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A COMPREHENSIVE STUDY ON THE EFFECT OF FIBERS AND LOADING ON FLEXURAL CREEP OF SFRC

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Summary: This paper reports the results of a research whose aim was to study how the following variables affect the way SFRC behaves in the postcrack region when under sustained flexural loads: fibers length and slenderness, fibers content, maximum aggregate size, and the load applied. A new methodology based on a test setup developed by the authors has been followed in this research, where notched prismatic 150x150x600 mm specimens are subject to a flexural creep test which follows the four-point bending scheme. Several parameters have been measured: initial crack width, crack width at 90 days, and crack opening rates and creep coefficients at 14, 30, and 90 days. The effect of the variation of the variables considered on these parameters has been evaluated by means of statistical inference based on multiple linear regression models. Results clearly show that varying fiber slenderness leads to important differences regarding concrete's flexural creep behavior. The mere fact of adding fibers is good from the point of view of controlling creep strain, though variation in fiber content between 40 kg/m^3 and 70 kg/m^3 has turned out to be not so important when compared to the effect that varying the load applied has on many of the parameters analysed.

1 INTRODUCTION

Creep is a term used to define the tendency of a material to develop increasing strains through time when under a sustained load, this resulting in increasing deflection or elongation values (depending on the type of loading) with time in relation to the initial, instantaneous strain that the material experiences directly after the load is applied.

Creep of SFRC under flexural loads in the cracked state, or postcrack region, and to what extent different factors determine creep behavior are quite understudied topics within the general field of SFRC mechanical properties.

SFRC elements are designed in most applications to take advantage of SFRC differential properties, i.e. the material is brought to function in its cracked state, where cracks are under control and residual strength gives the element further mechanical resistance. Therefore, and considering that SFRC contribution to structural load-bearing capacity is mainly related to its flexural response (as said, in the cracked state), the extent to which the material is able to keep crack opening values low enough so as to guarantee the reinforcement effectiveness is to be assessed [1].

Relatively few studies directly dealing with creep behavior of SFRC under flexural loads have been published. Publications directly related to flexural creep behavior of pre-cracked FRC beams are scarce. Most of them explore the contribution of plastic, or glass fibres to creep behavior, but consider steel fibres only on a comparative basis, not as the main effect they aim to study.

When some of the most relevant research papers and reports [1,2,3,4,5] are brought together, several general aspects are observed:

- There is a great variety of test setups and methodologies. Furthermore, there is no standardized methodology to assess creep behavior of concrete, which added to the fact that SFRCs usually show considerable variability in their properties, contributes to the uncertainty about how they behave under sustained flexural loads. Some attempt to develop a consistent methodology on the basis of an appropriate test setup to study the flexural creep behavior of pre-cracked FRC specimens was needed.

- Sometimes the goal is not to study creep of SFRC under flexural loading for its own sake, but in order to find differences between the behavior of SFRC and that of concrete reinforced with synthetic fibers.
- Most studies limit their scope to one mix design, one type of steel fiber, or one fixed fiber content, and do not consider how varying these variables may affect creep behavior of SFRC.
- When it comes to the levels considered for the stress/strength ratio, most studies do consider different values, though the way they are selected (parameters this selection is based upon) varies.
- The heterogeneity in the procedures is evidenced: the use of different standards in relation to flexural tests leads to important variations concerning how load is applied to specimens, whether they are notched or not, etc.

The aforementioned general aspects justified the need of establishing a more general methodology when it comes to study creep of concrete under flexural loading and, at the same time, the need of studying the case of SFRC in the postcrack region in a rather comprehensive fashion, considering several parameters simultaneously.

In relation to the first aspect, the authors have made an effort to develop a methodology which has been extensively described elsewhere [6] to make it possible to study creep of concrete in standard-like conditions so that future results can be easily comparable. This is the methodology that has been followed in the experimental program reported herein.

