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INFLUENCE OF FIBRE REINFORCEMENT ON THE LONG-TERM BEHAVIOUR OF CRACKED CONCRETE

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Abstract

The influence of fibre reinforcement on the long-term behaviour of cracked concrete is analysed in this work by means of a creep test. Nine concrete mixes were prepared (7 SFRCs and 2 conventional RCs) based on two basic mix designs. Concretes type I were conceived for structural precast applications and concretes type II reproduce a general purpose. Fibre dosages and conventional reinforcements were varied to represent a wide spectrum of post-peak flexural responses. In all cases with fibre reinforcement steel fibres were used. Conventional RC specimens were reinforced with two steel rebars. In addition to the variables of mix design of concrete, there are two significant variables related to the creep test: the pre-crack opening level ($CMOD_{pn}$) and the stress level (I_c) sustained during the test. Creep tests were performed by applying a constant flexural load on notched pre-cracked specimens and controlling crack opening evolution. Some of the specimens developed a sudden increase of crack opening deformations during the creep test. Creep coefficients and Crack Opening Rates were calculated and analysed. Creep coefficients show significant dependence on the analysed variables. The results of this experimental campaign show that creep of SFRC specimens may be similar to a traditional RC.

Keywords: Creep, Steel Fibre Reinforced Concrete, SFRC, steel fibres, long-term, crack opening.

1. INTRODUCTION

The knowledge of the concrete materials and properties is essential to better assess their structural applications, not only in terms of instantaneous responses but also in the long-term along the service life.

Creep is a term used to define the tendency of materials to develop increasing strains through time when under a sustained load. Commonly, the increasing strains are accounted for by means of creep coefficients that relate long-term strains with respect to short-term strains. The long-term strains of concrete have been reported to become multiple times larger than the initial instantaneous strain [1]; therefore, creep becomes an important factor to be considered.

Long-term strains can be beneficial to some types of structures because they can lead to stress redistributions that can limit the extent of cracking. At the same time, in the case of decreasing residual strength or significant strains the influence of creep may be unfavourable.

In many applications, fibres have been included in concrete to improve structural serviceability based on benefits in crack control [2]. The mechanical behaviour of fibre reinforced concrete (FRC) has been widely studied over the past decades [3], and important advances have been achieved regarding the residual strength characterization and applications of FRC [2]. On the other hand the analysis of flexural creep behaviour of cracked FRC elements is a relatively new topic which has not been entirely researched yet. However, there is no standardized method to assess such behaviour at this time, and some researchers are working on proposals [1,4].

When considering combinations of reinforcing bars and fibres, studies have shown that the addition of steel fibres considerably reduces the time-dependent deflection and crack widening of reinforced concrete [5,6]. However, in terms of structural design, recommendations and codes do not take into account the long-term behaviour under cracked conditions.

As the contribution of fibres to structural load-bearing capacity is based on the flexural response of FRC, and mainly in the cracked state, the capacity of the material to keep the crack opening values low enough is a topic of interest to be assessed [4]. Although residual strength parameters are applied in structural design, the knowledge of the long-term behaviour of FRC in cracked conditions is limited to a few reports on the subject [1-3,5,7-9].

The study of creep behaviour of cracked FRC constitutes a key point of interest mainly for cases in which fibres are the only reinforcement. In these cases, serviceability of the material will depend on its capacity to transfer the sustained stresses through the fibres and the stability of the cracks [5].

A previous study on cracked SFRC [10] has found low coefficients of creep at different long-term load levels for a 90-day period, but the type of fibre, the load level and the concrete strength significantly affected the creep behaviour. Besides, it is not possible to uncouple the behaviour of concrete from that of the fibres because of the post-cracking creep phenomena in SFRC is not caused by deformation of fibres, but rather by pullout of the fibres from the matrix [5].

This paper studies the influence of fibre reinforcement on long-term behaviour of cracked SFRC by means of a creep test with the aim of analyzing not only creep coefficients but also Crack Opening Rates.

