 mm long and 0.3 mm in diameter.
- Fibre 3: straight drawn fibre – 20 mm long and 0.25 mm in diameter.

* Tel.: +33 6 80 01 72 26; fax: +33 1 40 43 54 93.
E-mail address: pierre.rossi@ifsttar.fr

0958-9465/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconcomp.2012.08.005

Table 1
Material mix design.

Component	Quantity	Units
Cement	1050	kg/m^3
Sand	514	kg/m^3
Silica fume	268	kg/m^3
Superplasticizer	44	kg/m^3
Total water	211	L/m^3
Steel fibres	858	kg/m^3
Silica fume/cement	0.255	Superplasticizer/binder: 1.02%
Sand/cement	0.49	Density: 2.98
Total water/binder	0.16	

The slenderness, defined as the *fibre length/diameter ratio* $(L_f/_f)$, is about the same for all three fibres, with a value of 83.3 for the first two and 80 for the third fibre. This parameter influences, in part, the mechanical efficiency of the fibre. It is important to report that, concerning the twisted fibre type, Tony Naaman is at the origin of its design and development [7].

3. Specimen production and test protocol

Within the scope of the first series of tests, the two cement-based composites containing Fibres 1 and 3 respectively were tested at the same age of 28 days. A second test series was organised to test the two cement-based composites containing Fibres 1 and 2 respectively at similar ages, i.e. between 10 and 14 months.

All of the specimens tested (for all mix designs taken together) underwent heat treatment, which consists of placing the specimens in an oven at 90 °C for 4 days, at a time 48 h after demolding. Just after this heat treatment, the specimens were protected from humidity exchanges by using two layers of an auto-adhesive aluminium foil and stored in a temperature (20 °C) controlled room.

4. Mechanical tests

The mechanical tests conducted were identical, except for the geometries of the long fibre and the material maturities. The tests involved were four-point bending on specimens of the following dimensions: length – 600 mm, width – 200 mm, thickness – 40 mm. During these bending tests, the distance between lower supports was set at 420 mm and the distance between upper supports at 140 mm. The support system allows for the specimen to move freely in parallel with its length. The test was performed at an imposed jacking speed of 0.3 mm/min; deflection was measured using a special extensometer [2] positioned on the specimen and designed to eliminate parasitic displacements at the level of the supports. Nine bend specimens were tested for each mix design at each material age.

5. Influence of material age

Fig. 1 presents the average *bending tensile stress–deflection* curves representative of the mix design using Fibre 1. One curve is related to a material age of one month at the time of testing, while the other is indicative of an age of more than 10 months. The curves shown are confined to the part prior to the peak load. This figure reveals that the more mature specimens display better mechanical behaviour in bending than the less mature ones with respect to both the modulus of rupture (*bending tensile stress–deflection*) and the corresponding deflection. The relative gain in modulus of rupture amounts to 20%.

Only the evolution in matrix mechanical characteristics, correlated with an increase in matrix level of compactness, provides an explanation for this result. The increase in tensile strength of both the matrix and matrix/fibre interface (caused by a rise in matrix compactness) invariably leads to improved bending behaviour of the composite. It would thus seem that the heat treatment is not a sufficient source for activating the entire set of hydration reactions, especially that involving silica fume. This finding may be explained by the extremely high amorphous silica content (25.5% of cement weight), as indicated in Table 1.

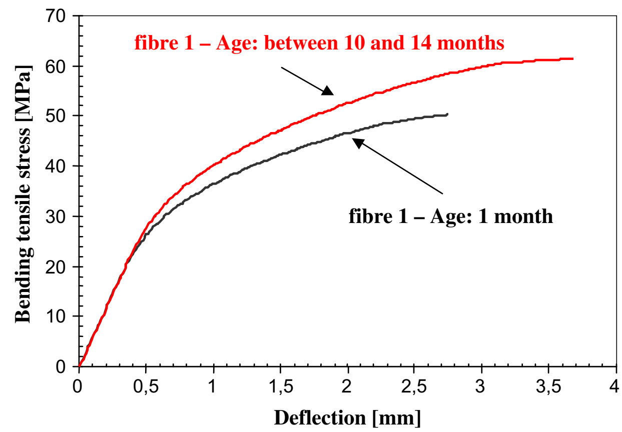

Fig. 1. Bending tensile stress–deflection curves (average curves, 9 results) for Fibre 1 cement-based composite at two different ages.

