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FLEXURAL CREEP BEHAVIOR OF STEEL AND POLYPROPYLENE FIBER REINFORCED CONCRETE

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Abstract: Creep in pre-cracked fiber reinforced cementitious composites has become an important topic of study recently. This is due to the fact that under serviceability limit state the concrete may crack and its stability will depend on the fiber and fiber-matrix interface properties. The time dependent behaviour of FRC and long term stability of cracks under sustained bending loads are still poorly understood. This work seeks to explore the use of steel and PP fibers in order to define their influence on creep, by analysing the crack opening displacement rate in FRC specimens. For the creep tests, the specimens were pre-cracked to 0.5 mm, and then tested under constant load during 45 days. The constant load applied was calculated based on the residual stress found for 0.5 mm of crack opening, which corresponds to 30% of its residual load. In order to better understand the related mechanisms, creep tests were also carried on a fiber pullout configuration. Analysing the creep tests results, it was verified that the COD rate is an interesting tool to evaluate the long-term behaviour of the cracked FRC and to define a stability criterion. In addition, it was found that concrete incorporating macro synthetic fibers presents higher creep deformations and higher creep rate than concrete reinforced with steel fibers. This can be explained by the different fiber-matrix bond characteristics. Finally, the residual properties of creep tested specimens were determined by monotonic flexural tests performed in the FRC specimens after the creep tests.

1 INTRODUCTION

Until now, concrete is the most widely used construction material in the world, and its use may be dated to ancient times [1]. Concrete is capable to be cast into almost any shape or size, has relatively high compressive strength and is a durable material. Because of these properties, concrete remains a popular material in the construction industry. One of the disadvantages of concrete is its brittle behavior, especially when analyzed for its tensile strength, in which it presents poor resistance to crack opening and propagation [2].

From the 60's, fiber reinforced concrete has been studied intensively in order to overcome the fragile nature of concrete and to bring new possibilities for its use as a building material. The combination of fibrous concrete with reinforced and prestressed concrete, as well as the potential to replace conventional reinforcement, can give the concrete special features such as pseudo-ductility and crack opening control.

Most of the research done on fiber reinforced concrete concerns the behaviour under short-term loading. However, concrete properties change according to age and according to the level of applied loading.

The progression of crack openings through time is crucial for the durability of concrete structures. The time-dependent properties such as creep and shrinkage must be considered besides instantaneous strain and cracking [3–5].

Although the structural concrete codes consider only the compressive creep for FRC it is necessary to take into account the process of pullout and elongation of the fiber when under sustained load [5,6]. As stated earlier, this cracking process is directly related to the durability of the structure.

Before Fiber Reinforced Concrete (FRC) can be considered as a widespread commercial building material, design models are required to describe time-dependent behaviour and, for this, the behaviour under sustained load should be investigated.

In this study, the flexural strength of fiber reinforced concrete with two different fibers have been studied over a period of 45 days. In addition, investigations on the fibre mechanical anchorage and stress level on the pullout response have been performed.

2 EXPERIMENTAL PROGRAMME

2.1 Materials and mix design

The concrete mixture materials used to produce specimens for all the tests performed in this investigation are Portland cement CPII-F32, locally available fine and coarse crushed aggregates. The compressive strength of this matrix was 35 MPa, characterized according to NBR 5739 [7]. Other constituents are hooked-end steel fibres and polypropylene fibres, superplasticiser and potable water. The fine aggregate passed through a 4.75 mm sieve and had a fineness modulus (FM) of 2.74. Two different types of coarse aggregates were used: one with at maximum diameter of 9 mm and the other with 19 mm. The properties of the fibres, as provided by the suppliers (Belgo Bekaert and Viapol®), are presented in Table 1. The superplasticizer, PLASTOL® 4100, supplied by Viapol Brazil, and conforming to the requirement of NBR 11768 [8], was used to adjust the workability of the mixes.

