COMPRESSIVE AND TENSILE CREEP AND SHRINKAGE OF SYNTHETIC FRC: EXPERIMENTAL RESULTS AND COMPARISON TO CODES

Razan H. Al Marahla (1), Emilio Garcia-Taengua (2) *

(1) School of Civil Engineering, University of Leeds, UK

(2) School of Civil Engineering, University of Leeds, UK

* Corresponding author: E.Garcia-Taengua@leeds.ac.uk

ABSTRACT

The mechanical properties of FRC mixes, namely compressive and tensile strength, are generally improved with respect to their unreinforced counterparts due to the contribution of fibres. This has implications in aspects like crack propagation or the development of time-deferred strains such as those resulting from creep and shrinkage, which in turn influence the long-term deformation of structural elements. The effect of fibres on compressive creep has been studied by various researchers, and codes and guidelines for the design of concrete structures include provisions to predict creep under compression. However, tensile creep of FRC has not attracted the same level of coverage despite its relevance to the loss of tension stiffening. This paper presents the results of an experimental study in concrete specimens reinforced with synthetic fibres were subjected to constant loading in uniaxial tension and in compression in order to evaluate the effect that increasing dosages of synthetic fibres have on the resulting time-dependent strains. The evolution of shrinkage, creep strains and the creep coefficient were analyzed in relation to the fibres dosage. The experimental strain-time curves were compared to the theoretical curves from the models adopted in the Eurocode 2, the Model Code, or by the ACI Committee 209.

KEYWORDS: Synthetic fibres, strains, time-dependant.

1. INTRODUCTION

Concrete exhibits volume changes with time. Due to the partial or total restraint of concrete deformation, shrinkage induce stresses even in the absence of externally applied loads, and the resulting tensile stresses can result in cracking [1, 2]. The long-term behaviour of concrete structures is also influenced by creep deformations under sustained stresses. Time-dependent strains due to shrinkage and creep affect the mechanical capacity of reinforced concrete sections [3]. The creep and shrinkage equations included in the Eurocode 2 [4], Model Code 2010 [5], or in ACI 209.2R [6] are tools for estimating shrinkage and creep of concrete as a function of time.

The presence of fibres in concrete plays a significant role in controlling the propagation and growth of microcracks, and increase the tensile strength of concrete [7] as well as its toughness in the cracked state [8]. The behaviour of FRC under sustained tensile and flexural loads, and how this behaviour is influenced by the combined effect of creep and shrinkage, remain issues that attract considerable research interest.

The behaviour of concrete under sustained compressive loads has been studied by different authors, who have investigated the effect of different variables such as the compressive strength of concrete, the specimen shape, the stress level applied, the duration of the sustained loading, or the temperature and relative humidity conditions [9, 10]. An empirical expression to estimate concrete creep under compression was developed by [11], based on experimental data obtained for FRC mixes with different types and dosages of steel fibres, and the effect of fibres geometry and dosage was studied in terms of bond of fibres to the cementitious matrix.

Different methodologies have been proposed for evaluating tensile creep. Domone [12] evaluated the tensile creep of both sealed and immersed concrete specimens, adopting the uniaxial tensile test introduced by Elvery and Haroun [13], in which cylindrical (bobbin) specimens are tapered at both ends and a concentric load is applied. Tensile creep reduces the stresses caused by restrained shrinkage to some extent [14-16]. Swamy and Stavrides investigated the influence of fibres on restrained shrinkage and subsequent cracking and concluded that the addition of fibres to normal and lightweight concrete mixes can reduce shrinkage deformations up to 20% [17]. Various experimental and analytical investigations considered different fibre types and contents and studied the effect that higher fibre dosages have on interfacial bond and to what extent fibres contribute to crack control [18-20].

The effect of steel fibres on concrete time-dependent deformations has been investigated widely and results show that steel fibres improve the tensile and flexural capacity of FRC under sustained loads [21, 22]. This paper is concerned with the effect that synthetic fibres have on creep and shrinkage under sustained tensile and compressive loads. Different contents of synthetic fibres were added to the same reference mix design and the sensitivity to this parameter was evaluated.