In order to verify whether this explanation is relevant, it was decided to extract prisms from the bending specimens, thereby making it possible to perform compression tests. It is widely known [8] that the compressive strength of this type of composite is basically due to the compressive strength of its matrix and hence to its compactness.

To resume, for evaluating the possible increasing of the tensile strength of the matrix and of the matrix/fibre interface, the compressive strength of the matrix is a good mechanical indicator. For the two maturity levels, compression specimens were extracted by means of sawing into the previously-tested bending specimens, in an area however beyond the constant moment zone. The compression specimens were prisms 180 × 80 × 40 mm in dimension.

The average compressive strengths of the specimens were respectively 225 MPa and 268 MPa, as matrix aging extended from 28 days to over 10 months. A gain of approximately 19% could therefore be observed, which remained close to that obtained during the bending test campaign. This supports the hypothesis that hydration reactions continue after heat treatment, even for the extremely low water to binder ratio considered.

6. Influence of the longest fibre geometry

Fig. 2 shows the average *bending tensile stress–deflection* curves related to the two mix designs containing, respectively, Fibres 1 and 3. Both materials were 28 days old at the loading date. Fig. 3 then presents the average *bending tensile stress–deflection* curves that depicted the two mix designs containing, respectively, Fibres 1 and 2. The age of these two materials was between 10 and 14 months.

According to Fig. 2, the mixture design containing Fibre 3 leads to a mechanical behaviour in bending significantly stronger than that associated with the mixture design containing Fibre 1. The objective differences between the two mix designs were the following:

- Fibre 1 offered a better mechanical anchorage than Fibre 3 since it had hooks at its ends.

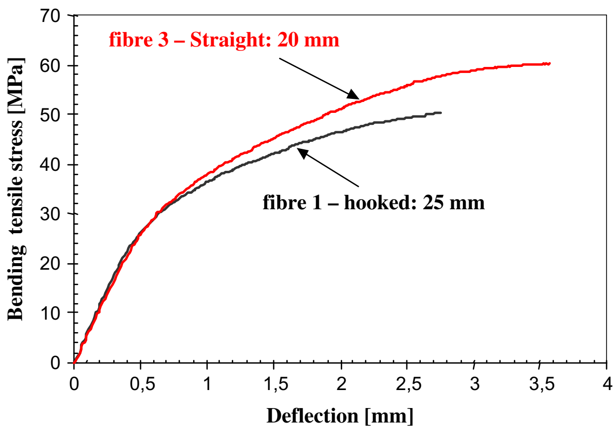

Fig. 2. Bending tensile stress–deflection curves (average curves, 9 results) for Fibre 1 and Fibre 3 cement-based composites at the same age.

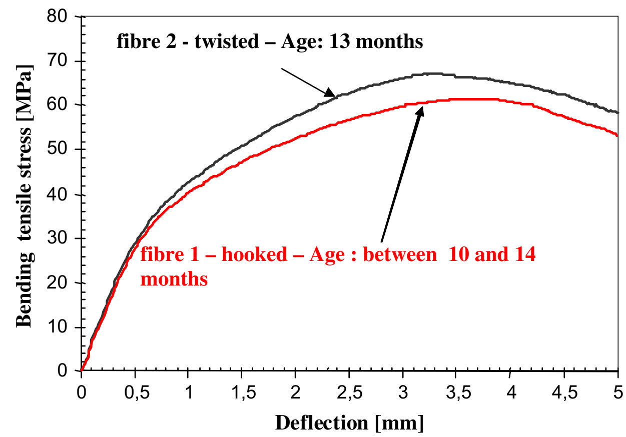

Fig. 3. Bending tensile stress–deflection curves (average curves, 9 results) for Fibre 1 and Fibre 2 cement-based composites at the same age.