The FRC mixture proportions are shown in Table 2. Dry materials in the order of sand, cement and coarse aggregate were added to the concrete mixer (30 l or 400 l, depending on the amount of concrete), mixed for one minute before 70% of the water was added. Then the remainder of the water was added with the superplasticizer. Further mixing with all the constituent materials, except the fibres, was done for about 5 min. The specimens without fibres were cast after this stage. However, for FRC mixture, the fibres were gradually added over a minute to ensure they were well distributed and then mixed for 2 min.

Table 1: Properties of the fibres.

Property	PP	Steel
Length (mm)	40	35
Aspect ratio	58	65
Tensile strength (MPa)	625	1345
Modulus of elasticity (GPa)	9,5	210

Table 2: Mixture composition.

Material type	kg/m3
Cement (CPII-F32)	336
Aggregates	
Sand	642
Coarse Aggregate(Maximum diameter = 9 mm)	441
Coarse Aggregate (Maximum diameter = 19 mm)	782
Water	168
Superplasticizer	1,01

2.2 Mould and specimen preparation

In this study, the size recommendations of the prismatic specimens determined by EN 14651 [9] (550 x 150 x 150 mm) were used for flexural sample molding. For compression, cylindrical specimens were molded with 100 mm diameter and 200 mm height. Both molds were metal and prepared with a release agent. At the end of the casting, a plastic film was placed on the upper face of the prism, the face exposed to the air, in order to avoid excessive water loss in the early ages. The specimens were allowed to cure under controlled temperature and humidity for 28 days when testing commenced.

The single fibre pullout test specimens were prepared using cylindrical moulds with 25 mm diameter and 10 mm height. It should be noted that mortar mix cast into the moulds have no fibres and no aggregates in it. Each of the two fibre types was carefully inserted to the pre-marked embedment length in the middle of the specimen. Thereafter, the moulds were gentle vibrated to ensure closure of void created during the fibre insertion. All specimens were tested after curing for 28 days.

3 TEST SETUPS AND PROGRAMMES

In this study, two major categories of tests were performed: flexural creep tests and pullout creep tests. The specific details of each test are further described in subsequent sub-sections.

3.1 Flexural creep test

Prismatic specimens of 150 x 150 x 550 mm were produced, notched, pre-cracked and then tested under sustained bending loads for 30 days, with a further 15 days of recovery. The test procedure was carried out according to the methodology developed by the author, based on Arango et al. [10] and García-Taengua [5]. An overview of this methodology is given in Figure 1. For the flexural creep tests, the same matrix of the previous tests was used, with the variation of the fiber type.

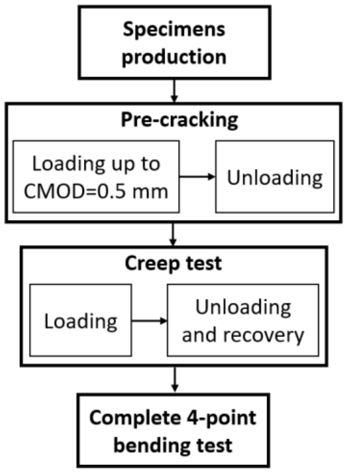

Figure 1: General testing procedure.

In a first step, the specimens are pre-cracked after 28 days of curing. Each sample is notched and loaded according to a scheme based on four point bending test configuration [9], with a 500 mm spacing between supports, until a predefined opening crack of 0.5 mm is reached. The residual stress corresponding to that crack opening displacement is stored and the specimen is then completely unloaded upon acquisition of the data.

The pre-cracked samples were reloaded and subjected to sustained loading conditions in accordance with the test configuration shown in Figure 2.

Figure 2: Flexural creep test setup.

Three specimens were tested in the same frame to rationalize the requirements of time and space. The structure of the creep test and all of its components, in particular components and load carriers, are designed to be rigid enough to avoid undesired and sudden movements, as well as friction in the supports. The load of the test was given by applying torque on the gantry nuts, ensuring an approximately constant load application. Therefore, all three samples are loaded according to the four-point bending configuration and the load test is kept constant for a certain period of time. In the case of this research, this time interval was 30 days, with a further 15 days of recovery. Considering that

most of the creep deformation of fiber reinforced concrete specimens subjected to sustained bending loads occurs in the first 2 months [11], the data obtained were significant for the performed analyzes.
The creep test ends after 30 days, when the specimens are unloaded and part of the deformation is recovered. Thereafter, each specimen is subjected to a complete flexure test until the CMOD reaches 4 mm, as suggested by EN 14651 [9], thus characterizing the residual strength of the specimens after long-term tests.

