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COMPILATION AND STUDY OF A DATABASE OF TESTS AND RESULTS ON FLEXURAL CREEP BEHAVIOR OF FIBRE REINFORCED CONCRETE SPECIMENS

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Abstract

This paper examines the effect of fibres on the flexural creep of fibre reinforced concrete (FRC) in the cracked state based on the analysis of experimental results compiled over the last years. These creep tests were carried out on pre-cracked FRC prismatic specimens, reinforced with either steel, glass, or synthetic fibres. Besides the fibre material, the following variables have also been taken into account: fibre contents, concrete compressive strength resulting from different mix designs, and level of load applied during the flexural creep test. All the specimens have been subjected to sustained flexural loads for at least 90 days following the test setup methodology developed by the authors. Several experimental outputs were retained as main parameters of the residual flexural response under sustained loads: creep coefficients referred to both the origin and the beginning of creep stage, and crack opening rates, all of them at 14, 30 and 90 days. The relationships between these parameters and concrete compressive strength, applied flexural load, fibre type and content have been analysed.

Keywords: Cracked state, Creep database, Fibre Reinforced Concrete, Glass fibres, Steel fibres, Synthetic fibres.

1 Introduction

Creep defines the tendency of a material to develop deferred strains in time when subjected to a sustained load. This phenomenon usually results in increasing deflection or elongation trough time, but in case of Fibre Reinforced Concrete (FRC) in cracked state, creep also gives a deferred crack opening in the cracked section.

Fibres provide concrete a residual strength after cracking. The residual capacity of FRC depends on different parameters, most importantly several variables related to the fibres, namely: their geometry (slenderness and length), their content, and their material. FRC elements work often in service in cracked state. Therefore, considering this residual strength as a contribution to load-bearing capacity of the structure, it is really important to keep crack opening values low enough in order to guarantee the effectiveness of the fibre reinforcement. The control and evolution of these deferred strains and crack openings through time is also very important considering the durability of concrete structures in those elements in which the fibre reinforcement has not a structural purpose.

Aiming at a better understanding the long-term behaviour of FRC in the cracked state, several groups of researchers over the world focus their studies on creep. Tensile creep in cracked state has been studied by some authors (Zhao, Di Prisco & Vandewalle 2012, Babafemi & Boshoff 2015), but there is not yet a complete explanation on how the obtained conclusions can be related with the flexural creep behaviour. A greater number of studies have been reported on flexural creep. Some of these studies are focused on the material characterisation (Bast, Eder & Kusterle 2007, Zerbino

& Barragán 2012, Kanstad & Žirgulis 2012) and others focused in the behaviour of FRC in structural elements or beams (Buratti & Mazzotti 2012, Vasanelli & al. 2013). Different setups for the flexural creep test have been used by different authors, and therefore it is not possible to draw accurate conclusions from the comparison of results from different sources.

Therefore, the following general aspects are observed when some of the recent research papers are brought together:

- Most of these studies are usually focused on quantifying the creep behaviour of Steel Fibre or Synthetic Fibre Reinforced Concrete, but also the other types of fibres must be taken into account.
- Research studies on flexural creep of FRC reinforced with synthetic or glass fibres are usually aimed at comparing the response of these fibres with that of steel fibres, instead of addressing the quantification of their effect.
- Most of these studies are limited to one type of fibre, one concrete mix design, or a certain fibre content or level load. Therefore, they are not covering a general review of FRC creep.
- Nowadays there is no standardised methodology to analyze FRC flexural creep behaviour in cracked state either tensile creep response. This is one of the reasons of the dispersion of the experimental results. FRCs usually shows a great variability in their mechanical properties as residual strength, that contributes also to the heterogeneity of experimental outputs and variability.

Data sets described in the literature are often incomplete and contain unexpected inconsistencies. There are several test setup developed to identify the performance of FRC. Recently, as an attempt to establish a basis for the purpose of standardising, specific terminology and analysis parameters for the different stages of a creep test process which includes pre-cracking, loading, unloading, recovery and a final bending test until failure, have been proposed by Arango & al. 2012.

Following the aforementioned creep test and specific terminology, in this study, the authors have put together a database of experimental data from flexural creep tests performed with FRC made with different types of fibres. The results in this database are consistent as they all were obtained following the same methodology and using the same creep test setup so that the experimental results could be easily compared. This database includes 80 specimens over 5 year’s research and is extending enough in order to analyse the relation between input variables and output parameters.

Statistical analysis is used to obtain general conclusions of all FRCs behaviour. In addition to the conclusions of each research, it is possible to obtain general tendencies that could not be advised without an overall review. This creep database would be very helpful in all future investigations.

2 Objectives and scope

The main objective of this paper is to carry out an exhaustive compilation and research of creep behaviour conclusions and results in our broad database of FRC studies realized over the last years. This database only collects results of similar bending tensile creep behaviour test in order to avoid dispersion of tests results.

An important effort has been made to have a homogeneous data collection with a significantly larger number of input variables. With the collected information, this study aim to draw up an extended database comprising more than five years of research in long term behaviour of FRC taking into account different types of fibres: steel, glass and synthetic.

Several independent variables and creep parameters have been rigorously analysed in this work. The results obtained in this statistical analysis are a global perspective of the relations of the variables considered to study flexural creep behaviour of FRC in cracked state that may predict creep parameters and creep response.