2 RESEARCH SIGNIFICANCE AND OBJECTIVES

The aim of this research was to study how different variables affect the way SFRC behaves in the postcrack region when under sustained flexural loads, i.e. flexural creep behavior of pre-cracked SFRC specimens, since it is one of the topics that has attracted less attention when it comes to characterise the mechanical properties of this material. This constitutes the core matter of this contribution. Different types of fibers (in terms of length and slenderness), fiber contents, flexural loads, and mix designs have been considered to produce a series of prismatic specimens that have been subjected to sustained loads. The effect of such a number of variables on flexural creep has never before been studied in such a comprehensive fashion. Several response parameters have been measured. Accordingly, the main objective of this research has been to analyze how the different variables considered affect these creep parameters. Such analyses have been performed by means of statistical inference tests based on multiple linear regression models. Different models have been used to assess such effects. The result is a wide view on the effects of the different variables considered, and a further conceptualization of the phenomenon under study.

3 EXPERIMENTAL PROGRAM, AND METHODS

3.1 Creep Test Methodology

The experimental part of this research comprised a series of creep tests carried out on prismatic 150x150x600 mm specimens. A more detailed description of the creep test methodology has been already published [6]. An overview of this methodology is given in Figure 1. In a first stage, specimens were pre-cracked: each specimen was notched and loaded according to the four-point scheme of the standard bending test [7] until the crack width value reached 0.50 mm (crack width throughout the text is CMOD). The load corresponding to that crack width, Fw, was retained and the specimen was then unloaded. After that, pre-cracked specimens were subject to the creep test, being tested in groups of three, according to the test setup shown in Figure 2. All three specimens are loaded following the scheme of the four-point bending test, the load being kept at a fixed value (this achieved by means of a counterweight) for a determined lapse of time.

In addition to prismatic specimens for the creep test, all batches of concrete were characterized by assessing their compressive strength and flexural behavior [7,8].

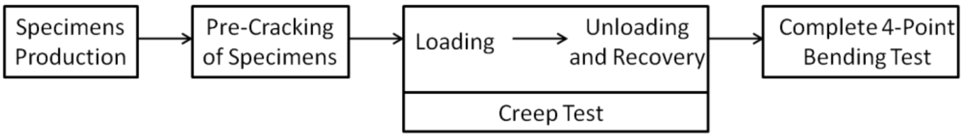

Figure 1: General testing procedure.

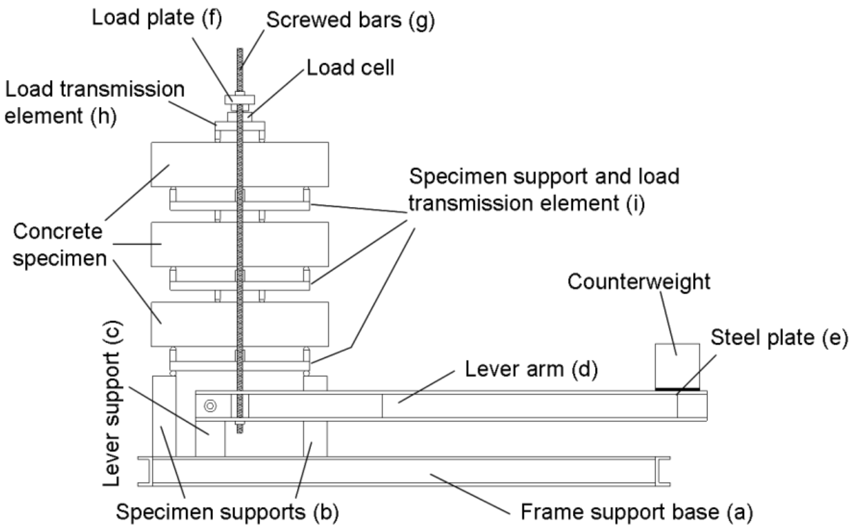

Figure 2: Test setup.