2. EXPERIMENTAL PROGRAMME

2.1. Materials and reference mix design

The reference mix design considered in this study had a water-to-cement (*w/c*) ratio of 0.29 and an average compressive strength of 60 MPa at 28 days. It was adjusted for a slump value of 120-150 mm so it could incorporate synthetic fibres at different dosages without further adjustments. The mix proportions are given in Table 1. The synthetic fibres were high-modulus 54 mm long polymeric fibres, with a tensile strength of 600 MPa. A picture of these fibres is shown in Figure 1.

Table 1. Mixture proportions kg/m^3.

Specimen	w/c= 0.29
Cement	510
Water	147
Fine aggregate	950
Coarse aggregate (20 mm)	300
Coarse aggregate (10 mm)	580
Superplasticiser	9

2.2. Mixes production and testing methodology

In total, three different mix designs were considered in this study, all based on the reference mix design summarised in Table 1 and differing in the synthetic fibre content only: 0, 5, and 10 kg/m^3. Two identical batches of each of these mixes were produced, and the same number of specimens were cast from each batch, with the objective of generating a sufficient number of replicates for better accuracy of the results.

Figure 1. Synthetic fibres used in this study.

The same mixing sequence was followed in all cases. Prior to the mixing of every batch, the total amount of water to be added was separated in two buckets: one containing only 80% of the water, and the other containing the mixture of the required amount of superplasticiser and the remaining 20% of the water. First, cement and all aggregates were poured into the mixer and dry-mixed for 2 minutes. After that, 80% of the water was added and mixed with the cement and aggregates for 3 minutes. During this time, the fibres were poured gradually into the mixer. Finally, the remaining 20% of the water with the superplasticiser predispersed in it was added, and the mixing continued for 4 minutes. In all cases, a uniform distribution of the fibres in the mix was observed.

From each batch, specimens were cast and tested as follows:

- Characterisation: 3 cubic specimens (100 mm side) and 3 cylindrical specimens (150x300 mm), to determine the compressive strength and splitting tensile strength at 28 days.
- Creep and shrinkage under compression: 8 prismatic specimens with a 75x75 mm cross-sectional area and a length of 200 mm. Of these specimens, 4 were tested under sustained compressive load, and 4 were not loaded but instrumented to measure free shrinkage strains.
- Creep and shrinkage under tension: 3 cylindrical specimens with a diameter of 75 mm and a length of 365 mm. Throughout this paper, these are referred to as ‘bobbins’, to distinguish them from the 150x300 mm cylindrical specimens. Out of these 3 bobbins, 2 were tested under sustained tensile load, and 1 was not loaded but instrumented to measure free shrinkage.

Characterisation specimens were tested at the age of 28 days. Prior to this, they were kept in a fog room with a controlled temperature of 20C and a relative humidity of 90%.

Creep and shrinkage specimens were instrumented with DEMEC points, which were glued and fixed to their sides and positioned 150 mm apart from each other, in order to measure the average surface strain. A picture of the specimens and test instrumentation is shown in Figure 2. For the specimens tested under compression, a sustained load corresponding to 25% of the average compressive strength measured at 28 days was applied. For the specimens tested in tension, the sustained tensile stress applied was 1 MPa. Measurements were taken daily for 90 days. In both cases, the tests were set up in a controlled room where the temperature and relative humidity were kept at 21 ± 2 C and a relative humidity of 50 ± 5 % throughout the duration of the tests.

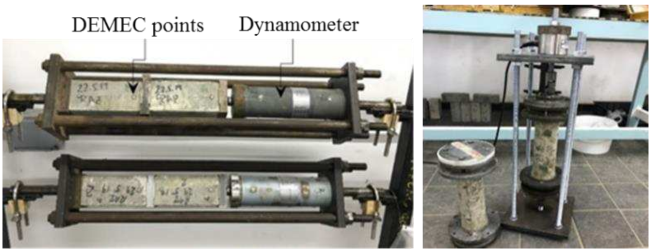

Figure 2. Experimental setup for specimens in compression (left) and in tension (right).

3. RESULTS AND DISCUSSION

3.1 Compressive strength and splitting tensile strength

For each of the batches, compressive strength and tensile splitting strength were measured at 28 days. The average results as well as the corresponding standard deviation values are shown in Table 2.

Table 2. Compressive and splitting tensile strength results.