3 Methodology and experimental results

3.1 The Creep Test setup

The flexural creep tests were carried out on notched prismatic specimens who were individually pre-cracked until a CMOD of 0.5 mm in a 4-point bending test following the standard EN 14651. After that, specimens have been transferred to the creep frames and tested under sustained flexural load for at least 90 days. A detailed description of the creep test setup up and methodology is given in previous papers by the authors (Arango & al. 2012, García-Taengua & al. 2014). This general test procedure is shown in Fig. 1, whereas Fig. 2 shows the creep frames in test at the creep chamber.

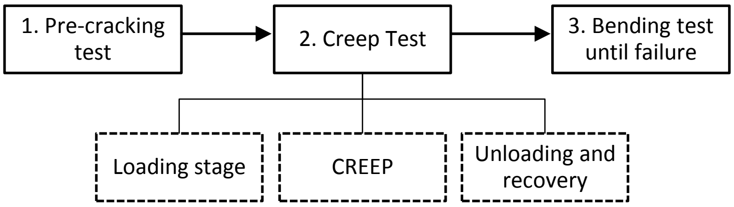

Fig. 1 General testing procedure.

The pre-cracking test is the first stage, where each specimen is notched and loaded according to a four point bending test setup. This stage finishes when the crack mouth opening displacement (CMOD) desired is reached. The criterion followed to define this CMOD in these experimental campaigns is usually 0.5 mm, where it is obtained de residual strength f_{R1}.

Creep test stage starts when all the specimens pre-cracked are placed into the creep frames. The creep frames (Fig. 2) have been designed in order to be loaded, in columns of three specimens, in a four point scheme.

Once the creep test is finished, creep frames are unloaded and elastic deformations are recovered. The last stage is a bending test until failure to characterise the residual performance of FRC after creep test.

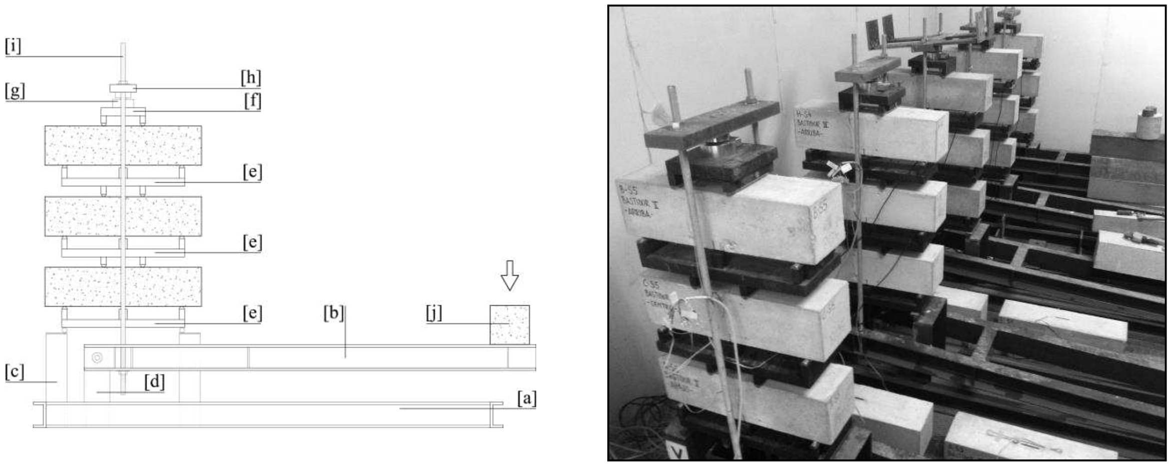

Fig. 2 Creep test setup.

Creep stage occurs in a control chamber where Temperature and humidity are continuously controlled to ensure stable environmental conditions, this being aimed at minimising variability in the results that could derive from uncontrolled conditions. One Data Acquisition System (DAS) inside the creep chamber record CMOD readings continuously.

Moreover, other companion tests for characterisation purposes are made to all batches of FRC to evaluate their compressive strength and flexural response.

3.2 Variables considered

Several types of fibres have been considered in reinforcement: steel, synthetic or glass fibres. This assures a complete overall of all range of fibres produced around the world. This serves to compare the creep behaviour between the different materials of fibres and their response in a similar amount of dosage.

Compressive strength (f_c) of concretes tacked account varies from 25 to 70 MPa, covering the range of low and mid-strength concretes and different aggregates sizes.

Depending on the material of the fibres, different fibre contents (C_f) are used. Due to the variety between the densities of the materials of fibres, dosages range from 3.5 to 9.0 kg/m^3 in synthetic fibres, from 10 to 20 kg/m^3 in glass fibres and from 35 to 70 kg/m^3 in steel fibres.

The nominal load ratio (IF_n) is defined as the ratio between the load applied in creep frames to the specimens and the residual load at the pre-cracking test, usually corresponding to CMOD of 0.5 mm. That means that this load variable represents a percentage of the residual performance of each specimen.

The main variables considered in this database are presented in Table 1.