3.2 Variables Considered

The variables considered, as well as their different levels, are summarized in Table 1.

Several different mixes have been produced, each of them resulting from modifying one of the so-called 'base' mix designs by using a certain content of a determined type of steel fiber. Two different base mix designs have been considered: one whose specified compressive strength was 40 MPa (A), the other one being 25 MPa (B), hence covering the range of low and normal strength concretes. All mixes deriving from base mix design A were produced with a maximum aggregate size of 10 mm, while all mixes deriving from base mix design B were produced with a maximum aggregate size of 20 mm with the exception of some batches in which it was adjusted to a maximum aggregate size of 10 mm. Hence, maximum aggregate size has also been considered as variable.

Five different steel fibers have been considered, this resulting in having both fiber slenderness and fiber length considered as variables –though not all combinations of these slenderness and length values have been considered. Fiber contents used are 40 kg/m^3, and 70 kg/m^3, both below the 1% in volume, as it is the case in most of applications using SFRC.

Load ratio as applied to the specimens (IFa) differs from the aforementioned variables in that this is not a variable that could be pre-fixed at determined levels. The nominal load ratio (IFn), this could be pre-fixed. The nominal load ratio (IFn) is defined as the ratio between the load applied to the specimen at the top and Fw, the load corresponding to a crack width of 0.50 mm in the precracking stage (averaged from three specimens), in percentage. The applied load ratio (IFa) depends on the intended, nominal load ratio (IFn), and on each particular specimen: different specimens from the same batch are never the same and, furthermore, since they are tested in columns of three (see Figure 1), the specimen at the bottom bears a slightly higher load than the one at the top. Two different nominal load ratios have been considered: 60%, and 80%. However, when it comes to analyze the results it is better to consider IFa instead of IFn, since the former represents more exactly the loading applied to each particular specimen than the latter.

Taking all that into consideration, the relative position of each specimen in each group of three may somehow affect the results. This is why it has been considered as one more variable, so that the effect of the position upon the results, whenever present, could be detected in order not to ofuscate the effects that the other variables have on the different creep parameters to be analyzed. As it is derived from Figure 1, there are three different positions: 1 for the specimen at the top, 2, and 3 for the specimen at the bottom.

Table 1: Variables considered.

Variables	Levels
Base Mix Design	A (fc 40 MPa) B (fc 25 MPa)
Max Aggregate Size	10 mm 20 mm
Fiber Slenderness Fiber Length	80/35 80/50 65/40 45/50 50/30
Fiber content	40 kg/m^3 70 kg/m^3
Applied Load Ratio, IFa	not fixed (IFn=60%) not fixed (IFn=80%)
Position of Specimen	1 (top) 2 3 (bottom)

Table 2 summarizes all specimens produced and tested in this research as combinations of the variables considered. Each set of three specimens listed consecutively in Table 2 corresponds to a same batch.

3.3 Creep Parameters Measured

For each one of the specimens tested, as listed in Table 2, several parameters that describe creep behavior have been obtained. These parameters are defined from the load vs crack opening curve which is obtained from a complete creep test, as the scheme in Figure 3 shows. Further details on these curves and the parameters which are to be obtained from them can be found in [6].

The first part of the plot corresponds to the pre-cracking stage, having an ascending linear branch until the first crack occurs (A). Then the specimen is gradually loaded until the load value corresponding to a crack width of 0.50 mm is reached (B), and then is totally unloaded. The creep test as such begins at point (C): the ascending line (CD) corresponds to the loading process, which is followed by a horizontal branch (DE) corresponding to the increasing deferred deformations (load sustained through time) that end up when the specimen is unloaded. Post-creep unloading then takes place (EF). Finally, the third part of the plot is the post-creep bending test, which begins with an ascending line (FG) and continues with the residual performance curve of the specimen (GH).

Table 2: Combinations of variables corresponding to all specimens tested.