2. EXPERIMENTAL PROGRAM

2.1. Materials and mix design

Nine concretes were prepared based on two concrete base mix designs as presented in Table Seven steel fibre reinforced concretes (SFRC) and two conventional reinforced concretes (RC) were included. Concretes type I were conceived to simulate a concrete for structural pre-casting purposes with a compressive strength higher than 40 MPa, and concretes type II were designed to reproduce general purpose concretes with a 10 or 20 mm maximum aggregate size and a specified compressive strength ranging from 25 to 35 MPa.

For type I concretes a cement CEM I 52.5R type and a polycarboxylate-based high-range water reducing admixture were used, whereas for type II concretes the cement was I 42.5R SR or CEM II/BM 42.5R. In those cases the water reducer was a poly-functional plasticizer. The dosage of plasticiser was adjusted for each concrete to obtain a 100 ± 20 mm slump. For all concretes, sand and coarse aggregates were crushed limestone.

Table 1. Base mixture proportions and concrete properties

Parameter	Concrete type	
	I	II

Compressive strength (f_c)	≥40 MPa	25-35 MPa
Cement type	CEM I 52.5R	CEM I 42.5R SR CEM II/B-M 42.5R
Cement amount	375 kg/m^3	325 kg/m^3
W/C	0.5	0.6
Fibre application	Structural-precast	Pavements
Fibre volume (V_f)	40 and 70 kg/m^3	40 kg/m^3
Maximum aggregate size (MAS)	10 mm	10 and 20 mm
Admixture	High-range water reducer	Poly-functional plasticizer

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2.2. Reinforcements

Fibre dosages and conventional reinforcement were designed to obtain a wide spectrum of post-peak flexural performance. In all cases of fibre reinforcement steel fibres were used. Some characteristics of the steel fibres used are given in Table 2~~Table 2~~.

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Table 2. Characteristics of fibres used

Designation	Slenderness (λ)	Length (mm)	End type	Type
Dramix RC 80/35 BN	80	35	Hooked	Cold drawn
Dramix RC 80/50 BN	80	50	Hooked	Cold drawn
Dramix RC 65/40 BN	65	40	Hooked	Cold drawn
Dramix RL 45/50 BN	45	50	Hooked	Cold drawn
Fibrocev F-Due 50/30	50	30	Straight	Cut sheet

Concrete specimens without fibres as reinforcement, both for characterisation and creep tests, were reinforced simulating a traditional RC by means of two steel rebars positioned as shown in Figure 1~~Figure 1~~.

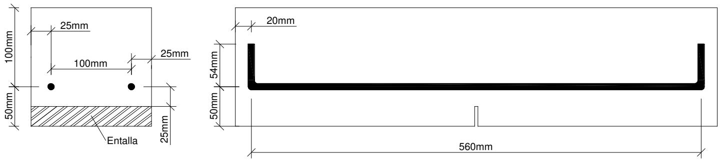

Figure 1. Rebar reinforced specimens

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Table 3~~Table 3~~ summarises for all designations of batches the reinforcement characteristics like fibre dosages, fibre brand and dimensions of traditional reinforcement.

Table 3. Mix proportions tested

Concrete type	Designation	Reinforcement	Type	Dosage [kg/m^3]

Type I	I-80/35-40-10	Fibres	RC 80/35 BN	40
	I-80/35-70-10	Fibres	RC 80/35 BN	70
	I-80/50-40-10	Fibres	RC 80/50 BN	40
	I-2Ø8	Steel rebars	8 mm bars (x2)	
Type II	II-80/50-40-20	Fibres	RC 80/50 BN	40
	II-65/40-40-20	Fibres	RC 65/40 BN	40
	II-45/50-40-20	Fibres	RL 45/50 BN	40
	II-50/30-40-10	Fibres	F-DUE 50/30	40
	II-2Ø6	Steel rebars	6 mm bars (x2)	

2.3. Test specimens

Both FRC and RC specimens were cast in 150x150x600mm size moulds, cured and prepared by following the recommendations of the EN 14651:2007 standard **Error! Reference source not found.**~~[11]~~ for flexural tests.

Compaction was carried out by external vibration in order to avoid any differential effect on the fibre orientation along the control section among the tested concretes.

Prior to the test, specimens were rotated over 90º around their longitudinal axis and then notched by sawing through the width of the test specimen at mid span. The notch depth was 25 mm.