Fibre content (kg/m^3)	Compressive strength (MPa)		Splitting tensile strength (MPa)	
	Average	Std. deviation	Average	Std. deviation
0	60.9	0.8	3.9	0.1
0	60.4	0.6	3.9	0.4
5	61.1	0.7	4.4	0.2
5	61.6	0.7	4.3	0.2
10	60.4	0.6	4.6	0.5
10	59.8	1.4	4.6	0.4

Regarding the average compressive strength, the addition of synthetic fibres at 5 or 10 kg/m^3 did not introduce statistically significant differences with respect to the batches without fibres. The same can be said in relation to the standard deviation values. In terms of the splitting tensile strength, an improvement was observed due to the introduction of synthetic fibres. With respect to the batches without fibres, the average splitting tensile strength increased by 11.5% when synthetic fibres were dosed at 5 kg/m^3, and by 18% when the fibres content was 10 kg/m^3.

3.2 Creep under sustained compression

For the analysis of creep and shrinkage under compression, strains were measured over a period of 90 days on unloaded as well as loaded specimens. Measurements were taken daily on a total of eight specimens per case. Table 2 shows the measurements corresponding to 14, 30, and 90 days, as well as the elastic strains, which were measured immediately after the compressive load was applied.

Table 2. Strains measured in prismatic specimens under compression (in microstrain).

Fibre content	Elastic strains	Strains at 14 days		Strains at 30 days		Strains at 90 days	
		Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
0 kg/m^3	-395	-807	-156	-968	-231	-1146	-325
	-390	-811	-162	-966	-237	-1140	-326
	-412	-789	-151	-962	-228	-1150	-319
	-389	-819	-149	-958	-240	-1136	-312
5 kg/m^3	-365	-728	-145	-858	-201	-1033	-288
	-359	-730	-134	-864	-189	-1042	-286
	-373	-724	-128	-851	-193	-1038	-280
	-376	-731	-149	-863	-210	-1022	-277
10 kg/m^3	-356	-655	-100	-786	-168	-881	-267
	-353	-661	-92	-797	-178	-876	-256
	-347	-647	-110	-814	-179	-890	-274
	-354	-639	-118	-789	-163	-871	-265

Individual values for the compressive creep strain at any age were determined as the difference between the loaded and unloaded specimen strains, minus the corresponding elastic strain. The average compressive creep strains for the three synthetic fibre contents considered are shown in Figure 3, together with the theoretical strains as predicted by the equations in Model Code and Eurocode 2. The compressive creep strains corresponding to the reference mix without fibres showed good agreement with the theoretical values. In particular, strain values after 5 days were observed to be very close to the predictions calculated according to the Model Code.

The addition of fibres was correlated with a reduction in compressive creep strains, consistently observed at all ages. Strain values corresponding to FRC mixes with 5 kg/m^3 of synthetic fibres were between 10% and 15% lower than those observed in mixes without fibres (strains were reduced in 15%, 11% and 10% at 14, 30, and 90 days, respectively). For the FRC mixes where the fibre content was 10 kg/m^3, these reductions were between 15% and 22% (strains were reduced in 22%, 16% and 15% at 14, 30, and 90 days, respectively).

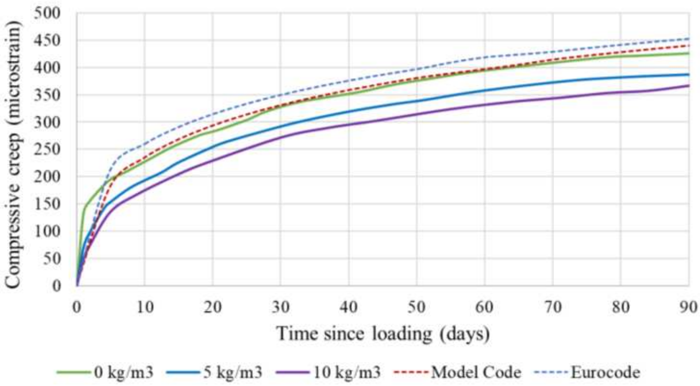

Figure 3. Average compressive creep strains and comparison to codes.

The analysis of the results was also made in terms of the creep coefficient values, and these are shown in Figure 4, together with the theoretical values as predicted by the equations in the Model Code, the Eurocode, and the ACI Committee 209 report. Again, it was observed that the values corresponding the case without fibres showed very good agreement with the theoretical values as per the Model Code.