Base Mix Design	Max Aggr Size, mm	Fiber Slenderness	Fiber Length, mm	Fiber Content, kg/m^3	IFn, %	Position of Specimen
A (fc 40 MPa)	10	80	35	40	60	1
	10	80	35	40	60	2
	10	80	35	40	60	3
	10	80	35	40	80	1
	10	80	35	40	80	2
	10	80	35	40	80	3
	10	80	35	70	60	1
	10	80	35	70	60	2
	10	80	35	70	60	3
	10	80	35	70	80	1
	10	80	35	70	80	2
	10	80	35	70	80	3
	10	80	50	40	80	2
	10	80	50	40	80	3
B (fc 25 MPa)	20	80	50	40	80	1
	20	80	50	40	80	2
	20	80	50	40	80	3
	20	65	40	40	60	1
	20	65	40	40	60	2
	20	65	40	40	60	3
	20	45	50	40	80	1
	20	45	50	40	80	2
	20	45	50	40	80	3
	20	45	50	40	80	1
	20	45	50	40	80	2
	20	45	50	40	80	3
	10	50	30	40	60	1
	10	50	30	40	60	2
	10	50	30	40	60	3
	10	50	30	40	80	1
	10	50	30	40	80	2
	10	50	30	40	80	3

Creep parameters to be obtained from each specimen are determined from the corresponding load – crack opening curve, and constitute the outputs to be analyzed in this research:

- The ratio (w_p – w_{pr}) / w_p, which measures the ability of the specimen to recover right after being precracked, where:
    - w_p is the maximum crack width reached when precracking the specimen.
    - w_{pr} is the residual crack width after precracking.
- w_{ci}, initial crack width, i.e. crack width at the beginning of the creep test, measured one minute after the load has been applied.
- $w_{cd}(90)$, crack width measured at 90 days after loading.

- Crack opening rates (for further reference, see [1]):
    - COR(i-14), crack opening rate between the initial time and the 14th day, which is determined as follows:

      $$COR\ (i\text{-}14) = [\ w(14) - w_{ci}\ ] / (14 - 0)$$
    - COR(14-30), crack opening rate between the 14th and the 30th day.
    - COR (30-90), crack opening rate between the 30th and the 90th day.
- Specific crack opening rates (for further reference, see [1]):
    - spCOR(i-14), specific crack opening rate between the initial time and the 14th day.
    - spCOR(14-30), specific crack opening rate between the 14th and the 30th day.
    - spCOR(30-90), specific crack opening rate between the 30th and the 90th day.
- $\varphi(14)$, $\varphi(30)$, $\varphi(90)$, creep coefficients at 14, 30, and 90 days, respectively (for further reference, see [1]).
- $\varphi_o(14)$, $\varphi_o(30)$, $\varphi_o(90)$, creep coefficients referred to the initial time at 14, 30, and 90 days, respectively (for further reference, see [1]).

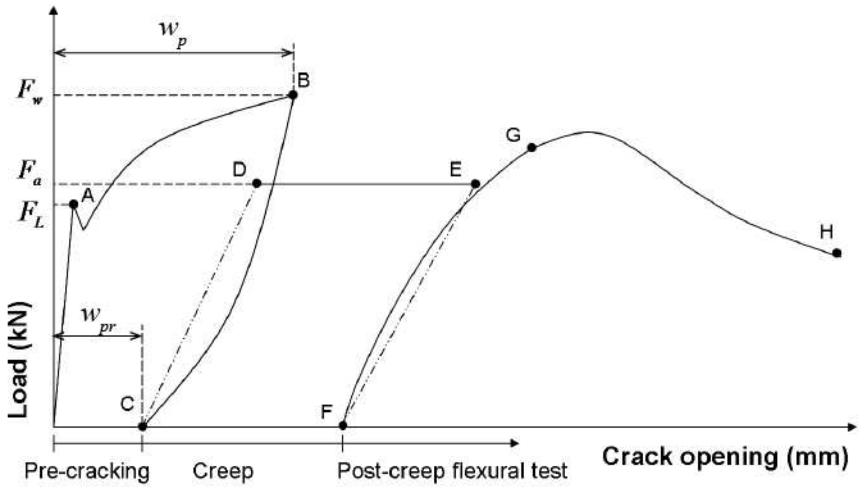

Figure 3: Idealized plot of all results from the creep test.