Table 1
Independent variables considered

Independent Variables	Values for fibres		
	Steel	Synthetic	Glass
Compressive strength, f_c [MPa]	25	--	25
	40	40	--
	45	--	45
	--	70	--
Fibre content, C_f [kg/m^3] / [% Vol.]	--	3.5 / 0.37	--
	--	4.5 / 0.47	--
	--	6.9 / 0.73	--
	--	9.0 / 0.95	--
	--	--	10 / 0.4
	--	--	15 / 0.6
	--	--	20 / 0.8
	35 / 0.45	--	--
	40 / 0.51	--	--
	70 / 0.89	--	--
Nominal Load ratio, IF_n [%]	--	40	--
	--	--	45
	60	--	--
	--	75	75
	80	--	--
	95	--	--

All these variables values are summarised for all specimens depending the material of the fibres in Tables 2, 3, and 4. In these tables it can be observed each specimen actual values instead of the nominal values, since they represent more exactly the real state.

In addition, other concrete variables like residual strengths (f_{R1} & f_{R3}) have been considered. These intrinsic FRCs variables provide extra information of the post-peak performances of the concretes, hardening or softening post-peak behaviour. This performance is related most of times to the type of fibres and the fibre contents of FRCs (fib Model Code 2010**)**. The ratio f_{R3}/f_{R1} provides this hardening or softening post-peak behaviour. If values are lower than unity means softening response.

3.3 Experimental results and parameters

The idealized curve of the complete process after testing is shown in Fig. 3. This curve represents the three stages of the creep test. The first part of the curve corresponds to the pre-cracking test, where the specimen is loaded until the crack width determined (B), and then unloaded (C). This pre-cracking test has been carried out in a four points bending test for each specimen.

The second part of the idealized curve corresponds to the creep test starting at point (C). The ascending line (CD) represents the loading process until the IF_n is reached (D). Then appears a horizontal branch (DE) corresponding to the deferred crack opening under sustained load during creep test (at least 90 days). Once the creep test is finished, the creep frames are unloaded (E) and the recovery process occurs until point (F).

The last part of the curve represents a final four point bending test until failure, which starts with an ascending line (FG) and then continues with the residual performance curve (GH) until failure.

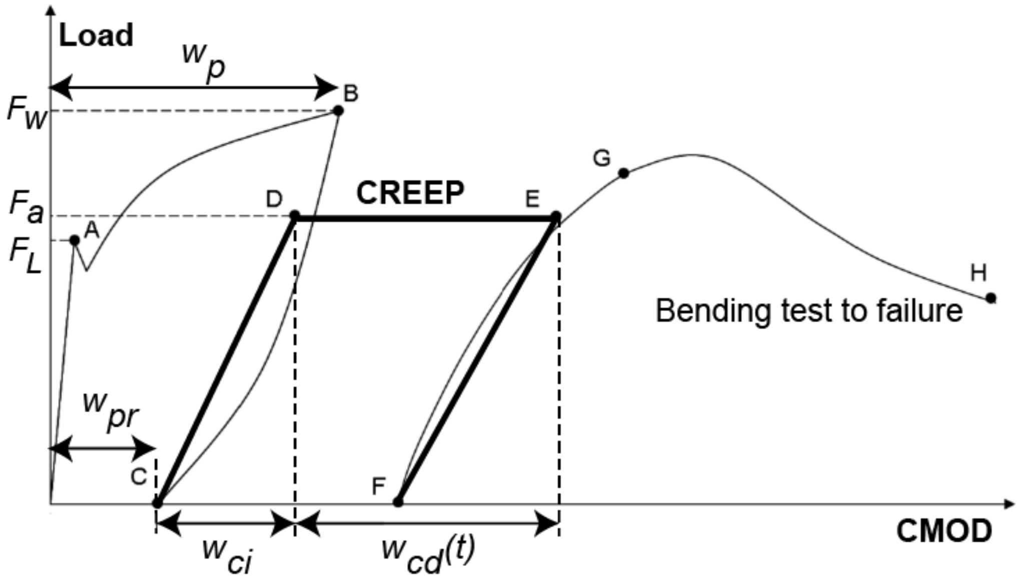

Fig. 3 Idealized curve obtained in a complete testing process.

In the creep stage, several experimental outputs have been recorded during the test such as instant crack opening at loading stage (w_{ci}) and deferred crack opening (w_{cd}). The main creep parameters considered to evaluate creep behavior are obtained by the experimental outputs following these expressions:

- Creep coefficient φ_c (j):

$$\varphi_{c\,(j)} = w_{cd}^{\,(j)} / w_{ci} \tag{1}$$

- Creep coefficient φ_o (j) referred to origin:

$$\varphi_{o\,(j)} = w_{cd}^{\,(j)} / w^{o}_{ci} \tag{2}$$

where:

$$w^{o}_{ci} = w_{pr} + w_{ci} \tag{3}$$

- Crack Opening Rates COR(t_1-t_2) at different time periods (14, 30 and 90 days):

$$COR^{\,t1\text{-}t2} = (w^{\,t2}_{cd} - w^{\,t1}_{cd}) / (t_2 - t_1) \tag{4}$$

Other sub-parameters could be considered, as creep coefficients for different time periods (14, 30 and 90 days) referred to origin and creep stage, but the authors consider that the main creep parameters are enough in order to evaluate the different models of analysis chosen.

These main parameters are reported in Tables 2, 3, and 4 for each type of fibres: steel fibres, synthetic fibres and glass fibres. These tables configure the dataset of the experimental results obtained from the creep tests in FRC specimens realised over 5 years and complete the database for this analysis.