At all ages, the presence of synthetic fibres was correlated with lower creep coefficients than without fibres, and the reduction associated with a fibre content of 10 kg/m^3 was higher than that observed for a fibre content of 5 kg/m^3. If the compressive creep coefficient at 90 days is considered, reductions of 5% and 8% were observed for fibres contents of 5 kg/m^3 and 10 kg/m^3, respectively.

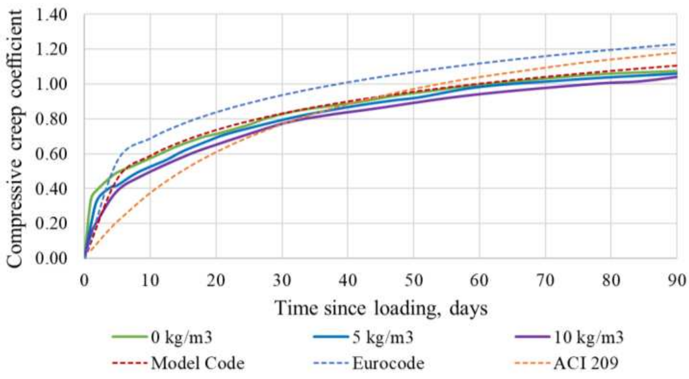

Figure 4. Average compressive creep coefficient values and comparison to codes.

3.3 Shrinkage

Shrinkage strains were determined from the strains measure in unloaded conditions (values in Table 2). The average shrinkage strains for the different synthetic fibre contents considered, together with the theoretical values according to the Model Code, Eurocode 2 and the ACI Committee 209 report, are shown in Figure 5. Shrinkage strains observed in specimens without fibres were well in agreement with the ACI 209 predictions up to approximately 50 days. For later ages, the model proposed by the Eurocode 2 yielded better predictions. In any case, the experimental results seemed conclusive in showing that the theoretical models tend to overestimate shrinkage strains.

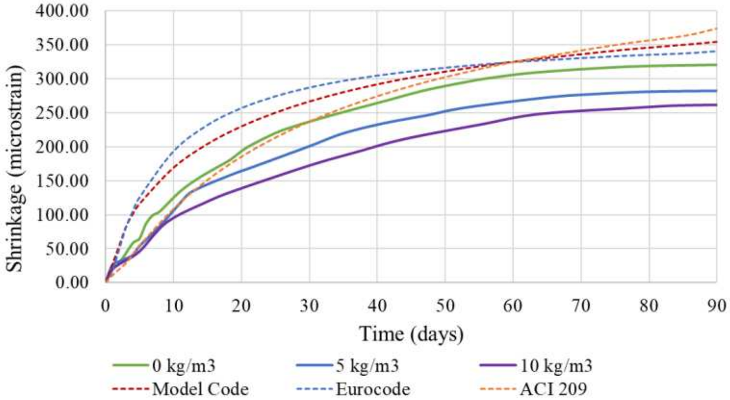

Figure 5. Average shrinkage strains and comparison to codes.

Similarly to what was observed in relation to creep under compression, the addition of synthetic fibres led to generalised reductions in shrinkage strains, and these reductions were directly related to the fibre content. The addition of synthetic fibres at a dosage of 10 kg/m^3 decreased shrinkage strains in between 20% and 26% (the reductions observed were 23%, 26%, and 20% at 14, 30, and 90 days, respectively). In those cases where the fibre dosage was 5 kg/m^3, shrinkage strains were between 8% and 16% lower than the values corresponding to the specimens without fibres.

3.4. Creep under sustained tension

To characterise the tensile creep, strains were measured for 90 days on unloaded as well as loaded specimens. Table 3 summarises the measurements corresponding to 14, 30, and 90 days, as well as the elastic strains, which were measured immediately after the tensile load was applied.

Table 3. Strains obtained from loaded and unloaded bobbins under tensile creep

Fibre content	Elastic strains	Strains at 14 days		Strains at 30 days		Strains at 90 days	
		Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
0 kg/m^3	31.6 27.9	101 99	-244	145 139	-322	168 155	-381
5 kg/m^3	26.2 27.4	78 75	-191	85 88	-241.5	126 101	-311
10 kg/m^3	24.4 23.8	65 66	-172	85 79	-218	98 94	-282

Individual tensile creep values were determined as the difference between the loaded and unloaded specimen strains, minus the corresponding elastic strain. The average tensile creep strains observed for the three synthetic fibre contents considered in this study are shown in Figure 6.