4 RESULTS AND DISCUSSION

4.1 Analysis of Results: Overview of the Methodology

The effect that the variables considered (Table 1) have on each one of the outputs of the experiment (creep parameters) has been assessed by means of multiple linear regression [9]. Statistical inference regarding the importance of each variable has been made by means of significance tests associated to the coefficients estimated in the construction of a particular linear model for each creep parameter related to the variables considered.

The core of this methodology is finding models which relate each creep parameter to the variables considered. But there is much more than simply predictive equations to be obtained, since variables that are statistically significant can be identified. This way it is possible to assess which variables have a really important, statistically significant effect on most of the creep parameters considered, which is a more general and valuable conclusion than predictive equations themselves.

To study separately the effect of each one of the variables considered on creep parameters, on the basis of one-to-one regression lines instead of applying multiple linear regression models would be a defective approach since it would offer no such assessment of their relative importance.

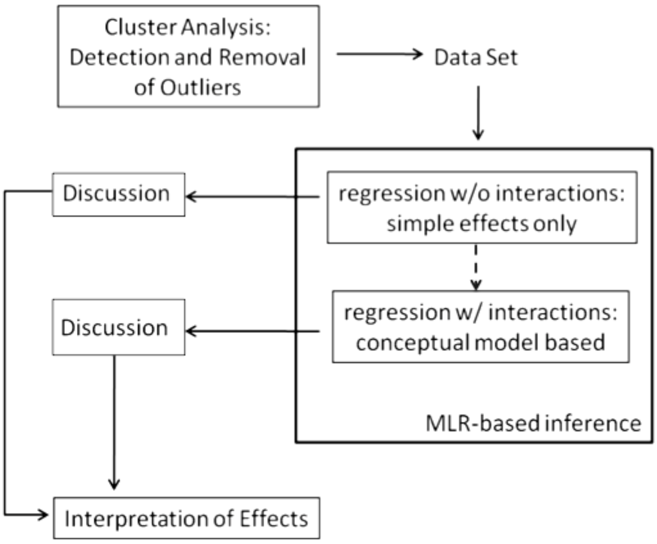

Figure 4: Summary of the steps followed to analyse the experimental results.

Figure 4 summarizes the process that has been followed to analyze the results of the experiment reported herein. First of all, anomalous results have to be detected in order to remove them from the results dataset. Since several creep parameters have been measured for each one of the specimens tested, this search for outliers has to be carried out in a multi-dimensional context instead of looking at each creep parameter results separately. The tools used has been cluster analysis and the k-means algorithm [10]. Results from three out of thirty-two specimens had to be discarded.

After that, multiple linear regression (MLR hereafter) is applied in a first stage, by using models which relate each creep parameter to the simple effects of the variables considered, without considering interactions between any of them. Once the outputs of these regression studies have been analyzed, models for the creep parameters can be reformulated in order to include some interactions between variables to be chosen on a reasonable basis.

Finally, results of the analysis concerning statistical significance of the effect of the different variables upon the creep parameters considered in this research will be put together and interpreted. In a multivariate context like this, where the experimental output is composed of several variables, n-dimensional plots are not an option and therefore the signs of the coefficient estimates are going to be the tool to interpret the effects.