3.2 Pullout creep test

In order to understand the mechanisms causing creep in the macrostructure, time-dependent pullout tests were performed on fibers embedded in concrete matrix, as discussed in other papers [12–15]. A simple experimental arrangement was developed using a grip at the upper end to attach the fiber, two steel plates at the bottom to secure the cementitious matrix, and free suspended weights as the sample loading system (Figure 3).

Figure 3: Pull-out creep test setup.

The steel fiber pullout creep test was done at an embedment length of 9 mm. On the other hand, the polypropylene pullout creep test was done at an embedment length of 10 mm. According to Hannant [16], when composite failure occurs due to fiber pullout, the average embedment length is about one-fourth the length of the fiber ($1_f/4$). This statement justifies the choices of the used embedment lengths.

The pullout displacement of the fibers was measured using a LVDT attached on the upper plate. The sustained loads applied were 50% and 75% of the average interfacial shear strength of monotonically tested samples.

4 TEST RESULTS AND DISCUSSION

As described in the experimental program, variations of the fiber type were used. The combination of this variation related to the identification of the samples and their particular positions in the test are presented in Table 3. The graphs of the test process are shown in Figure 4 and 5, containing the pre-cracking, creep, recovery and rupture.

Analyzing the parameters w_{ci} and $w_{cd}(30)$ (Table 4), which are respectively related to the crack aperture at the beginning and after 30 days of the flexural creep test, it is noted that the general behavior of the samples after the creep test was compatible, considering that both had a mean and standard deviation of 0.25 ± 0.07 mm. The reason for this behavior may be related to the fact that although there are more polypropylene fibers in the cracked section, the long-term properties of the steel fiber have a lower impact response when subjected to sustained loading. The steel fiber, in the environment of controlled temperature and humidity, does not deform by creep. In addition, in the sustained load applied in the pullout test, the mechanical anchorage is in charge of transferring the forces to the surrounding concrete mass. Therefore, the creep displacement depends much more on the deformation of the concrete than on the displacement of the fiber itself [14,17,18].

Table 3: Identification of the specimens with specifications.

Id.	Nominal load	Absolute load	Position
P PP 6 #1	30%	35%	1
P PP 6 #2		35%	2
P PP 6 #3		34%	3
P ACO 15 #1		31%	1
P ACO 15 #2		35%	2
P ACO 15 #3		39%	3

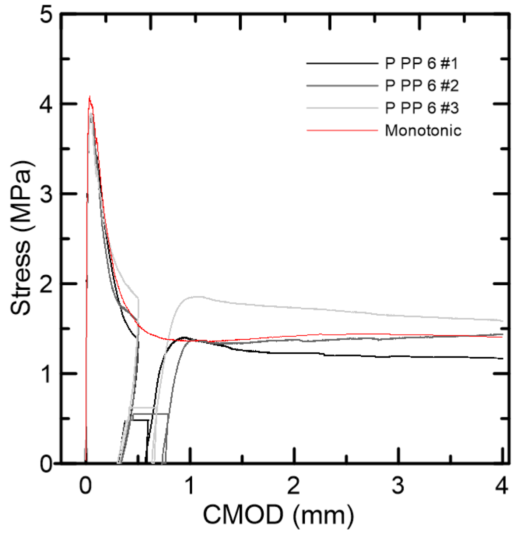

Figure 4: Stress versus CMOD curves comparing the monotonic test with the creep process in specimens of fiber reinforced concrete with 6 kg/m^3 of polypropylene fiber.