All batches were tested and characterised in terms of their compressive strength and flexural residual strength.

2.4. Test variables

Variables related to concrete mix design that influence mechanical behaviour of the concrete were selected to cover a wide range of post-peak flexural response of the SFRC elements as shown in Figure 2~~Figure 2~~. As observed, there are concretes showing an increase in the residual strength on cracked state (strain hardening behaviour), concretes that keep the load bearing capacity practically constant (flat post-peak region) and concretes with steep losses of residual strength after first crack (softening behaviour).

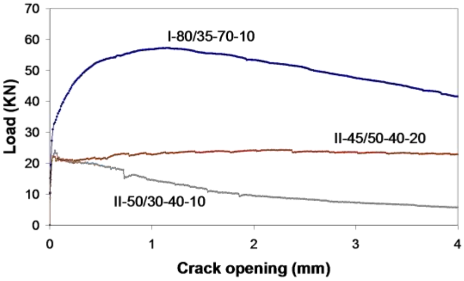

Figure 2. Post-peak flexural performance spectrum for different SFRC

In addition to the variables of mix design of concrete, there are two significant variables related to the creep test: the pre-crack opening level ($CMOD_{pn}$) and the stress level (I_c) sustained during creep test. In this work, the $\mathrm{CMOD_{pn}}$ takes values of 0.5 mm and 1.5 mm which represent the first and second level where the corresponding flexural residual strength (f_{R1} and f_{R2}) are calculated following the EN 14651:2007 standard **Error! Reference source not found.**~~[11]~~. I_c values were defined aiming testing the concretes at a service load level (60% of the stress at CMOD$_{pn}$, $f_{R,p}$), at a relatively high load level (80% of $f_{R,p}$) and at an exceptional load level (95% of $f_{R,p}$).

2.5. Creep test program

The experimental campaign included a total of 45 SFRC specimens which were tested according the flexural creep test methodology detailed in the next section. **Error! Reference source not** shows the tested combinations. For each combination a column of three specimens was tested.

Table 4. Creep test program

Designation	Creep stress level (I_c, %)	Pre-crack (CMOD$_{pn}$, mm)
I 80/35-40-10	60, 80	0.5
	80	1.5
I 80/35-70-10	60, 80, 95	0.5
I 80/50-40-10	80	0.5
I 2Ø8-10	80	0.5
II 80/50-40-20	80	0.5
II 65/40-40-20	60	0.5
II 45/50-40-20	80, 95	0.5
II 50/30-40-10	60, 80	0.5
II 2Ø6-20	80	0.5

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3. FLEXURAL CREEP TEST METHODOLOGY

Creep tests were performed by applying a constant bending load on 150x150x600 mm notched pre-cracked specimens. The applied load and the crack opening evolution during the test were monitored. Figure 3~~Figure 3~~ shows a general view of the creep test specimens. Full explanation of the creep test methodology, details about frame and components and dimensions specifications can be found in Arango's PhD Thesis [1] (in Spanish) and further publications **Error! Reference source not found.**~~[2]~~.

Figure 3. General view of creep test specimens (overview -left- and column detail -right-)

As a multiple specimens setup in column was adopted, some aspects of the loading configuration required to be modified to ensure the column stability. In particular, the three point bending test proposed in **Error! Reference source not found.**~~[11]~~ was adapted to a four point bending test as in Figure 4~~Figure 4~~. Accordingly, some changes in stress formulation were also realised, since the configuration was changed.

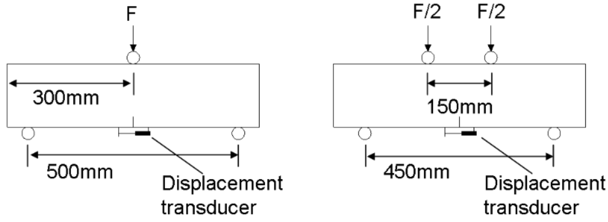

Figure 4. Flexural test diagrams: EN 14651:2007 (left) and creep test proposal (right)

A creep test consists basically on three main stages:
- *pre-cracking stage*: specimen pre-cracking up to a nominal crack opening value "CMOD_{pn}";
- *creep test stage*: test on creep of pre-cracked specimens subjected to a creep stress level "I_c";
- *final bending test stage*: final test in flexure to failure on specimen after creep process.