4.2 Analysis with Simple Effects Models

Table 3 summarizes the results of the significance tests carried out on the coefficients which multiply each one of the variables in the univariate models for creep parameters, where only simple effects of such variables are considered (no interactions, no transformations applied to variables). Each row in the table corresponds to a creep parameter and, accordingly, each row summarizes the output of a multiple linear regression, with R-squared values given in the last column.

The process followed to achieve the model finally assumed at each row, i.e. the model that best fits the data and considers only statistically significant variables, has been stepwise regression [11]. The threshold considered for p-values identifying significant effects is 0.05 in all cases. Where a variable has a statistically significant upon a creep parameter, it is marked in Table 3 with an 'X'.

There are important differences among the different creep parameters considered with respect to the variables which have been detected to have a statistically significant effect. A very simple way of looking at the overall significance of these variables is counting the number of creep parameters on which each particular variable has a statistically significant effect, as given in the last row of the table, 'count'. It is clear that key variables are: base mix design, fiber slenderness, load ratio (IFa), and the specimen's position in the test setup (see Figure 2).

Table 3: Results of the MLR analyses (simple effects only) on creep parameters.

	Base mix design	Max aggr size	Fiber slenderness	Fiber length	Fiber content	Load ratio, IFa	Spec position	R^2
(wp-wpr) / wp		X	X	X	X			0.87
wci	X					X	X	0.82
wcd(90)			X			X	X	0.83
COR(i-14)						X	X	0.81
COR(14-30)	X		X			X	X	0.76
COR(30-90)			X	X		X	X	0.77
spCOR(i-14)	X					X	X	0.80
spCOR(14-30)	X				X	X	X	0.87
spCOR(30-90)								--
φ14	X		X					0.80
φ30	X		X	X		X		0.61
φ90	X		X					0.70
φ_o14			X			X		0.71
φ_o30			X			X		0.63
φ_o90			X			X		0.66
(count)	7	1	10	3	2	11	7	

The authors suspected that the specimen's position in the creep test setup could be relevant, and so it turned out to be. In order to get more information about it, the effect of this variable upon all response variables has been analyzed with the help of box-and-whisker plots and it has been found a very similar tendency in all cases, as can be seen in some of these plots shown in Figure 5. If this effect was due to the fact that specimens in positions 2 and 3 receive not only the load which is directly applied but also the weight of specimen 1, and specimens 1 and 2, respectively, the tendency to be found in these plots had to be linear. But this is not the case, as it appears clear in Figure 5: there's almost no difference between positions 1 and 2, while position 3 is significantly different. In the opinion of the authors, this is due to the very different rigidity that support conditions under specimens 1 and 2 may have with respect to the bottom one.

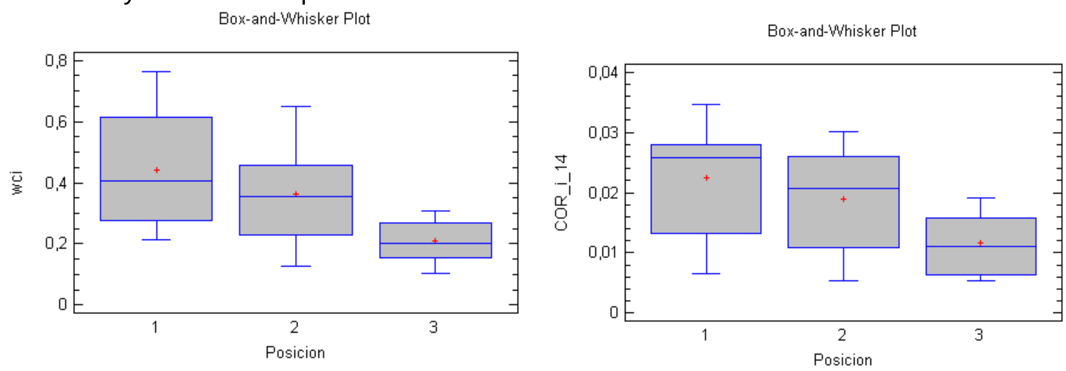

Figure 5: Box-and-whisker plots exemplifying the effect of 'position' upon creep behavior.