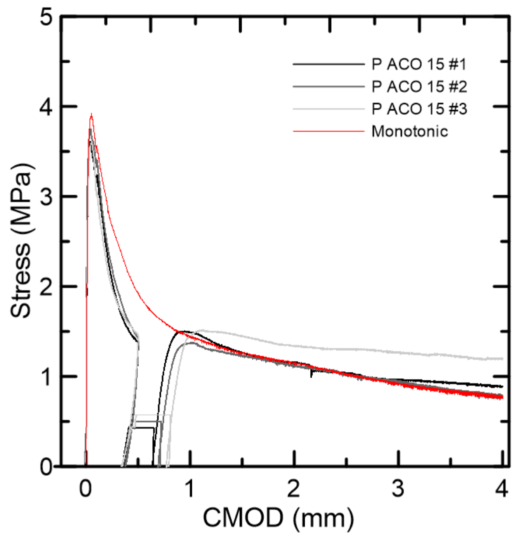

Figure 5: Stress versus CMOD curves comparing the monotonic test with the creep process in specimens of fiber reinforced concrete with 6 kg/m^3 of steel fiber.

The creep coefficients φ(j) (Table 4) are defined as the ratio between the delayed crack aperture at time j, w_{cd} (j), and the initial opening of the crack at the beginning of the creep stage, w_{ci}, considering values accumulated with the pre-cracking. In the case of this research, the coefficients of creep analyzed were φ(10), φ(20), φ(30), at 10, 20 and 30 days, respectively. In relation to the creep coefficients (φ), the superior behavior of steel fiber reinforced concrete is perceived. It is also noticed that, the longer the time j is analyzed in the coefficient of creep, the greater the difference of the crack opening between the specimens reinforced with different fibers. When comparing the different materials considering the parameters w_{ci} and w_{cd}, it was not possible to state which behavior was more expressive in terms of crack opening. However, according to the coefficient of creep, it can be concluded that the behavior of the composite reinforced with steel fiber is more efficient in the control of cracking, even with a lower fiber concentration.

Table 4: Parameters calculated to represent the data obtained in the flexural creep test of reinforced prisms with 6 kg/m^3 of polypropylene fiber and with 15 kg/m^3 of steel fiber.

Id.	w_{ci}*	w_{cd}* (30)	φ (10)	φ (20)	φ (30)
P PP 6 #1	0.41	0.59	1.35	1.41	1.44
P PP 6 #2	0.47	0.79	1.5	1.61	1.67
P PP 6 #3	0.41	0.67	1.39	1.55	1.64
P ACO 15 #1	0.46	0.65	1.34	1.4	1.43
P ACO 15 #2	0.49	0.72	1.37	1.44	1.48
P ACO 15 #3	0.49	0.81	1.5	1.6	1.66

* w_{ci} and w_{cd} in millimeters.

After the creep test, a recovery period was left for the samples and then taken to the universal test machine for testing. As previously stated, the specimen rupturing process was restricted to the maximum crack opening of EN 14651 [9], which is 4 mm.

From Figures 4 and 5, it can be seen that there was no significant change in the mechanical properties of the specimen, and it was concluded that, for the 30% loading level and 0.5 mm pre-crack aperture, there is no loss of resistance on account of sustained loading. It should further be considered that the rupture test occurred 73 days after molding, and that during the creep test the non-hydrated cement particles reacted in the deformed specimen, probably leading to an increase in mechanical properties.

5 CONCLUSION

This work presented the characterization of the long term properties of fiber reinforced concrete at different scales.

For the flexural creep tests, which was the focus of the work, the contribution of the fiber pullout strength to the overall response of the structure could be understood. Analysing the creep tests results, it was verified that the COD rate is an interesting tool to evaluate the long-term behaviour of the cracked FRC and to define a stability criterion. It was noted that in the case of specimens reinforced with polypropylene fibers the response resulted in higher deformations. In addition, the entire concept obtained with the sustained load pullout tests could be used to explain what happens in the behavior of the cracked section of a sample subjected to sustained bending load. Finally, the steel fibers, even in lower fiber concentration, were favored by the mechanical anchorage, which transfers the stresses to the surrounding concrete mass.

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