3.1. Test specimen pre-cracking

Test specimen pre-cracking is done with the proposed creep set up as proposed in EN 14651:2007 **Error! Reference source not found.**~~[11]~~, but when the nominal crack opening value CMOD_{pn} is reached the test is stopped and the specimen unloaded. The load–crack opening evolution during the loading, unloading and recovery process is registered. Figure 5~~Figure 5~~ presents an the pre-cracking process which include the following main parameters: first crack stress (f_L), maximum actual crack opening value on pre-cracking process (CMOD_{pn}), stress at CMOD_{pn} ($f_{R,p}$) and residual crack opening value after pre-cracking process (CMOD_{pr}).

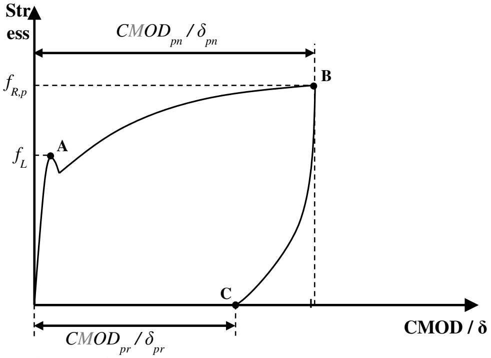

Figure 5. Pre-cracking stage parameters definition

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3.2. Creep test

After the pre-cracking stage, the test specimens are placed inside a chamber with controlled environmental conditions where the creep frames are located. The temperature of the chamber is 20ºC and the relative humidity is 50%.

Each frame is able to test simultaneously a column of three test specimens (see Figure 3~~Figure 3~~). the specimens were ready, the creep test stage starts when the load is applied. The sustained nominal stress level or nominal index of stress in creep (I_n) is defined as a percentage of the residual strength at CMOD_{pn} ($f_{R,p}$). Due to the multiple specimen set-up, the load applied is not the same for all the specimens. Therefore, the real stress level or real index of stress in creep (I_c) for each specimen is calculated and defined as the ratio between the sustained stress during creep phase ($f_{R,c}$) and the residual strength at CMOD_{pn} ($f_{R,p}$) by the equation (1).

$$I_c = f_{R,c} / f_{R,p}\ (\%) \qquad (1)$$

The test continues without interruption until it is decided to unload the specimens. Once specimens are unloaded they remain in the creep frame and the recovery of deformations is recorded for two weeks. Figure 6~~Figure 6~~ represents an idealisation of the creep stage, where it can be identified some parameters: the sustained stress during creep phase ($f_{R,c}$), the instantaneous crack opening deformation (CMOD_{ci}), the deferred crack opening deformations at different ages (CMOD^{j}_{cd}) and the total deformations during creep test (CMOD^{j}_{ct}) as the addition of instantaneous deformations and deferred deformations.

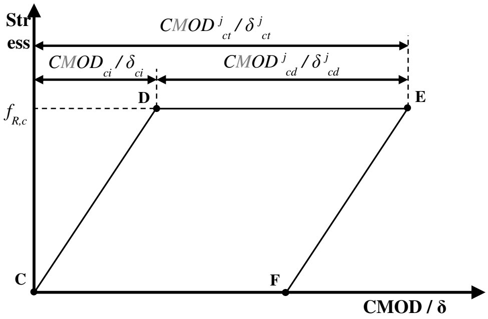

Figure 6. Creep tests phase parameters definition

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3.3. Post-creep flexural bending test to failure

When the creep test is over, the test specimens are subjected to post-creep flexural tests to failure, following the same methodology exposed in 3.1 reaching crack opening values higher than 4 mm.

By assembling the experimental results of the previously mentioned stages and plotting Stress-CMOD, the evolution of the measured test parameters is represented considering the complete test to establish a common origin for crack opening values for all test stages.

4. TEST RESULTS AND ANALYSIS

4.1. Characterization tests

Flexural characterisation tests were performed to all series of FRC following the EN 14651:2007 standard **Error! Reference source not found.**~~[11]~~. Figure 7~~Figure 7~~ shows the Load-CMOD curves these tests. As it can be observed, a wide spectrum of behaviours comprising hardening, flat and softening response was covered.

