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FLEXURAL POST-CRACKING CREEP BEHAVIOUR OF MACRO-SYNTHETIC AND STEEL FIBER REINFORCED CONCRETE

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Abstract

In this paper the post-cracking creep behaviour of FRC beams under flexural load is evaluated in order to determine whether under certain loading conditions plastic fibres may be safely used in the long-term without compromising the serviceability requirements. For that, an experimental program was conducted that involved the testing of 30 beams with dimensions of 150 x 150 x 600 mm reinforced either with plastic or steel fibres. The creep test setup consisted in a four-point bending test in previously cracked beams up to crack widths of 0.25 mm, 1.50 mm and 2.50 mm. The sustained load ranged between 50% and 60% of the cracking load and was applied by means of a lever system. The sustained load was controlled throughout the test with a load cell. The tests were performed under two different environmental conditions during 6 months. Despite the large deformations exhibited by plastic fibres under sustained load over time, their use as reinforcement should not be discarded as long as the effects of creep are considered in the design.

Keywords: plastic fibre, steel fibre, time dependent behaviour, creep, secondary creep, tertiary creep.

1. INTRODUCTION

Steel fibres are still preferably used over macro-synthetic fibres. One of the most recurrent reasons for that is its creep behavior which is the time-dependent strain that develops in concrete due to sustained stress. According to [1], in fibre reinforced concrete (FRC) it is not possible to uncouple the time dependent behavior of the concrete from that of the fibre reinforcement. In this sense, [2], [3] define the mechanism of creep in bending of a cracked element as the result of: (1) concrete creep in compression, (2) the time dependent debonding behavior at fibres-matrix interface and (3) the fibres creep at material level in tension. Thus, the latter is significantly susceptible to the fibre material and whereas in SFRC, the postcracking creep phenomena is not caused by the creep deformation of the actual fibres, but rather by the slow pullout of the fibres from the matrix [4], in PFRC, the creep behaviour of synthetic fibres is a complex phenomenon which depends not only on the stress and temperature [5] but also on intrinsic material properties such as the crystallinity and the molecular orientation as well as other external parameters such UV and moisture [6]. However, the extent to which the aforementioned factors affect the performances of PFRCs is still not completely clear and further experimental investigations are needed.

Despite the relevance of the issue, flexural creep behavior of FRC is still a controversial issue that requires thorough research, particularly in the case of plastic fibre reinforced concrete (PFRC) since it may exhibit additional creep due to the fibres. The main goal pursued in this paper is to evaluate the post-cracking creep behaviour of FRC beams under flexural load and to determine whether under certain loading and crack-width conditions plastic fibres may be safely used in the long-term without compromising the serviceability requirements of the structures.

2. EXPERIMENTAL METHOD

To investigate the FRC time-dependent behavior, a number of 30 flexural beam tests (with dimensions of 150 x 150 x 600 mm) reinforced either with plastic fibres (PF) or steel fibres (SF) were carried out following a 4-point bending test. The test were done in two different environmental conditions (S1 and S2) during 5 months considering different precrack-widths and load levels.

2.1 Materials and mix design

Four series of concrete were produced, one with 5 kg/m³ of PF and another 40 kg/m³ of SF for each of the two environmental conditions (S1 and S2). The details of the concrete mix for all series are presented in Table 1.

Table 1. Composition of the FRC mixture (in kg/m³)

Materialss	Characteristics	PLASTIC FIBRES		STEEL FIBRES	
		S1_PF	S2_PF	S1_SF	S2_SF
Gravel (6/15 mm) [kg/m ³]	Granite	520	520	520	520
Gravel(2,5/6 mm) [kg/m ³]	Granite	400	400	400	400
Sand (0/3 mm) [kg/m ³]	Granite	500	500	500	510
Cement [kg/m ³]	CEM I 52,5 R	400	400	400	350
Filler [kg/m ³]	Marble dust	260	260	260	300
Water [kg/m ³]	-	170	178	168	178
Superplasticizer [kg/m ³]	Adva® Flow 400	12	12	12	12
Fibres [kg/m ³]	PF/SF	5 (PF)	5 (PF)	40 (SF)	40 (SF)

The plastic macro-fibres (PF) used in the tests were derived from polyolefin with a continuously embossed surface texture to improve adherence and they had straight shape and a rectangular cross-section. The steel fibres (SF) were made of low carbon steel and are gathered into bundles by water-soluble glue and had a circular cross section and hooked ends. Further properties are presented in Table 2.

