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Time-dependent flexural behaviour of cracked steel fibre reinforced self-compacting concrete panels

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ABSTRACT

In the present work the results of an extensive experimental programme that aims to study the long-term behaviour of cracked steel fibre reinforced self-compacting concrete, SFRSCC, applied in laminar structures are described and discussed. In a first stage, the influence of the initial crack opening level ($w_{cr} = 0.3$ and 0.5 mm), applied stress level, fibre orientation/dispersion and distance from the casting point, on the flexural creep behaviour of SFRSCC was investigated. Moreover, in order to evaluate the effects of the creep phenomenon on the residual flexural strength, a series of monotonic tests were also executed. It was found that $w_{cr} = 0.5$ mm series showed a higher creep coefficient compared to the series with a lower initial crack opening. Furthermore, the creep performance of the SFRSCC was influenced by the orientation of the extracted prismatic specimens regarding the direction of the concrete flow within the cast panel.

1. Introduction

Discrete fibres are increasingly being used in the construction industry to overcome the brittle nature of plain concrete under tension, and either to avoid or reduce the use of conventional steel reinforcement. In fibre reinforced concrete, FRC, macro-cracks that arise within the cementicious matrix are bridged by fibres randomly distributed in the concrete. The fibres are able to transfer the stresses across the crack's surfaces improving the tensile post-cracking strength that enhances the composite's toughness and crack growth control, resulting in favourable effects in terms of load carrying capacity, ductility and durability of structures made by FRCs. It has been investigated extensively that mechanical properties of steel fibre reinforced concrete, SFRC, depend on both the fibre orientation and distribution [1–3]. Moreover, discrete fibres are more effective when preferentially aligned along the directions of the principal tensile stresses.

The effectiveness of a fibre as a reinforcing element becomes more predominant after it has been crossed by a crack. Determination of the tensile post-cracking behaviour of SFRC has been widely studied, either by direct or indirect tests [4–8]. However, regarding the long-term response of this composite, the available knowledge in literature is still somehow quite scarce.

The creep deformation of the material could ultimately lead to the failure mechanism of the structural element at a lower load than static ultimate load [9]. On the other hand, in some structural systems, the long-term deformation of the structural element can be beneficial, since it enforces stresses to redistribute, which can limit the crack propagation. From another point of view, if the creep deformation damages significantly affect the fibre/matrix interface bond, it will lead to an undesirable excessive decrease on the post-cracking strength, thus the influence of creep will be adverse [10]. Some information is available in literature regarding the time-dependent behaviour of FRC in the cracked state [10–14]. However, many of them mainly assessed the creep behaviour of concrete reinforced with synthetic fibres [15–17]. It was reported that the cracked micro/macro-synthetic fibre reinforced concrete presented significant crack widening over time under sustained uniaxial tensile load [9,18]. There are also some works regarding the creep evaluation of steel fibre reinforced concrete under uniaxial tensile loading [19,20] and flexural loading [10,14]. It was showed that application of steel fibres in concrete limited long-term crack widening considerably [13,21]. It is worth noting that focus of the mentioned studies was principally on the beams where, in the case of using steel fibre reinforced self-compacting concrete, the rotation of the fibres due to the concrete flow was completely distinct of planar structures [22,23].

Creep in bending of a cracked SFRC element is the result of the following phenomena: concrete creep in compression (produce basic creep); fibres creep at material level in tension; loss of fibre–matrix adherence and subsequent fibre free-sliding. Creep of fibres are only significant in fibres susceptible to thermo-hygrometric effects, not in the case of the steel fibres. It was shown that the time dependent alterations in the fibre–matrix interface zone influence significantly the long-term fibre reinforcement effectiveness, and, consequently, the creep behaviour of cracked fibre reinforced concrete [9,18]. The crack width opening and progression with time are strongly dependent of the long-term behaviour of concrete, load and environmental conditions. Therefore, it is important to evaluate the concrete capability to

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maintain the crack opening width relatively low under a sustained load, in order to guarantee the effectiveness of fibres under serviceability conditions. Moreover, despite being available some standards for designing SFRC structures [24,25], it seems that they still not take into account the long-term behaviour under cracked conditions. Therefore, information regarding the long-term behaviour of cracked SFRC elements, particularly planar structures, is still limited. Consequently, understanding the behaviour of cracked SFRC elements under a sustained load will help towards a more rational design and accurate prediction of the composite behaviour under serviceability conditions.

In the present work an extensive experimental programme that aims to study the long-term behaviour of cracked steel fibre reinforced self-compacting concrete, SFRSCC, is described. For this purpose, prismatic specimens were extracted from a SFRSCC panel cast from its centre, and the relevant results obtained from the creep tests with these specimens are presented and discussed. The influence of fibre orientation and dispersion on the creep behaviour of cracked SFRSCC elements was appraised. This was achieved based on the angle between the extracted specimen's notch plane and the expected concrete flow direction, since extracted specimens were notched in distinct directions. The prismatic specimens were previously subjected to a four-point bending test up to a certain crack width opening ($w_{cr} = 0.3$ and 0.5 mm). Then the bending test was carried out under a sustained load until the stabilization of the crack width opening. In a first stage the influence of the initial crack opening level, applied stress level [50–100%], fibre orientation/dispersion, and distance from the casting point on the flexural creep behaviour was investigated. Afterwards, the specimens used in the flexural creep tests were subjected to an instantaneous four-point bending test until failure. Finally, a series of instantaneous four-point bending tests were also executed on uncracked prismatic specimens, in order to quantify the influence of the creep phenomenon on the evolution of the flexural residual strength.