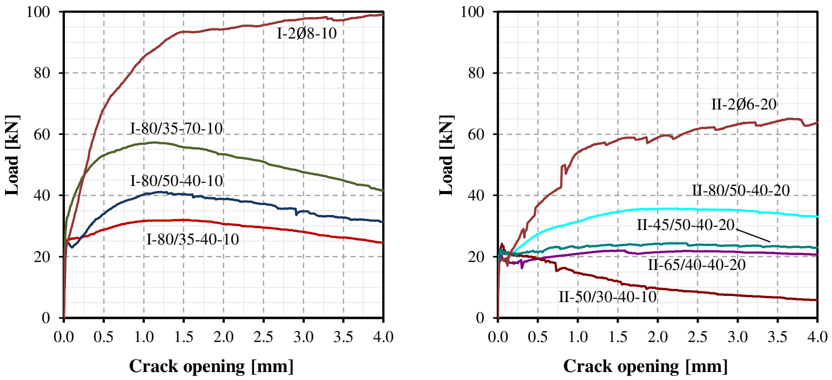

Figure 7. Flexural behaviour of concretes type I (left) and II (right)

Table 5~~Table 5~~ resumes both the compressive strength results for each series and the residual Limit of Proportionality and for CMOD values of 0.5 and 2.5 mm. The coefficient of variation is given as informative of the scatter of results.

Table 5. Characterisation tests results (compressive strength and residual strengths)

Concrete	Comp. strength		Flexural strength [MPa] / CoV [%]					
	f$_c$		*f*$_L$		*f*$_{R1}$		*f*$_{R3}$	
80/35-40-10	52.7	(10.0)	4.94	(6.5)	5.53	(6.0)	5.66	(6.1)
80/35-70-10	56.1	(4.9)	6.38	(4.9)	10.12	(10.6)	9.78	(9.8)
80/50-40-10	57,1	(4.3)	4.53	(4.9)	6.14	(11.7)	6.79	(5.4)
2Ø8-10	58,3	(5.3)	4.80		13.10		18.36	
80/50-40-20	39.0	(1.3)	3.93	(2.7)	5.01	(8.6)	6.48	(9.6)
65/40-40-20	24.9	(6.6)	4.03	(2.8)	3.72	(14.0)	3.79	(17.0)
45/50-40-20	38.8	(6.6)	4.27	(4.2)	4.09	(22.9)	4.58	(10.4)
50/30-40-10	41.3	(6.0)	4.68	(3.3)	3.69	(11.6)	1.63	(20.3)
2Ø6-20	36.4	(11.2)	3.68		7.03		11.85	

4.2. Creep tests

CMOD deformations were registered during flexural creep tests. As reference for both types of concretes, Figure 8~~Figure 8~~ shows the evolution with time of one specimen's deformation of each series.

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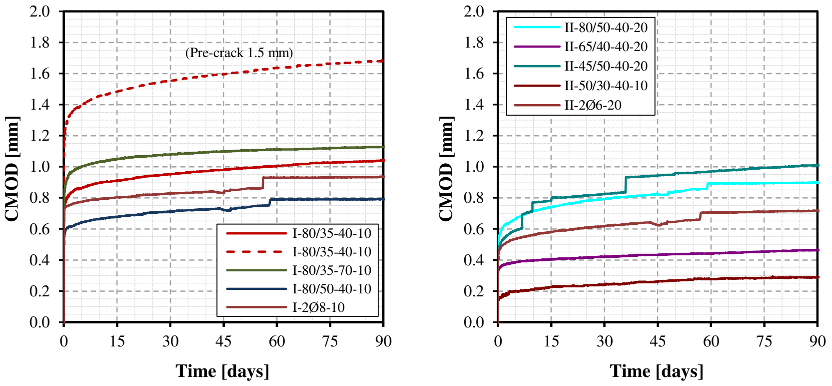

Figure 8. CMOD-Time curves for concretes type I (left) and II (right)

In addition, a number of specimens (40% of them) developed a sudden increase of crack opening deformations during creep stage. A visual example of these sudden increases is given in Figure 9~~Figure 9~~.