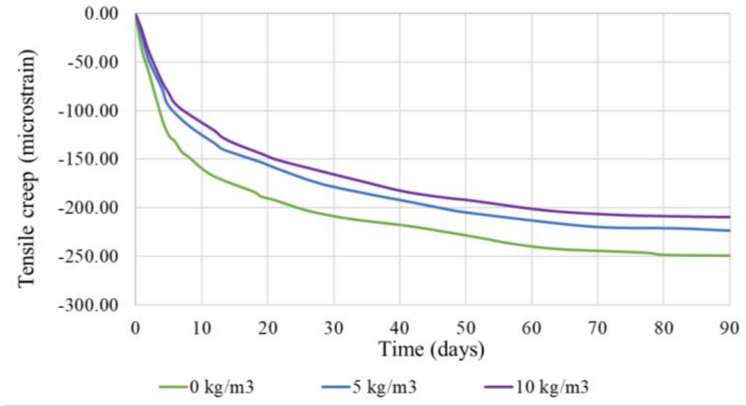

Figure 6. Tensile creep strain for samples with different fibre dosages.

Tensile creep strains were significantly reduced by the addition of synthetic fibres. The differences observed between the specimens without fibres and those with 5 kg/m^3 of fibres were significantly more pronounced than the differences observed when the fibre content was increased from 5 kg/m^3 to 10 kg/m^3. The introduction of 5 kg/m^3 of synthetic fibres led to reductions in tensile creep strains between 20% and 11% with respect to the unreinforced specimens (reductions were 20%, 16%, and 11% at 14, 30, and 90 days, respectively). With 10 kg/m^3 of synthetic fibres, reductions between 15% and 24% were observed (24%, 22%, and 15%, at 14, 30, and 90 days, respectively).

These observations led to the conclusion that, in terms of tensile creep reduction, the additional gains achieved by doubling the fibre content were less significant than those achieved by the incorporation of fibres at the intermediate dosage considered in this study. In consequence, dosing the fibres at the maximum dosage did not led to the most advantageous control of tensile creep from a cost-benefit point of view.

4. CONCLUSIONS

In this study, a reference mix with *w/c* ratio of 0.29 and an average compressive strength of 60 MPa at 28 days was considered as representative of most of the medium to high specification mixes prevalent in real scale production. The effect of synthetic fibres on compressive creep, tensile creep and shrinkage when dosed at 5 kg/m^3 and 10 kg/m^3 was analysed. To this end, daily measurements were taken on loaded and unloaded specimens over a period of 90 days. Multiple replicates were produced and tested to ensure accuracy of the final results and conclusions, and a comparison was made to the predictive models proposed by Eurocode 2, Model Code, and the ACI committee 209.

The following conclusions were drawn:

- In terms of compressive strength, no significant differences were observed between the reference mix without fibres and the FRC mixes, irrespective of the fibre content. However, the addition of 5 kg/m^3 or 10 kg/m^3 of synthetic fibres increased the spitting tensile strength by 11.5% or 18%, respectively.

- The incorporation of synthetic fibres was associated with a general, consistent decrease in compressive creep, shrinkage, and tensile creep strains. The magnitude of these reductions was observed to increase with the fibre content.
- Compressive creep strains measured on FRC specimens with 5 kg/m^3 of synthetic fibres were up to 15% lower than those corresponding to the reference mix without fibres. When the fibre content was 10 kg/m^3, hihger reductions (up to 22%) were observed. In terms of the creep coefficient at 90 days, it decreased by 5% and 8% for fibre contents of 5 kg/m^3 and 10 kg/m^3, respectively.
- Tensile creep strains observed in FRC specimens with 5 kg/m^3 of synthetic fibres were up to 20% lower than the values obtained for the reference mix without fibres. The additional gains achieved by doubling the fibre content were less significant: reductions of up to 24% were observed when the fibre content was 10 kg/m^3.
- The addition of 10 kg/m^3 of synthetic fibres led to shrinkage strains being up to 26% lower than those corresponding to the reference specimens without fibres. When the fibre content was 5 kg/m^3, reductions of up to 16% were obtained.
- The models proposed by the Model Code, Eurocode 2 and the ACI Committee 209 for the prediction of creep and shrinkage strains showed good agreement with the compressive creep strains observed in specimens without fibres, but they consistently overestimated shrinkage strains.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution of Oscrete Construction Products, part of Christeyns UK Ltd, and Sika Ltd (UK), which very kindly provided some of the materials used in this study, as well as the support and assistance provided by the technical staff of the School of Civil Engineering, University of Leeds. The authors are also thankful to Al-Zaytoonah University of Jordan for the financial support granted to Ms Al Marahla in undertaking her PhD studies at the University of Leeds.

