Construction and Building Materials 168 (2018) 906–922

Contents lists available at ScienceDirect

Construction and Building Materials

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

Fiber geometrical parameters of fiber-reinforced high strength concrete and their influence on the residual post-peak flexural tensile strength

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HIGHLIGHTS

- This work show empirical relations between fiber geometrical parameters and strength in FRHSC.
- Prismatic specimens scanned using a CT-Scan to extract position and orientation of each fiber.
- Fiber distribution and orientation show high scatter and it has a strong influence on the mechanical behavior.
- A strong relation between tensile strength and fiber efficiency index and fiber density can be empirically determined.
- CT-Scan will become a useful tool, where different dosages and building procedures need to be tested.

ARTICLE INFO

Article history:
Received 27 May 2017
Received in revised form 2 February 2018
Accepted 15 February 2018

Keywords:
Fiber density
Fiber orientation
CT-Scan technology
Fiber reinforced high-strength concrete
Residual flexural tensile strength

ABSTRACT

The mechanical behavior under flexural tensile stress of fiber-reinforced concretes is strongly conditioned by fiber density and orientation; in particular, the residual strength values under tensile stress forces. However, although a lot of research has been conducted to understand how the casting and type of compaction affects the fiber distribution and orientation, up to date neither fiber location nor fiber orientation can be controlled during the concreting process. The uncertainty of fiber distribution within the material implies scatter results, in such a way that apparently identical fiber-reinforced concrete specimens can show very different results, in terms of mechanical behavior. The use of CT-Scan technology means that the exact location and orientation of the fibers within a concrete specimen may be depicted. In addition, as a non-destructive test, it can be done prior to mechanical testing.

This paper studies the relation between fiber density and orientation and behavior under flexural tensile stress, through the use of CT-Scan technology. To do so, a high-strength steel-fiber reinforced concrete wall was constructed and 8 $100 \times 100 \times 350$ mm prismatic specimens were extracted from different sections of the wall, with the intention of revealing different fiber density and orientation values. First, the specimens were scanned using a CT-Scan, to obtain the real fiber density and orientation values. Subsequently, they were tested in a three-point-bending test, to obtain the curves tension – CMOD, and LOP values and residual strength under tension. Finally, empirical relations are shown between those values and fiber density and orientation.

1. Introduction

Fiber-reinforced concrete has become a very interesting solution in construction, because of the reduced workforce needed to cast concrete elements using them, resulting in significant savings. The presence of fibers can reduce and even eliminate the presence of passive reinforcement. In the case of concrete pieces with a very complex geometry, the arrangement of conventional reinforcement can be a problem. The use of fiber-reinforced concrete can be a solution, especially in combination with self-compacting concrete [1,2].

Model Code 2010 [3] permits the use of fiber-reinforced concrete in structural components. Its equations yield the values of residual flexural tensile strength ($f_{R,i}$), provided by fibers, particularly, those with crack openings of 0.5 mm ($f_{R,1}$) and 2.5 mm ($f_{R,3}$). Those values are obtained from a tensile stress curve – CMOD, on an empirical basis, as they are specific to each concrete.

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https://doi.org/10.1016/j.conbuildmat.2018.02.095
0950-0618/

The values of residual flexural tensile strength are strongly conditioned by the amount of fibers and by their orientation. In the case of orientation, it has been noted that the fibers work more efficiently when they are aligned in parallel to the tensile stress direction, and, in consequence, the greater the residual tensile strength of the concrete [4,5].

However, the main disadvantage is that the orientation of the fibers is unknown and, more importantly, is not controllable. There is much research that focuses on estimating the expected fiber orientation, through the development of flow models [6–8], although without conclusive results. Over recent years, research has been performed with the aim of controlling fiber orientation, with the objective of finding out how they can be arranged in a given direction from a numerical and/or experimental point of view [9–11]. The fibers tend to follow an orientation contained on their plane, in the proximity of the specimen mouldings. Moreover, they tend to position themselves in a perpendicular direction around the passive reinforcements [12,13]. In relation to this observation, much research has highlighted the existence of a scaling effect on the residual flexural tensile strength [14–16].