Load ratio has been detected as the most important variable determining creep behavior: its effect on most of the creep parameters considered is significant, and this is no surprise.

The effect that fiber content has on creep behavior is of rather little importance when compared to that of load ratio. However, it is important to bear in mind that variables have been considered as independent, simple effects in this first analysis, but fiber content is more important than it seems at first sight, as it is explained in the following paragraphs.

First of all, the effect that fibers have on bond behavior is hidened behind the load ratio. It is worth noting that load ratio, IFa, is the ratio between the load to be applied to the specimen and Fw, i.e. the load which corresponds to a crack width of 0.50 mm. Since such Fw clearly depends on fiber content, the fact that load ratio is statistically significant means that fiber content is as well, because the more fiber content considered, the more residual load bearing capacity concrete presents.

Another way of looking at the fact that the variable 'fiber content' turns out not to be highly significant as considered in Table 3 is coherent with the following statement: that, concerning creep behavior of concrete, there is no difference between adding 40 kg/m^3 or adding 70 kg/m^3.

However, any of the previous interpretations must be discarded, since both are coherent with the results that statistical inference tests on the coefficients of multiple linear regression models have offered. Furthermore, fiber content has to be relevant in relation to flexural creep behavior of SFRC: otherwise there would be no point in having fiber slenderness identified as a very significant variable.

After this first analyses based on regression models which consider only simple effects, a clearer understanding of creep behavior can be reached if interactions are also considered. To do so, it is a good strategy to use models, i.e. equation forms, that follow a structure which is easily interpretable in mechanical terms. As it has been detected that load ratio (IFa) is the key factor, it is highly reasonable to consider models where the creep parameter depends on IFa, its influence being modified by the other variables considered.

4.3 Analysis Based on Models Considering Interactions

According to the results of all MLR analyses summarized in Table 3, it follows that the load ratio, IFa, is the capital factor influencing most of creep parameters considered. Considering that all constitutive equations relate stress to strain, or vice versa, the MLR models for any creep parameter (i.e. strain) have to relate it to the load ratio, IFa (i.e. stress), where interactions have to represent the way that this relations are affected by the other variables considered. As a consequence, the multiple linear models considering interactions on which statistical inference has to be based are to follow this general expression:

$$Y = m + \left(n_0 + \quad n_i X_i\right) \quad IFa \tag{1}$$

where: Y is any creep parameter; X_i are the variables considered in this research (compressive strength or base mix design, maximum aggregate size, fiber content, etc); the term that multiplies IFa does not only relate to IFa itself (such standalone simple effect is coefficient n_0) but is also affected by the aforementioned X_i variables through the n_i coefficients; and m is the constant in the model. It is worth noting that assuming a model like (1) is similar to have results for all creep parameters typified by IFa. In order to have only quantitative variables, the variable 'base mix design' is reconsidered as the specified compressive strength of the mix (levels are 40 MPa and 25 MPa instead of A and B).

The process followed to achieve a final model that best fits the data and considers only statistically significant variables has been, as in the previous section, stepwise regression [11]. The threshold considered for p-values identifying significant effects is 0.05 in all cases. Table 4 summarizes the results of all significance tests for the aforementioned effects. The difference with respect to Table 3 is that in Table 4 signs for the coefficient estimates are given, since they are very useful to interpret these results.

The load ratio, IFa, has always a standalone simple effect which is statistically significant. The coefficient associated to this effect is positive in all cases, which is coherent with the fact that increasing the load ratio does always lead to increased strain, no matter which creep parameter is considered.

Specified compressive strength of concrete significantly interacts with the load ratio concerning some creep parameters. The coefficient associated with this interaction is positive in most of cases, which is not due to the fact that higher strength implies more creep, but a consequence of the definition of load ratio, IFa, as a variable: given a value for IFa, the higher compressive strength is, the higher load is applied to the specimen, therefore the higher creep strains are.