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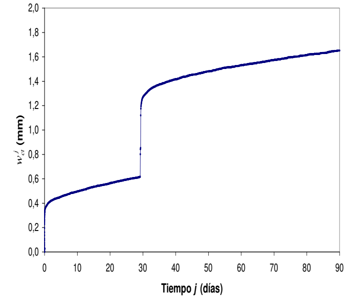

Figure 9. Detail of a sudden increase in crack openin (specimen ***)

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In case of concretes type I, these sudden increases were produced in some specimens of series reinforced with fibres with slenderness (λ) of 80 and stress level $I_c \geq 90\%$. For concretes type II, SFRC with fibres with slenderness (λ) of 45 and 50 developed sudden CMOD deformations when $I_c \geq 70\%$. The magnitude of these sudden increases of crack opening during creep tests varied from 0.012 to 0.559 mm, what supposed a percentage of 2 to 42% of deferred CMOD deformation at 90 days of the corresponding specimen.

4.3. Results analysis

During creep tests, the deferred Crack Mouth Opening Displacement (CMOD) was continuously registered for each specimen. These deferred measurements are needed to calculate some creep parameters to analyse the long-term behaviour. As time reference, three specific lapses of time were selected: 14, 30 and 90 days. The parameters worked out to evaluate creep behaviour were the creep coefficients and the Crack Opening Rates (COR).

4.3.1. Creep coefficients

The creep coefficient (φ) is defined as the ratio between the deferred deformation and instantaneous deformation. Deferred deformations were obtained for the selected time lapses to check the evolution of creep coefficients along time. Referring the creep coefficient to the creep stage, the instantaneous deformations occurred during the loading phase of creep tests. In this way, the instantaneous deformation was recorded just when the creep stress level I_c was reached (point D in Figure 6). Therefore, the creep coefficient referred to creep stage at time *j* (φ^{j}_{c}) can be calculated by means of equation (2):

$$\varphi^{j}_{c} = \mathrm{CMOD}^{\mathrm{j}}_{\mathrm{cd}} \,/\, \mathrm{CMOD}_{\mathrm{ci}} \tag{2}$$

where $\mathrm{CMOD}^{\mathrm{j}}_{\mathrm{cd}}$ is the deferred crack opening at time j and $\mathrm{CMOD}_{\mathrm{ci}}$ is the instantaneous crack opening occurred during the loading phase of creep tests (see Figure 6).

Since the specimens were previously pre-cracked, there was a previous crack opening deformation before the creep test. Therefore, a new creep coefficient referred to the origin of deformations at time *j* (φ^{j}_{o}) can be calculated by means of equation (3):

$$\varphi^{j}_{o} = \mathrm{CMOD}^{\mathrm{j}}_{\mathrm{cd}} \,/\, \mathrm{CMOD}^{\mathrm{o}}_{\mathrm{ci}} \tag{3}$$

where $\mathrm{CMOD}^{\mathrm{o}}_{\mathrm{ci}}$ is the total deformation referred to the origin obtained by means of equation (4):

$$CMOD^{o}_{ci} = CMOD_{pr} + CMOD_{ci} \tag{4}$$

where $CMOD_{pr}$ is the residual crack opening after the pre-cracking test and $CMOD_{ci}$ is the instantaneous deformations occurred during the loading phase of creep tests (see Figure 5).

These both creep coefficients, referred to creep stage and referred to origin, where obtained for all specimens and compared. Figure 10~~Figure 10~~ shows the creep coefficients results at 90 days for all creep stress levels I_c.