Table 2. Fibre characteristics (data provided by the manufacturer)

		PF	SF
Length (<i>L</i>)	[mm]	48	50
Equivalent Diameter (<i>d</i>)	[mm]	-	0.62
Aspect ratio (<i>L/d</i>)	[-]	-	83
Tensile strength (<i>f_t</i>)	[MPa]	550	1270
Modulus of elasticity (<i>E</i>)	[GPa]	10	210
Number of fibres per kg	[fibras]	>35000	8100

Table 3 shows the average compressive strength (f_{cm}), average modulus of elasticity (E_{cm}), limit of proportionality (f_L) and the residual flexural tensile strengths ($f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$) corresponding to CMODs of 0.05 mm, 0.50 mm, 1.50 mm, 2.50 mm and 3.50 mm, respectively.

Table 3. Characterization of the FRC at 28 days

	S1_PF		S2_PF		S1_SF		S2_SF	
	Average [MPa]	CV %	Average [MPa]	CV %	Average [MPa]	CV %	Average [MPa]	CV %
E_{cm}	31150	1.69	-	-	31597	1.08	30160	2.20
f_{cm}	52.15	1.52	48.89	1.57	54.30	1.51	46.77	2.54
f_L	4.61	2.19	4.22	2.66	3.73	8.57	3.76	7.96
$f_{R,1}$	2.01	22.30	2.38	15.54	4.62	12.15	3.75	22.29
$f_{R,2}$	2.25	28.53	2.93	20.89	5.09	13.77	4.24	17.91
$f_{R,3}$	2.46	26.84	3.32	24.15	5.10	15.91	4.30	15.88
$f_{R,4}$	2.48	23.47	3.49	27.40	4.87	14.08	4.17	15.68

2.2 Test procedure

The specimens tested were subjected to two different stages (see scheme in Figure 1): phase 1 or pre-cracking and phase 2 or long term loading test which was extended up to the unloading and recovery. In the first phase the specimens were tested in a closed-loop servo-hydraulic system according to a four-point bending with a 450 mm span and 25 mm notch, using crack mouth opening displacement (CMOD) as the control signal. In addition to the clip gauge placed at the bottom of the beam, the crack-opening displacement (w_p^f) was monitored through a linear variation differential transducer (LVDT) fixed on a lateral side of the specimen 12 mm above the bottom surface of the beam. The process was interrupted at different w_p^f levels ($w_p^f=0.25 - 1.50 - 2.50$). Table 4 shows the w_p^f of each of the beams tested.

Figure 1: Diagram of the complete creep test procedure

The pre-cracked beams were then unloaded and immediately after placed in a creep frame. The design of the test set up for the long term flexural test were based on the previous work by Bast et al. [7] and basically identical to that used by [4], [8], [9]. The steel frame used allows to simultaneously

perform the long term test in various specimens set in a column. In this case, three specimens were loaded in each column, under a 4-point bending test configuration using steel rollers as a free supports (see Figure 2). The lateral LVDT used to measure the w_p^f during the first stage (which always remained settled to the beam) was used for the control of the crack evolution.

Figure 2: Creep frames during the specimens loading a) S1 and b) S2

The humidity and temperature in the S1 and S2 conditions of the experimental program were different. Table 4 shows the variation in environmental conditions over the test duration

Table 4. Variation in environmental conditions over the test days

S1	Apr	May	Jun	Jul	Aug	Sep
Humidity[%]						
Max.	59.6	56.4	73.7	78.7	80.7	81.3
Min.	48.2	43.2	36.3	60.3	73.1	53.1
Average	52.7	50.4	57.9	69.1	78.3	73.3
Temperature[°C]						
Max.	22.3	24.9	25.7	26.4	26.6	26.7
Min.	20.8	20.8	23.3	23.7	24.5	24.3
Average	21.3	21.8	24.5	24.7	25.5	25.8
S2	Feb	Mar	Apr	May		
Humidity[%]						
Max.	78.0	78.8	65.5	73.0		
Min.	12.3	16.5	27.3	34.8		
Average	36.9	49.9	48.8	50.3		
Temperature[°C]						
Max.	19.2	19.7	24.1	25.7		
Min.	6.5	9.1	15.3	17.1		
Average	12.7	15.3	19.2	21.3		

In the S1 the specimens were tested in a climate-controlled room under relatively constant conditions of humidity and temperature (Table 4). The S2 beams were exposed to ambient conditions with alternating humidity and temperature (as observed in Table 4). The theoretical load levels considered in the study were between 50% and 60% of the load F_p , registered when the pre-cracking stage was stopped (see Table 5).