Table 2
Experimental database from steel fibres reinforced specimens

Id	fc (Mpa)	C_f (kg/m^3)	IF_a (%)	f_{R1} (Mpa)	f_{R3} (Mpa)	f_{R3}/f_{R1}	φ^{o}_{w90}	φ^{c}_{w90}	COR^{0-14} (10^{-3} mm/day)	COR^{14-30}	COR^{30-90}
1	40.0	40	60.9	5.1	5.4	1.049	0.433	0.870	11.23	1.42	0.82
2	40.0	40	54.9	6.7	6.9	1.044	0.394	0.902	10.90	1.21	0.60
3	40.0	40	54.2	7.1	6.5	0.922	0.268	0.840	6.46	0.79	0.34
4	40.0	70	61.9	12.0	11.0	0.914	0.506	0.933	13.26	1.96	0.70
5	40.0	70	59.2	11.5	10.9	0.953	0.638	1.183	17.71	1.63	1.23
6	40.0	70	59.2	11.9	10.5	0.881	0.306	0.856	6.35	0.90	0.46
7	40.0	70	81.0	9.2	9.6	1.042	0.540	0.762	25.80	1.97	1.29
8	40.0	70	82.2	9.7	9.8	1.012	0.531	0.738	28.38	2.08	0.80
9	40.0	70	81.3	10.4	10.0	0.955	0.516	0.947	15.83	1.38	0.58
10	25.0	40	56.2	3.1	3.6	1.165	0.137	0.489	6.47	1.05	0.75
11	25.0	40	60.4	3.3	4.0	1.224	0.199	0.585	5.44	1.06	0.60
12	25.0	40	70.8	3.1	3.8	1.235	0.307	0.836	7.52	1.49	0.51
13	25.0	40	76.3	1.7	--	--	0.814	2.361	24.34	3.03	1.84
14	25.0	40	57.7	--	--	--	0.318	1.277	6.72	1.16	0.82
15	25.0	40	54.4	3.3	1.2	0.378	0.319	1.401	5.38	1.28	0.78
16	25.0	40	72.9	--	--	--	1.851	4.023	14.09	46.26	6.43
17	25.0	40	72.4	3.1	--	--	1.016	3.315	12.30	7.09	4.13
18	40.0	40	97.0	5.6	--	--	0.771	1.043	32.80	13.80	1.96
19	40.0	40	81.9	7.2	--	--	0.594	0.911	25.97	2.67	1.50
20	40.0	40	70.5	9.1	8.2	0.902	0.297	0.706	6.79	1.01	0.58
21	40.0	40	82.9	5.8	5.3	0.911	0.395	0.882	38.91	5.72	2.70
22	40.0	40	81.0	5.8	6.3	1.095	0.374	0.801	38.70	4.65	2.23
23	40.0	40	77.4	6.0	7.0	1.178	0.394	1.379	29.22	3.69	2.24
24	40.0	70	93.7	9.2	9.0	0.982	1.113	1.463	59.72	6.74	4.15
25	40.0	70	92.1	9.7	9.6	0.990	0.783	0.997	44.30	4.11	3.34
26	40.0	70	80.9	10.2	11.1	1.085	0.574	0.956	13.03	2.72	1.72
27	25.0	40	97.2	3.3	3.7	1.109	0.728	1.369	27.86	1.44	2.34
28	25.0	40	80.2	3.9	4.9	1.249	0.914	1.825	30.16	2.83	3.07
29	25.0	40	78.3	4.6	5.2	1.138	0.608	1.643	14.79	1.82	1.40
30	25.0	40	90.9	3.3	4.1	1.252	0.793	1.254	34.73	5.72	3.21
31	25.0	40	84.4	4.1	5.4	1.308	1.164	2.354	23.69	19.48	3.12
32	25.0	40	75.1	4.4	5.2	1.174	0.900	2.048	19.24	8.82	2.32
33	25.0	40	88.1	4.6	6.3	1.380	0.770	1.157	26.27	4.40	2.45
34	25.0	40	82.5	4.8	6.6	1.387	0.711	1.240	23.95	3.54	1.75
35	25.0	40	82.2	5.1	6.3	1.226	0.796	1.846	18.96	3.01	1.53
36	40.0	40	79.6	6.3	8.0	1.262	0.472	0.731	15.61	2.26	1.32
37	40.0	40	78.8	5.8	--	--	0.568	1.085	15.26	1.56	1.55
38	41.4	39	75.0	4.8	5.1	1.063	0.583	1.180	18.82	2.24	0.81
39	41.4	39	75.0	4.7	2.0	0.430	0.360	0.870	7.74	2.83	0.38
40	41.4	39	75.0	5.1	4.8	0.951	0.071	0.170	1.60	0.13	0.25
41	48.3	35	51.7	4.6	5.3	1.144	0.045	0.076	1.23	0.66	0.37
42	48.3	35	40.0	6.2	6.4	1.022	0.050	0.170	1.02	0.17	0.24

{--} Specimens corresponding to unavailable data due to problems with DAS.

In some cases, specimens are marked as unavailable data due to problems with the Data Acquisition System. The creep parameters of those specimens can neither be calculated.