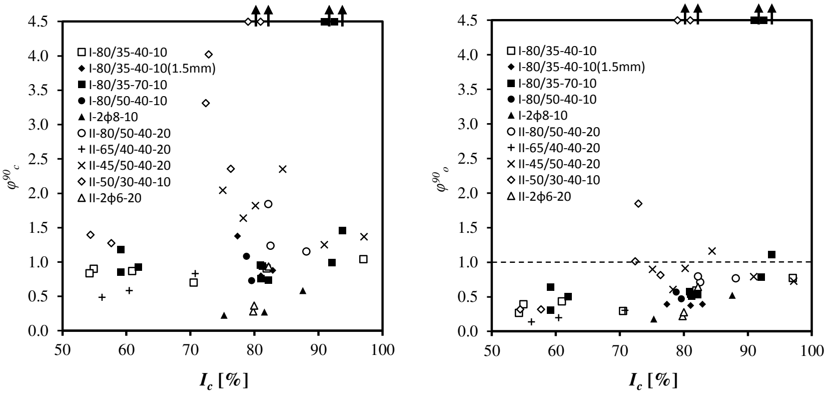

Figure 10. Creep coefficients at 90 days referred to creep stage ($\varphi^{90}{}_{c}$) -left- and origin of deformations ($\varphi^{90}{}_{o}$) -right-

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4.3.2. Crack Opening Rate (COR)

The Crack Opening Rate or COR is a parameter that helps to evaluate the average velocity of deferred deformations during a time period. This COR parameter is obtained by means of equation (5)

$$COR^{j\text{-}k} = (CMOD^{k}_{cd} - CMOD^{j}_{cd}) / (k - j) \tag{5}$$

where *j* and *k* are two different time lapses in days. This parameter is expressed in µm/day units. In this work, three lapses of time of creep test were analysed: from 0 to 14 days (2.74-59.72 µm/day), from 14 to 30 days (0.76-46.26 µm/day) and from 30 to 90 days (0.34-6.43 µm/day). Figure 11~~Figure 11~~ shows the COR trends in two lapses of time: 14-30 and 30-90 days.

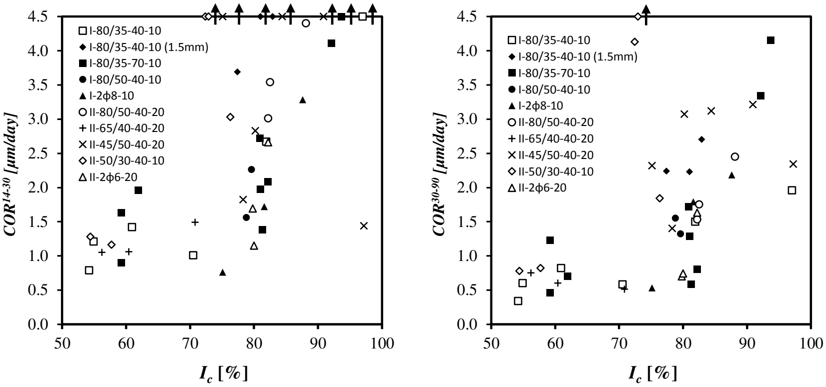

Figure 11. COR^{14-30} (left) and COR^{30-90} (right) for all tested concretes

A global trend to reduce velocity with time can be observed. In case of FRCs type I, the minimum values were obtained for $I_c \geq 80\%$ whereas for FRCs type II, minimum values were obtained for $I_c \geq 70\%$. In both concretes, lower values of COR were detected in case of traditional rebar reinforcement and SFRCs with low I_c.

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5. CONCLUSIONS

The influence of fibre reinforcement on long-term behaviour of cracked concrete was analysed in this work. Concretes incorporating steel fibres and standard rebar reinforcement were studied. Creep coefficients referred to creep stage and referred to origin were obtained. Moreover, COR parameters were also calculated and analysed. The main conclusions obtained are:

- SFRC specimens with softening post-crack behaviour, develop more deferred deformations and higher risk of failure.
- Some of the specimens (18 out of 45) developed sudden increases of crack opening deformations.
- All rupture cases occurred during the loading phase in the creep test frames or a few minutes after finishing load application.
- Creep coefficients show significant dependence of analysed variables.
- For low stress levels ($I_c > 80\%$), creep coefficients remains at low values and regular.
- High values of creep coefficients correspond with high values of crack opening deformations.
- Longest fibres and those with lower slenderness develop higher values of creep coefficients. The rest of fibres only present ruptures in cases of high stress level.
- The results of this experimental campaign show that creep in SFRC specimens may be similar than in a traditional RC.
- The use of fibres, even at low contents, is a good strategy to control flexural creep in the cracked state.

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