– Fibres 3 were 1.8 times more abundant in the matrix than Fibres 1, for a given volume percentage.

A steel fibre that acts on a crack dissipates energy in two forms: by friction along the fibre; and by plasticization at the level of the mechanical anchorages. As the level of the matrix compactness drops, fibre plasticization (when the fibre is working) exerts greater influence with respect to total dissipated energy during rupture of the composite fibre. In contrast, with a more compact matrix, the frictional form of energy dissipation is preferred. It becomes critical therefore to compare the total frictional surface area generated by the two fibre dimensions.

Knowing the fibres dimensions and the n_1/n_2 ratio, where n_1 and n_2 are the total numbers of hooked and straight fibres, respectively, it is easy to calculate the $_1/_2$ ratio, which is the total frictional area of the hooked fibres to that of the straight ones. It is found that $_1/_2 = 0.84$.

Fig. 2 shows that the modulus of rupture increases by approximately 20% when changing from a hooked fibre to a straight fibre (50 and 60 MPa thresholds, respectively), which underscores the apparent pertinence of the relationship between this rise in strength and the increase in total frictional surface area.

If the Fig. 3 is considered, it can be observed that the mixture design containing Fibre 2 generates a stronger mechanical behaviour in bending than the mixture design containing Fibre 1, with their geometry as unique difference between them. Fibre 1 has hooks at its ends, whereas Fibre 2 is twisted over its entire length. The most plausible hypothesis to explain this difference, in remaining consistent with the findings discussed above, is that the fibre–matrix friction generated by the presence of twists is greater than that inherent in the smooth fibre. Moreover, it is worthwhile to point out that when taking into account the fact that the modulus of rupture of the composite increases by 20% as the age of the matrix extends from 1 month to more than 10 months, the materials composed of Fibres 1 and 3 display similar bending behaviour.

7. Conclusions

The primary results from studying the influence of two parameters (age of cement matrix and geometry of the longest fibre) on the bending behaviour of specimens of an ultra high-performance fibre cement-based composite with multi-scale reinforcements can be summarised as follows:

– Despite application of a heat treatment, the ultra high-performance cement matrix with a very low water/binder ratio continues to mature and density over time. This tendency leads to a significant increase (20%) in the material modulus of rupture as the age of the material advances from 1 month to over 10 months (with a maximum of 14 months examined in the present study).
– Two solutions would appear relevant in the effort to improve the material's bending behaviour:
  - To choose fibre dimensions that enable, given a similar length/diameter ratio, expanding the total frictional surface area between fibres and matrix.
  - To choose fibre geometries that allow increasing the level of friction between the matrix and the fibre. With this objective in mind, a twisted fibre is more effective than a fibre with hooks at its ends.

References

[1] Rossi P, Acker P, Malier Y. Effect of steel fibres at two stages: the material and the structure. Mater Struct 1987;20:436–9.
[2] Rossi P, Arca A, Parant E, Laurence O, Fakhri P. Bending and compressive behaviours of a new cement-based composite. Cem Concr Res 2005;35:27–33.
[3] Parant E, Rossi P, Boulay C. Fatigue behaviour of a multi-scale fibre reinforced cement composite. Cem Concr Res 2007;37:264–9.
[4] Parant E, Rossi P, Le Maou C. Durability of fatigue behaviour off a multi-scale fibre reinforced cement composite. Cem Concr Res 2007;37:1106–14.
[5] Parant E, Rossi P, Jacquelin E, Boulay C. Strain rate effect on the bending behaviour of a new ultra-high performance cement composite. ACI Mater J 2007;104(5):458–63.
[6] Rossi P, Parant E. Damage mechanisms analysis of a multi-scale fibre reinforced cement-based composite subjected to impact and fatigue loading conditions. Cem Concr Res 2007;38:413–21.
[7] Naaman AE. Engineered steel fibers with optimal properties for reinforcement of cement composites. J Adv Concr Technol 2003;1(3):241–52.
[8] Rossi P. Les Bétons de fibres métalliques. Paris: Presses de l'Ecole Nationale des Ponts et Chaussée; 1998 [in French].