Table 3
Experimental database from synthetic fibres reinforced specimens

Id	fc (Mpa)	C_f (kg/m^3)	IF_a (%)	f_{R1} (Mpa)	f_{R3} (Mpa)	f_{R3}/f_{R1}	φ^{o}_{w90}	φ^{c}_{w90}	COR^{0-14} (10^{-3} mm/day)	COR^{14-30}	COR^{30-90}
43	73.7	4.5	36.0	0.7	1.0	1.301	0.200	1.410	0.80	1.21	0.72
44	73.7	4.5	42.0	0.9	1.6	1.822	0.240	1.850	1.05	1.19	0.90
45	73.7	4.5	56.0	0.9	1.5	1.690	0.300	1.910	2.23	1.22	0.87
46	70.0	9	37.0	2.3	3.5	1.506	0.350	1.070	3.33	1.51	0.95
47	70.0	9	39.0	1.9	3.9	2.016	0.240	1.050	2.19	0.94	0.75
48	70.0	9	55.0	1.2	3.9	3.353	0.180	0.880	1.67	0.54	0.45
49	70.1	3.5	39.0	1.3	0.2	0.164	0.250	1.500	2.82	1.24	--
50	70.1	3.5	40.0	1.0	--	--	--	--	3.04	2.73	5.05
51	70.1	3.5	45.0	0.7	--	--	--	--	--	--	--
52	70.4	9	40.0	3.4	5.2	1.551	0.180	0.710	2.91	1.52	0.51
53	70.4	9	39.0	3.2	4.4	1.393	0.300	0.940	2.91	1.93	0.79
54	70.4	9	39.0	3.0	4.0	1.357	0.350	1.150	2.89	2.31	1.09
55	72.4	6.3	39.0	2.7	1.3	0.494	0.190	1.220	2.57	0.56	0.21
56	72.4	6.3	43.0	2.2	0.8	0.389	0.180	0.550	3.37	0.41	0.29
57	72.4	6.3	47.0	1.8	0.8	0.452	0.220	0.720	4.83	0.52	0.44
58	42.0	4.5	75.0	1.0	1.1	1.080	0.419	0.820	6.57	4.94	1.54
59	42.0	4.5	75.0	1.2	1.1	0.897	0.871	1.680	27.21	3.25	3.02
60	42.0	4.5	75.0	1.2	1.3	1.067	0.461	0.900	13.58	3.58	1.73
61	37.1	4.5	75.0	1.8	1.9	1.055	1.033	1.960	20.40	12.25	2.41
62	37.1	4.5	75.0	1.8	1.7	0.956	1.225	2.010	31.24	10.14	4.52
63	37.1	4.5	75.0	1.9	2.5	1.319	0.259	0.560	6.83	1.09	0.49
64	40.1	4.5	75.0	1.7	2.1	1.213	0.552	1.050	14.00	5.07	1.62
65	40.1	4.5	75.0	1.7	2.0	1.127	1.058	1.850	39.74	2.91	2.05
66	40.1	4.5	75.0	1.8	2.4	1.326	0.373	0.750	10.34	2.22	0.66
67	42.1	4.5	75.0	0.9	1.4	1.628	0.390	0.960	7.96	3.59	1.06
68	42.1	4.5	75.0	0.9	1.1	1.256	1.034	2.600	21.93	3.07	2.68
69	42.1	4.5	75.0	0.9	1.5	1.724	0.235	1.020	5.51	1.27	0.42

{--} Specimens corresponding to unavailable data due to problems with DAS.

Table 4
Experimental database from glass fibres reinforced specimens

Id	fc (Mpa)	C_f (kg/m^3)	IF_a (%)	f_{R1} (Mpa)	f_{R3} (Mpa)	f_{R3}/f_{R1}	φ^{o}_{w90}	φ^{c}_{w90}	COR^{0-14} (10^{-3} mm/day)	COR^{14-30}	COR^{30-90}
70	48.7	20	44.5	5.1	6.4	1.262	0.032	0.049	0.74	0.25	0.39
71	48.7	20	44.4	4.8	6.7	1.383	0.031	0.046	0.65	0.12	0.54
72	48.7	20	46.1	4.4	5.7	1.285	0.023	0.033	0.44	0.15	0.39
73	48.7	20	74.0	4.7	6.0	1.268	0.126	0.164	4.59	2.39	2.09
74	48.7	20	77.1	4.3	--	--	0.180	0.204	21.50	7.71	4.23
75	36.6	15	42.1	3.5	1.6	0.456	0.135	0.207	5.76	2.53	1.19
76	36.6	15	44.5	3.1	1.6	0.511	--	--	--	--	--
77	36.6	15	49.5	2.5	1.4	0.543	0.236	0.955	4.07	1.54	0.93
78	47.9	10	44.4	2.5	2.8	1.118	0.120	0.354	1.21	0.63	0.85
79	47.9	10	45.6	1.9	2.2	1.148	0.069	0.134	0.17	0.57	0.98
80	47.9	10	44.1	2.2	2.1	0.934	0.085	0.161	0.35	0.98	1.12

{--} Specimens corresponding to unavailable data due to problems with DAS.

These obtained values represent the full database of experimental results obtained from the pre-cracking stage (f_{R1}), creep stage (φ^{o}_{w90}, φ^{c}_{w90}, COR^{0-14}, COR^{14-30} and COR^{30-90}) and final bending test stage (f_{R3}).