2. Experimental programme

2.1. Concrete mixture

A SFRSCC was produced according to the mixture composition given in Table 1. W/C abbreviates water (W) to cement (C) ratio. Superplasticizer Sika® 3005 (SP) has been used to assure the required self-compactibility requirements due to the low water content. A crushed granite coarse aggregate was used with a maximum aggregate size of 12 mm. A fibre content of 60 kg/m^3 of hooked-end steel fibres was used. The fibres had the following characteristics: 33 mm of length, l_f; 0.55 mm of diameter, d_f; aspect ratio, l_f/d_f, of 60 and a yield stress of about 1100 MPa. The fresh concrete behaviour was determined by the Abrams cone slump test in the inverted position according to EFNARC recommendations [26]. The spread diameter was approximately 590 mm.

The SFRSCC's compressive strength was assessed by testing 6 cylinders with a diameter of 150 mm and a height of 300 mm. After casting, the specimens were stored in a climatic chamber room at constant temperature of 20 °C and relative humidity of 60%. The cylinders were tested at the age of 28 days, and an average compressive strength and an average young modulus of 72 MPa and 42.15 GPa was obtained, respectively, with a coefficient of variation (CoV) of 8.23 and 0.26%, respectively.

2.2. Specimens

The panel represents the outer layers of a sandwich panel conceived under the framework of a research project for the development of modular prefabricated affordable houses [27,28]. The casting of this panel for the SFRSCC cracked creep tests was performed from its geometrical centre. However, previous research has revealed that this casting procedure improves the residual tensile behaviour since due to the circular distribution of fibres through the panel, a higher number of effective fibres exist in order to bridge the radial cracks formed when the panel was loaded from its centre [29]. The fresh concrete was poured directly from a mixing truck by a U-shape channel almost in the vertical position into a mould with the dimensions of 1500 × 1500 mm^2 in plan and 60 mm of thickness. A total of one hundred and twelve prismatic specimens with the dimensions of 240 × 60 × 60 mm^3 were extracted from distinct locations of the panel. The orientation of the extracted prismatic specimens within the panel was established having in mind the expected concrete flow direction, see Fig. 1(a). In this scheme, the light grey solid hatched specimens were used for assessing the long-term behaviour, whereas the rest of the specimens were tested under instantaneous monotonic load conditions at the same age of the specimens cracked for the creep test. Since the panel was cast in its centre point, the symmetry of the panel assures that for each specimen in the creep test, there will be a mirror specimen on the other side of the panel for the execution of the monotonic test to estimate the effects of creep crack width propagation on the residual strength. For instance, in Fig. 1(a), specimen L-7.5°-8 was tested under monotonic load condition while specimen L-0.5-7.5°-5 was used for the creep test. After the extraction of the prismatic specimens, a notch was executed at its middle length. The notch depth and thickness were 10 and 2 mm, respectively.

The influence of the crack plane orientation towards the expected concrete flow was assessed in four different directions. The orientation of the notched plane was defined accordingly to the following strategy: by considering β as the angle between the direction of the concrete flow and the notched plane direction, four series of prismatic specimens with different notched plane orientations towards the concrete flow directions can be defined (Fig. 1b). Fig. 1 depicts a scheme of the adopted classification methodology based on the angle β. The four intervals established for the angle β were [0–15°[, [15–45°[, [45–75°[and [75–90°]. Since in previous research [1] it was found that the radial flow of the SFRSCC promotes a preferential fibre alignment perpendicularly to the flow direction, the present adopted strategy enables to appraise the influence of fibre orientation, at a certain distance from the casting position, on the instantaneous force-crack width (σ-w) and on the creep coefficient–time (φ–t) relationships. Hereinafter, each series was designated by an alphanumeric string according to: in the case of the specimens for the long-term tests, the first character represents the distance from the casing point (L—Low: [0–375 mm]; A—Average: [375–565 mm] and H—High: [565–750 mm]); the second numeral refers to the two studied pre-crack widths (w_{cr}), 0.3 and 0.5 mm; the third numeral defines the β angle, in degrees, for four intervals of the relative orientation between the notched plane and the SFRSCC flow lines (7.5: [0–15°[, 30: [15–45°[, 60: [45–75°[and 87.5: [75–90°]), and the last numeral represents the number of the series' specimen. For instance, L-0.3-7.5°-1 represents the specimen number 1 located at a low distance from the casting point, with a pre-crack width of 0.3 mm, and with an angle β in the [0–15°[interval. A similar strategy for the designation of the instantaneous monotonic test

Table 1
Mix design of steel fibre reinforced self-compacting concrete per m^3.

Cement [kg]	Water [kg]	W/C [−]	SP [kg]	Filler [kg]	Fine sand [kg]	Coarse sand [kg]	Coarse aggregate [kg]	Fibre [kg]
413	124	0.30	7.83	353	237	710	590	60