Table 5. Summary of loading conditions and pre-crack-width

		<i>SPECIMENS</i>	w_p^f [mm]	F_c/F_p [%]
S1	PF	<i>S1/PF_0.25P1</i>	0.25	48.9
		<i>S1/PF_0.25P2</i>		58.2
		<i>S1/PF_0.25P3</i>		69.1
		<i>S1/PF_0.25P4</i>		57.3
		<i>S1/PF_0.25P5</i>		60.5
		<i>S1/PF_1.50P6</i>	1.50	50.0
		<i>S1/PF_1.50P7</i>		50.4
		<i>S1/PF_2.50P8</i>	2.50	54.0
		<i>S1/PF_2.50P9</i>		48.6
	SF	<i>S1/SF_0.25P1</i>	0.25	53.9
		<i>S1/SF_0.25P2</i>		61.6
		<i>S1/SF_0.25P3</i>		69.8
		<i>S1/SF_1.50P4</i>	1,50	52.9
		<i>S1/SF_2.50P5</i>	2,50	49.5
		<i>S1/SF_2.50P6</i>		47.5
S2	PF	<i>S2/PF_0.25P1</i>	0.25	48.9
		<i>S2/PF_0.25P2</i>		48.3
		<i>S2/PF_0.25P3</i>		48.6
		<i>S2/PF_0.25P4</i>		52.6
		<i>S2/PF_1.50P5</i>	1.50	43.1
		<i>S2/PF_2.50P6</i>	2.50	49.3
	SF	<i>S2/SF_0.25P1</i>	0.25	47.0
		<i>S2/SF_0.25P2</i>		62.2
		<i>S2/SF_0.25P3</i>		52.3
		<i>S2/SF_0.25P4</i>		52.3
		<i>S2/SF_0.25P5</i>		46.5
		<i>S2/SF_0.25P6</i>		53.7
		<i>S2/SF_1.50P7</i>	1.50	46.8
		<i>S2/SF_1.50P8</i>		48.0
		<i>S2/SF_2.50P9</i>	2.50	37.1

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Creep crack width results

For the case of the S1 beam, after 150 days of loading the values of Δw_c^t (increment of crack width) registered for the specimens precracked at w_p^f of 0.25 mm vary between 0.30 and 0.45 mm for PF (see Figure 3a) and between 0.08 and 0.13 for SF (see Figure 3b). The specimens with a w_p^f of 1.50 mm, reached values of Δw_c^t between 1.20 and 1.40 mm for PF (see Figure 3c), whereas SF reached only 0.15 mm (see Figure 3d).

Figure 3: Diagram Δw_c^t – time curves for the specimens:
a) S1/PF_0.25Pi; b) S1/SF_0.25Pi; c) S1/PF_1.50Pi; d) S1/SF_1.50Pi

The creep curve of figure comprises two stages: primary and secondary creep. The increase of Δw_c^t is relatively high the first days just right after the sustained load is applied (primary creep), subsequently decreases progressively (secondary creep). On average, about half (50%) of Δw_c^t recorded after 150 days of the test occurs in the first 5 days, after 30 days 70% and after 90 days 90% of the final Δw_c^t is reached.

In the case of the S2 beams (under ambient environmental conditions) after 90 days of testing the values Δw_c^t obtained vary between 0.30 and 0.45 mm for the specimens precracked with w_p^f of 0.25 mm (see Figure 4a). The S2/PF_1.50P5 precracked with a w_p^f of 1.50 mm reach approximately 0.90 mm (see Figure 4b).

Notice that the nature of the S2 creep curve is considerably different from that of S1. In the S2 specimens, creep increases monotonously in time, while in the S1 specimens creep stabilizes within several days. However, the initial rate of the S1-creep curve is larger. Unexpectedly during some initial period (about 7-8 days in our tests) the S2 creep width is less than the S1 creep for equivalent specimens. Only then the S2 creep begins to exceed the S1 creep.