4 Analysis of database and results

The main objective of this analysis is to evaluate the relations between the variables and the parameters under study, identifying the variables that have a statistical significance on most of creep parameters. Once these variables are identified, creep tests and creep parameters can be regarded in a global view and the global conclusions will be helpful in future for the design of experiments stage of new creep test.

Multiple linear regression (MLR) has been applied in order to relate each creep parameter to the simple effect of the independent variables considered. These MLR models have been obtained by means of a stepwise regression (Hair et al. 2009) considering a threshold for p-values identifying significant effects as 0.05 in all cases. That means a confidence level of 95% in all analysis.

4.1 Multiple Linear Regressions MLR

After some preliminary analyses, a high degree of multicolinearity was detected if all variables of fibre concrete mechanical properties were considered, as the concrete compressive strength f_c and the residual strengths f_{R1} and f_{R3} are highly correlated. Therefore it is not possible to consider the three of them in the same model, as their not being independent would compromise the reliability of any conclusion. Instead, two alternative MLR modelling approaches have been considered.

The first formulation (analysis A) takes as independent variables the type of fibre, concrete compressive strength f_c, fibre content C_f, and load ratio IFa, following this general expression:

$$cp_i = K_i + a_i\, IF_a + b_i\, f_c + c_i\, C_f \tag{5}$$

where cp_i refers to each creep parameter analysed; K_i is a coefficient dependent on the fibre type; a_i, b_i, and c_i are coefficients to be fitted; IF_a is the real applied load ratio in %; f_c is the compressive strength of concrete in MPa, C_f is the fibre content in kg/m^3.

Remark that in this work, fibre content C_f has been considered as the weight of fibres by volume of concrete. This option includes the effect of fibre type into the dosage effect. An analysis with the fibre content evaluated as % of the concrete volume will be done in future studies.

For each analysis of creep parameters cp_i, all coefficients of variables are estimated by least squares when the model is fitted to experimental data. Table 5 summarizes the results of these significance tests on creep coefficients. Each row represents a MLR analysis by mean of one cross in case of significant effect of the variable and the R-squared value of the analysis. Blank cells in the table mean no statistically significant effects.

As for each parameter a MLR model has been done, there may be differences between the statistical significant effects of the variables into each parameter. A quick way of looking the significance of each variable is counting the number of parameters on which each particular variable has a statistically significant effect. Last row of the Tables 5 and 6 gives this count of significant effects for each variable.

Table 5
Results from the MLR analyses A on creep parameters.

	fc	C_f	IFa	fr_1	fr_3	R^2
φ^{o}_{w90}	x	x	x			0.8383
φ^{c}_{w90}	x	x				0.7707
$COR^{0\text{-}14}$		x				0.4769
$COR^{14\text{-}30}$	x	x	x			0.4059
$COR^{30\text{-}90}$	x	x	x			0.3493
(Count)	4	5	3	Not considered		

A different, but complementary formulation (analysis B) has been taken into account aiming at relating the creep parameters to the mechanical properties of FRC rather than its composition. From an engineering point of view, this relation helps to engineers to order the concrete suppliers certain properties of FRC. Characterizing the FRC behaviour from the properties of the concrete simplifies the production control and let producers to define the concrete compositions.

In this analysis will be studied the significances of FRCs residual strength parameters and will take as independent variables load ratio IF_a and residual strengths f_{R1} and f_{R3}. Remark that in this analysis compressive strength f_c is not considered because it is not significant. This complementary analysis follows this similar expression:

$$cp_i = K_i + a_i\, IF_a + b_i\, f_{R1} + c_i\, f_{R3} + d_i\, f_{R1}\, f_{R3} \tag{6}$$

where cp_i refers to each creep parameter analysed; K_i is a coefficient dependent on the fibre type; a_i, b_i, and c_i are coefficients to be fitted; IF_a is the real applied load ratio in %; f_{R1} is the residual strength at CMOD of 0.5 mm in MPa; f_{R3} is the residual strength at CMOD of 2.5 mm in MPa.

Table 6 resumes the results of these significance tests on creep coefficients for the analysis B. Each row also represents a MLR analysis. The crosses of statistically significant effects are given for interpretative purposes.

Table 6
Results from the MLR analyses B on creep parameters.

	f_c	C_f	IFa	fr_1	fr_3	R^2
φ^o_{w90}			x	x	x	0.7837
φ^c_{w90}			x	x	x	0.5643
COR^{0-14}			x	x	x	0.4110
COR^{14-30}			x	x	x	0.4731
COR^{30-90}			x	x	x	0.4999
(Count)	Not considered		6	6	6	

In this case there are no blank cells in the table meaning no statistically significant effects. Load ratio IF_a and the residual strengths f_{R1} and f_{R3} are clearly detected as key variables with a high level of significance.

4.2 Discussion

Summarizing and tacking account the variables of the Analysis A, clear tendencies can be observed plotting the equations vs. each variable.

For creep coefficient $\varphi_{o\,(90)}$ referred to origin at 90 days, Fig. 4 shows the evolution of the parameter along the range of the variables load ratio IF_a and compressive strength f_c. These plots represent the creep coefficients transformed in a logarithm typified by the load ratio IF_a. In both cases, the tendency is straight and continuous, that means an exponential trend.

In case of load ratio IF_a plot, the creep parameter follows an ascendant evolution (positive), and that means that increasing the variable increases also the parameter. Therefore, that variable can be explained as statistically significant with positive sign.