There is much research that analyses the influence of fiber orientation on residual flexural tensile strength [17–20]. However, in all cases, fiber orientation is merely approximated and never measured. In these cases, the specimen manufacturing processes have been developed with the aim of conditioning a dominant fiber orientation. In those works, the hypothesis that the fibers of all the specimens show that orientation is assumed, without taking into account that the process is not perfect and that not all of the fibers present the expected orientation.

In the case of density, there is a direct relation between fiber density and the residual strength of the specimen, in such a way that the greater the fiber density, the greater the residual strength of the concrete. However, there is no linear relation, given that the fibers are not uniformly distributed in the structure. In the case of walls, for example, the heaviest fibers tend to fall to the bottom, while the lightest tend to accumulate (tending to float) in the highest part. In the case of slabs, disgregation commonly occurs in the mixture [21–23].

In a similar way to the above, different series of specimens with different fiber densities are performed in works that analyse their influence and it is implicitly assumed that their distribution is totally uniform.

This research has the purpose of determining the residual flexural tensile strength ($f_{R,i}$) of high-strength fiber-reinforced specimens, the fiber distribution of which was previously determined using a Computed Tomography Scan (CT-Scan). This technique has been intensively used over recent years for the measurement of fibers orientation and distribution in fiber-reinforced concretes [24,25].

2. Experimental program

In this work, a total of 8 prismatic specimens, measuring 100 × 100 × 350 mm, were analysed following their extraction from a 1000 × 400 × 100 mm wall. Each specimen was extracted from a different region of the wall and, in addition, in accordance with a different alignment. In consequence, each specimen showed different fibers densities and orientation. All the specimens were scanned before the completion of the three-point-bending tests to establish its particular fiber orientation and distribution.

Next, the material, the manufacturing process of the specimens and the scanning process are described.

2.1. Materials

The wall was manufactured with high-strength steel fiber-reinforced concrete. Mix proportions are shown in Table 1. The maximum size of the aggregate was 12 mm.

Hooked-end steel fibers of 45 mm in length and 1.2 mm in diameter (diameter/length 37.5) were used. The tensile strength of the fibers was 1700 MPa. The fibers used show a low aspect ratio. It was required to use fibers with a "big" diameter, in order to facilitate their identification using the CT-Scan. In addition, the relatively small length of the fibers allows that their orientation is not so strongly conditioned by the formwork. However, the fibers are not very efficient, from a structural point of view, and a higher amount of fiber is needed to reach a good mechanical behavior. As shown in Table 1, 140 kg/m^3 (1.78% in volume) of fibers have been considered. This is a value higher than the one recommended by the fibers' supplier (around 1% in volume). The explanation is that a concrete in which structural fibers replaces completely passive reinforcement has been designed, i.e., a fiber content that provides mechanical capacity to the concrete without the need of additional rebars has been considered. Since the structural effectivity of these fibers is low, an extra amount of fibers are needed.

A total of 7 cylindrical specimens of 150 mm in diameter and 300 m in height were manufactured to characterize the concrete: four underwent uniaxial compressive testing and three underwent diametric compression testing. The parameters obtained from the material were, compressive strength, tensile strength (according to EN 12390-6:2009 [26]) and elasticity modulus. European standard EN 12390-13:2013 [27] was used to obtain the modulus of elasticity. In Table 2, the mechanical parameters of the concrete are shown. The data between the parentheses represent the standard deviation.

2.2. Specimen manufacturing process

The specimens were cut from a concrete wall measuring 1000 × 400 × 100 mm (Fig. 1). The pouring of the concrete was done from the upper face and its vibration was done with a conventional needle vibrator. Since there was a small pouring height (maximum 400 mm), concrete was poured directly from the top, moving the pouring point along the top of the mould, from one end to the other.

The concrete wall was maintained at 20 °C and 100% humidity for 3 days, until it reached enough consistency to remove the mould and cut the specimens. A total of 8 specimens were cut from

Table 1
Mix proportions.

Cement (kg/m^3)	400
Water (kg/m^3)	125
Superplasticizer (kg/m^3)	14
Nanosilica (kg/m^3)	6
Fine aggregate (kg/m^3)	800
Coarse aggregate (kg/m^3)	1080
Fiber (kg/m^3)	140

Table 2
Mechanical parameters of concrete.

$f_{c,m}$ (MPa)	82.1 (4.6)
$f_{ct,m}$ (MPa)	6.0 (0.6)
E_{cm} (MPa)	45144.3 (1562.2)