Figure 4: Diagram Δw_c^t – time curves for the specimens:
a) S2/PF_0.25Pi; b) S2/SF_0.25Pi; c) S2/PF_1.50Pi; b) S2/SF_1.50Pi

During the execution of the test, none of the beams previously analysed (with w_p^f of 0.25 mm and 1,5 mm) entered into the tertiary creep stage (a period of increasing creep rate, prior to failure). However, for all those beams with a w_p^f of 2.50 mm a three-stage creep response: primary, secondary, and tertiary creep with a sudden failure was observed (see Figure 5). In this experimental campaign, failure took place after 41, 112 and 108 days of loading for S1/PF_2,50P8 (with load ratio of $\%F_p=54\%$), S1/PF_2,50P9 ($\%F_p=48\%$) and S2/PF_2,50P6 ($\%F_p=49\%$) respectively. On the contrary, none of the SF beams with a w_p^f of 2.50 mm entered in tertiary creep. The values of Δw_c^t recorded range between 0.1 and 0.2 mm, lower values than those obtained for PF with a w_p^f of 0.25 mm

Figure 5: Diagram Δw_c^t – time curves for the specimens:
a) S1/PF_2.50Pi; b) S2/PF_2.50Pi

3.2 Creep coefficient results

Considering the inherent scatter of creep, and the intrinsic scatter of the material together with the fact that each specimen was tested under different conditions of width and load, it is difficult to draw obvious conclusions from a direct analysis of the results. To overcome these drawbacks, the analysis of the creep coefficient is proposed.

For the purpose of this research, the creep coefficient ($\varphi(t)$) at a time t defined in terms of crack width is the ratio between the crack at t time t in phase 2 (w_c^t) and the initial crack width (w_c^0), as indicated in expression:

$$\varphi(t) = \frac{w_c^t}{w_c^0} \quad (1)$$

The evolution of the creep coefficient is presented in Figure 6 for each beam. The curves are grouped by stages S1/PF (Figure 5a), S2/PF (Figure 5b), S1/SF (Figure 5c) or S2/SF (Figure 5d).

Figure 6: $\varphi(t)$ – time curves of the specimens:

- a) S1/PF_0.25Pi and 1,50Pi; b) S2/PF_0.25Pi and 1,50Pi;
c) S1/SF_0.25Pi and 1,50Pi; b) S2/SF_0.25Pi and 1,50Pi

Using $t=90$ days as reference, a value of $\varphi(t=90)$ between 0.5 and 4.0 is reached for all the specimens of both conditions S1 and S2. PF creep coefficients for 90 days ($\varphi^{t \rightarrow 90}$) ranged between 1.5 and 4.0 for both S1 and S2 campaigns, although in the former an asymptotic value of the creep coefficient was reached during the secondary stage. In this stage, creep is not significantly affected by the w_p^f value. Moreover, at similar loading level and for $w_p^f \leq 1.50$ cracked PFRC can be expected to experience creep coefficients of around twice those of SFRC.

4. CONCLUSIONS

The largest crack widths during secondary creep were obtained for those specimens with higher pre-cracked width. Such outcome is reasonable since the pull-out and the tensile creep of the plastic fibre is accentuated with the load level and the cracking level. It is important to highlight that although creep rate of plastic fibre is twice the value for steel fibres, all along secondary creep, this rate is not affected by the pre-cracked width value. Such fact may be advantageous in order to predict the creep behaviour in secondary creep, and meet the design crack widths criterion.

However, for advanced cracking levels the reinforcing action of plastic fibres is no longer effective due to the significant tensile creep deformation they suffer (although the fibres did not break in any of the analysed cases). Consequently, the concrete crack progresses and reduces the compression zone

until it is depleted, causing the tertiary creep and consequently the failure of the specimens. This failure mode was not observed in the SFRC beams, even for those specimens with a pre-cracked width of 2,5 mm.

Despite the large deformations exhibited by plastic fibres under sustained load over time, their use as reinforcement should not be discarded as long as the effects of creep are considered in the design as it is indicated in the Model Code 2010. For that, design criteria defining the scope of application of fibre reinforcement, particularly in the case of plastic fibres, needs to be established to ensure the ULS and SLS requirements. The secondary creep should be considered as a design criterion of prime importance in order to determine the life of a given PFRC structure. For that, it should be ensured that with adequate probability, cracks will not impair the functionality, durability and appearance of the structure and define or limit the range of applications of this material.

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