For the compressive strength f_c plot, the creep coefficient follows a descendant evolution (negative), what means that increasing the variable, the parameter decreases. This behaviour shows a statistically significances in a negative way.

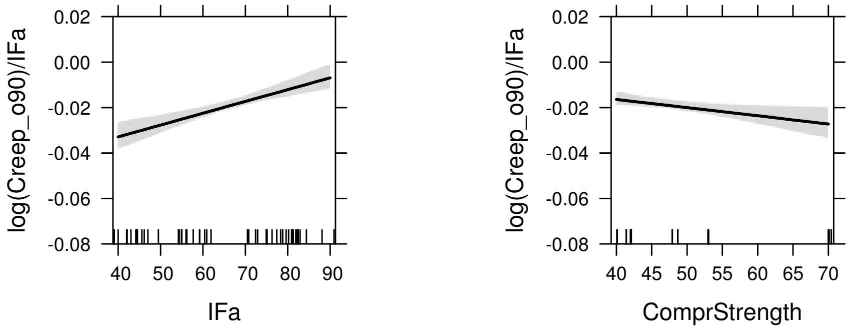

Fig. 4 Tendencies of φ^o_{w90} variations among the ranges of IF_a and f_c variables.

For creep coefficient $\varphi_{c\,(90)}$ referred to creep stage at 90 days, Fig. 5 shows in a similar way the evolution of this parameter along the variables presented, and in both cases, the tendency is also straight and continuous.

In case of compressive strength f_c plot, the creep coefficient follows also a descendant evolution (negative), what means a statistically significances in a negative way: the higher compressive strength, the lower creep coefficient. But in case of load ratio IF_a plot, the creep parameter follows a straight and continuous quasi-horizontal evolution. That means that this variable has no statistical significance and this creep parameter remains stable in load ratio range. Therefore this variable has a blank cell in the results in Table 5.

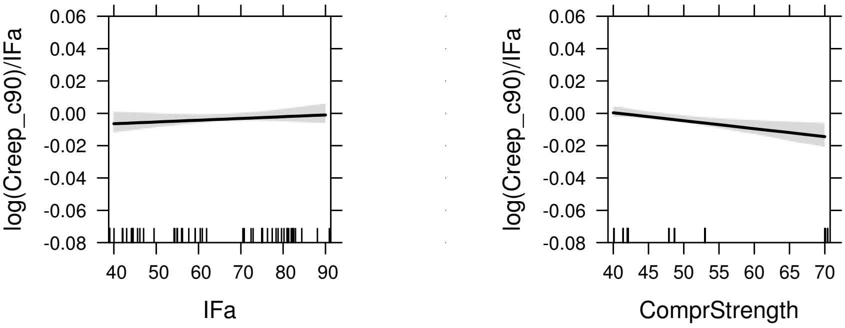

Fig. 5 Tendencies of φ^{c}_{w90} variations among the ranges of IF_a and f_c variables.

The tendency observed in the previous figures with de nominalized creep coefficient, can be confirmed in Fig. 6, where creep coefficient to origin at 90 days values vs. load ratio IF_a are represented. In the $\varphi_{o\,(90)}$ plot, the parameter increases in an exponential way with the variable, as expected, while in the $\varphi_{c\,(90)}$ plot, the parameter values rest stables even with highest levels of load ratio IF_a

These results mean that in a pre-cracked FRC specimen, the creep coefficient do not depend on the load ratio IF_a. If that is analyzed in the opposite sense, that means that the deferred strains depends on the instantaneous strain when reload. As a consequence the toughness during the reloading process may be considered as a good parameter to characterize the creep behavior.

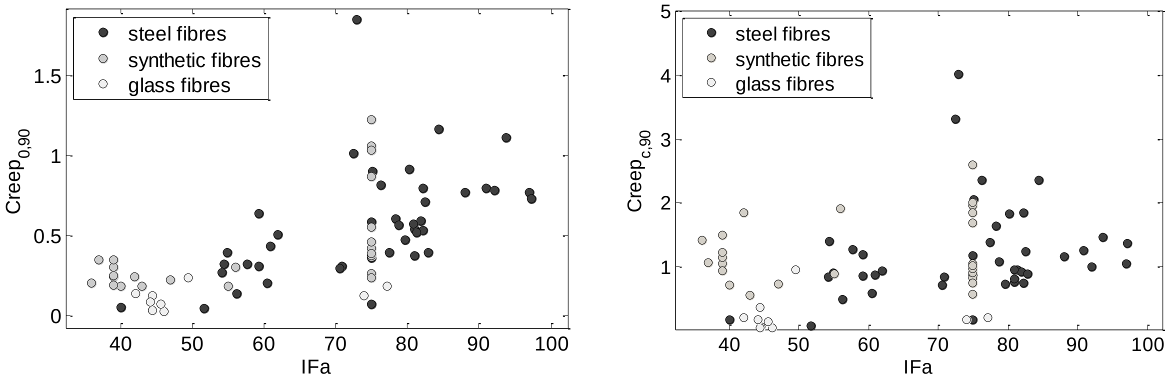

Fig. 6 Evolution of φ^{o}_{w90} and φ^{c}_{w90} depending the IF_a applied.