Maximum aggregate size significantly interacts with the load ratio concerning some of the creep parameters considered. The coefficient associated to such interaction is negative in all cases, this meaning that increasing the maximum aggregate size lessens the influence that increasing the load ratio has on creep strains.

Regarding fibers, their content does not interact with the load ratio concerning most of the creep parameters considered. All considerations given in the previous subsection with respect to fibers can be recalled here, especially that within the range of fiber contents considered in this research, the mere fact of adding fibers is a good strategy from the point of view of controlling creep strains (since it improves load bearing capacity of the material), but there is no difference regarding the amount of fibers added to the mix.

Fiber length does not interact with the load ratio either. On the contrary, fiber slenderness does make a difference. It significantly interacts with load ratio concerning several of the creep parameters considered. The sign of the coefficient affecting such interaction is negative in all cases: this means that using fibers with greater slenderness will soften the effect that increasing load ratio has on creep strain. That is to say: adding fibers is a good strategy in order to control creep strains and, though they are not required in high amounts, the best choice is to use fibers with high slenderness.

Table 4: Results of the MLR analyses (model with interactions) on creep parameters.

		Variables interacting with load ratio, IFa						
	Load ratio, IFa	Compr. strength	Max. aggr. size	Fiber slenderness	Fiber length	Fiber content	Spec. position	R^2
wci	+	−					− (3)	82.96
wcd(90)	+			−				79.61
COR(i-14)	+						− (3)	83.48
COR(14-30)	+							22.10
COR(30-90)	+			−	+		− (3)	81.43
spCOR(i-14)	+	+	−				− (3)	77.97
spCOR(14-30)	+			−				30.31
spCOR(30-90)	+	+	−	−		−	− (3)	87.92
φ14	+	+	−		+	+		49.97
φ30	+	+	−					44.32
φ90	+	+	−	−				55.54
$φ_o$14	+							56.39
$φ_o$30	+							53.26
$φ_o$90	+			−				58.38
(count)		6	5	6	2	2	5	
+/− in each case indicates the sign of the coefficient multiplying the corresponding simple effect or interaction. In the case of 'Spec. position', the sign is that of the coefficient multiplying the boolean variable which equals 1 when the specimen is in position 3 (see Figure 2).								

In relation to the specimen's position in the creep test setup, results of these analyses confirm what had already been stated in the previous section. The variable 'specimen's position' has been considered in the MLR analyses as a set of boolean variables. Results show that there are no significant differences between positions 1 and 2, but results from specimens in position 3 are significantly different. The coefficient associated to such boolean variable (position_3=true) is negative, which means that in position 3 the effect that increasing load ratios have on creep parameters is lessened, which is totally coherent with Figure 3.

5 CONCLUSIONS

Compressive strength of concrete and load ratio have been confirmed as being very important factors determining the flexural creep behavior of precracked SFRC specimens.

Fiber content does play a significant effect on most of creep parameters analyzed by means of increasing the material's load bearing capacity and therefore allowing more load to be applied for a determined load ratio without increasing creep strains.

The load ratio, IFa, has always a standalone simple effect which is statistically significant, and increasing the load ratio does always lead to increased strain, no matter which creep parameter is considered.

Several variables have been found to significantly modify the way load ratio affects flexural creep behavior of precracked SFRC specimens.

Compressive strength of concrete significantly interacts with the load ratio concerning some creep parameters.

Increasing the maximum aggregate size lessens the influence that increasing the load ratio has on creep strains.

Fiber slenderness has an important synergic effect with load ratio concerning several of the creep parameters considered: using fibers with greater slenderness will soften the effect that increasing load ratio has on creep strain. As a consequence, adding fibers is a good strategy in order to control creep strains and, though they are not required in high amounts, the best choice is to use fibers with high slenderness.

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