REFERENCES

[1] Kristiawan, S.A., 'Strength shrinkage and creep of concrete in tension and compression', Civil Engineering Dimension. **8**(2) (2006) 73-80.

[2] Gilbert, R.I. and Ranzi, G., 'Time-dependent behaviour of concrete structures', CRC Press (2010)

[3] Bazant, Z.P. and Wittmann, F.H., 'Creep and shrinkage in concrete structures'. (1982) 12-16.

[4] BS EN 1992-1-1. Eurocode 2: 'Design of concrete structures: Part 1-1: General rules and rules for buildings', European Committee for Standardization, (2004)

[5] FIB, fib model code for concrete structures 2010, Wiley-vch Verlag Gmbh, Germany, (2013).

[6] ACI Committee, ACI 209.2 R-08: 'Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete', American Concrete Institute Committee, (2008).

[7] Monteiro, P., 'Concrete: microstructure, properties, and materials', McGraw-Hill Publishing, (2006).

[8] Buratti, N., Mazzotti, C. and Savoia M., 'Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes', Construction and Building Materials. **25** (5) (2011) 2713-2722.

[9] Gamble, B.R. and Parrott, L.J, 'Creep of concrete in compression during drying and wetting', Magazine of concrete research. **30** (104) (1978) 129-138.

[10] Brooks, J. and Neville, A.M., 'A comparison of creep, elasticity and strength of concrete in tension and in compression', Magazine of Concrete research. **29** (100) (1977) 131-141.

[11] Mangat, P.S. and Azari, M.M, 'A theory for the creep of steel fibre reinforced cement matrices under compression', Journal of materials science. **20** (3) (1985) 1119-1133.

[12] Domone, P.L., 'Uniaxial tensile creep and failure of concrete', Magazine of concrete research. **26**(88) (1974) 144-152.

[13] Elvery, R.H. and Haroun, W., 'A direct tensile test for concrete under long-or short-term loading', Magazine of concrete research. **20**(63) (1968) 111-116.
[14] Igarashi, S.I., Bentur, A. and Kovler, K., 'Stresses and creep relaxation induced in restrained autogenous shrinkage of high-strength pastes and concretes', Advances in cement research. **11**(4) (1999) 169-177.
[15] Igarashi, S.I., Bentur, A. and Kovler, K., 'Autogenous shrinkage and induced restraining stresses in high-strength concretes', Cement and Concrete Research. **30** (11) (2000) 1701-1707.
[16] Forth, J.P., 'Predicting the tensile creep of concrete', Cement and Concrete Composites. **55** (2015) 70-80.
[17] Swamy, R.N. and Stavrides, H., 'Influence of fiber reinforcement on restrained shrinkage and cracking', In Journal Proceedings. **76** (3) (1979) 443-460.
[18] Chern, J.C. and Young, C.H., 'Factors influencing the drying shrinkage of steel fiber reinforced concrete', Materials Journal. **87**(2) (1990) 123-139.
[19] Mangat, P.S. and Azari, M.M., 'A theory for the free shrinkage of steel fibre reinforced cement matrices', Journal of materials science. **19** (7) (1984) 2183-2194.
[20] Shah, S.P. and Rangan, B.V., 'Fiber reinforced concrete properties', In Journal Proceedings. **68** (2) (1971) 126-137.
[21] Llano-Torre, A., Arango, S.E., García-Taengua, E., Martí-Vargas, J.R. and Serna, P., 'Influence of fibre reinforcement on the long-term behaviour of cracked concrete', in 'Creep Behaviour in Cracked Sections of Fibre Reinforced Concrete', Springer, Dordrecht, (2017) 195-209
[22] García-Taengua, E., Arango, S., Martí-Vargas, J.R. and Serna, P., 'Flexural creep of steel fiber reinforced concrete in the cracked state', Construction and Building Materials. **65** (2014) 321-329.