Referring to results of Table 6, compressive strength f_c of concrete is not statistically significant. In case of residual strengths, Fig. 7 represents the creep coefficient $\varphi_{o\,(90)}$ vs. both residual strengths f_{R1} and f_{R3} comparing the tendency depending of the different residual strengths.

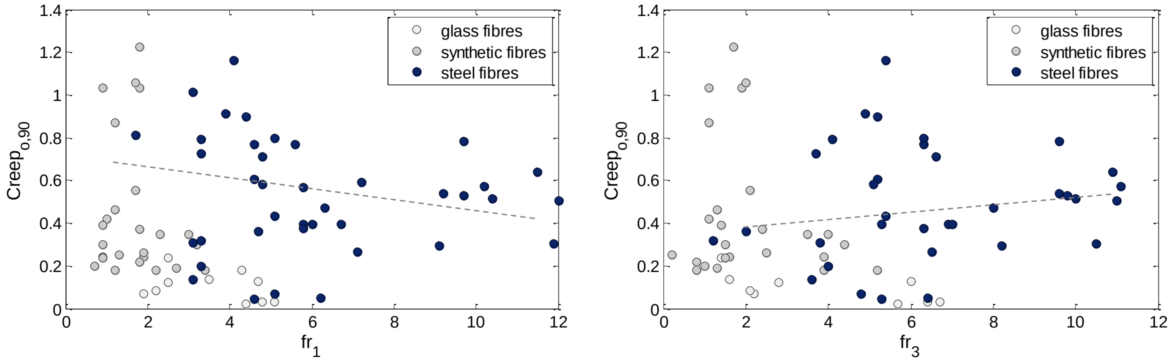

Fig. 7 Significance of variables f_{R1} and f_{R3} vs. creep coefficient $\varphi_{o\ (90)}$.

These plots show that, in case of residual strengths f_{R1}, the creep parameter trends in a descending way. That explains significance in a negative way of this residual strength f_{R1} variable. On the contrary, in case of residual strengths f_{R3}, the creep parameter evolution follows an ascendant trend meaning a positive statistical significance of this variable. This different behaviour between the most representative residual strengths must be analysed with the post crack behaviour of the FRC specimens: softening or hardening. All these tendencies must be verified in future due to the high variability of the parameters.

This post crack behaviour can be analysed as the ratio between the residual strengths f_{R3} and f_{R1}. Fig. 8 shows in a 3D plot the two residual strength variables and the creep coefficient $\varphi_{o\ (90)}$.

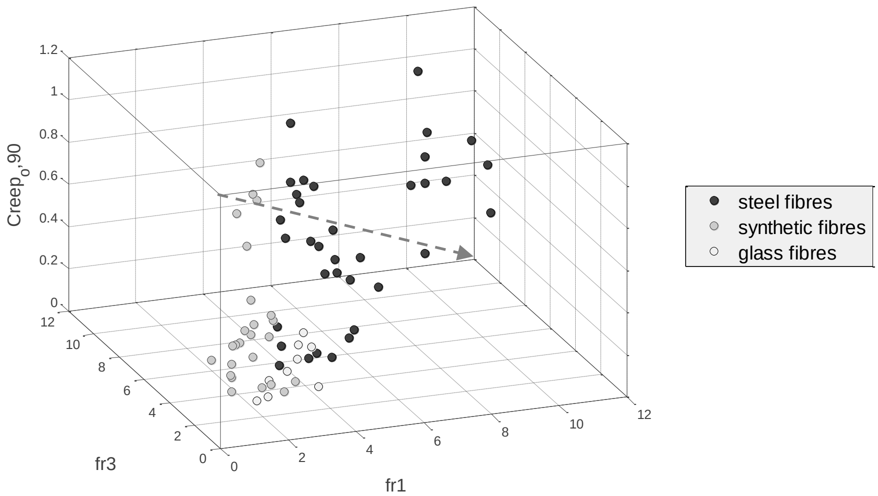

Fig. 8 3D plot of variables f_{R1} and f_{R3} with creep coefficient $\varphi_{o\ (90)}$.

The mean of creep parameter follows, as the result of the relation of both residual strength tendencies, the diagonal of the plot box in a descendent way. Similar general tendencies have been observed for the rest of creep parameters confirming in all cases the results of the MLR model and the statistical significances of the variables.

5 Conclusions

The statistical analysis of this database of FRC creep test results has made it possible to reach the following conclusions:

- The applied load ratio, IF_n, has been confirmed as a significant factor of the flexural creep behaviour of FRC specimens in cracked state. Regardless of the creep parameter considered in the analysis, the higher load ratio during creep test, the higher deferred creep coefficient referred to origin.

- Concerning creep coefficient referred only to creep stage, load ratio IF_n seems to have no significance in the flexural performance.
- The toughness during the reloading process may be considered as a good parameter to characterize the subsequent creep behavior.
- Compressive strength of concrete has also a significant effect on creep behaviour, but not as important as expected. More ranges of values of compressive strength of FRCs must be tested in creep in order to confirm this tendency.
- Fibres with low residual strength f_{R1} and higher residual strength f_{R3} tend to develop higher creep coefficients.
- In further analyses, the fibre content variable should take into account the density of the material of the fibres. The consideration of this variable as % of volume of fibres instead of kg/m^3 is suggested. This change will improve the results of significance of fibre type in the analyses.

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