TEMPERATURE AND LOADING LEVEL EFFECT ON THE LONG-TERM BEHAVIOUR OF MSFRC AND SFRC

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Abstract

This paper describes the results of an experimental campaign aimed at investigating the long-term behaviour of cracked SFRC and MSFRC beams. In particular it illustrates, the effects of temperature and loading level on the behaviour (in terms of crack opening and deflection) of four beams: two beams contained two different dosages of steel fibres and the remaining beams two different dosages of macro synthetic fibres. The tests showed large differences in the long-term behaviour of the different types of FRC and suggested that MSFRC may be more sensitive to loading level and temperature than SFRC.

Keywords: SFRC, MSFRC, crack opening, serviceability, long-term.

1. Introduction

In the last few years the construction industry, supported by the scientific advances and by new standards, has recognized that industrial concrete pavements have to be designed as actual structural elements, which must comply with some prescribed limit states [1]. The design of concrete pavements is mainly addressed by requirements in terms of serviceability limit states (short and long-term deformations, cracking, etc.) and only marginally by requirements in terms of ultimate limit states. In order to fulfil this types of requirements, in the last years there has been a great deal of technical development concerning the construction materials. In this framework, Steel- and Macro-Synthetic-Fibre-Reinforced Concretes (SFRC and MSFRC) have generated noteworthy advances in the concrete industrial pavement technology [2-5]. In fact, the traditional reinforcement mesh may, in some cases, be reduced or completely removed by using FRC.

Multiple research studies and tests have greatly contributed to a better characterization of FRC, in particular of SFRC, and have thus allowed to gain a better understanding of the instantaneous behaviour of this material and to specify minimum performance

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Tab. 1: Properties of the fibres used in the present study.

Type	Fibre Code	l_f	d_f	l_f/d_f	E	f_t
		mm	mm		GPa	MPa
Steel	SF	50	1	50	210	1100
Synthetic	MS	54	0.34	158	-	620-758

Tab. 2: Fibre content in the specimens considered

Group	Beam code	Fibre code	Fibre dosage	Volume of fibres
			kg/m^3	%
1 (Loading level)	MS2L	MS	2.0	0.22
1 (Loading level)	SF25L	SF	25.0	0.33
2 (Temperature)	MS4.8T	MS	4.8	0.53
2 (Temperature)	SF35T	SF	35.0	0.45

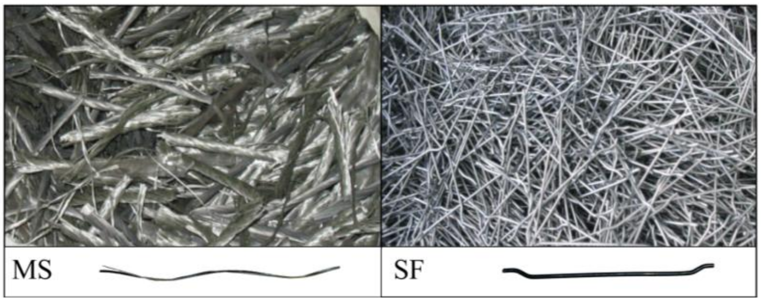

Fig. 1: Fibres considered in the present study.

requirements. The state of the art is well known and lots of international standards provide clear guidance and performance criteria to use safely SFRC. Structural Macro-Synthetic fibres appeared more recently on the market and even if their behaviour has not been studied as deeply as for steel fibres, specific technical strength and weaknesses of the different fibres are already well known. But, even if it is nowadays common practice to use SFRC or MSFRC for industrial pavements in order to improve their serviceability performances, a proper knowledge of their actual experimental long-term behaviour has not yet been achieved.

In fact, as far as serviceability limit states are concerned, it is important to define the target performance levels by taking into account the reference time-interval of application of the corresponding actions (characteristic, frequent and quasi-permanent). Furthermore, the verification of the required performance levels may be complicated in terms of both evaluation of the effects of applied actions and proper definition of target performances with respect to the long-term actions. In this case, the dependence of strains and of crack openings upon time must be considered, because of the important consequences on durability that this aspects can generate. For these reasons, the present study was focused on the long-term behaviour of cracked FRC structural elements. A specific test procedure has been developed to represent the serviceability limit state behaviour of cracked elements. In particular, the present paper discusses the results of tests comparing the long-term behaviour, in terms of deflection and crack opening, of SFRC and MSFRC concrete beams, investigating the effects of loading level and of temperature on this behaviour

2. The experimental campaign

2.1 Experimental program

The aim of the present study was investigating the long-term behaviour of cracked SFRC and MSFRC beams, and in particular evaluating the effects of loading level and temperature on their performance. Four 300×120×2000 mm (width × height × length) beams were tested in a long-term four-point-bending test. The size of the beams was defined in order to be representative of a strip of concrete pavement. The dosage and type of fibres used were chosen to be as close as possible to common practice.

The four beams were divided in two groups according to the type of test carried out: *group 1*) investigation of the loading-level effects; *group 2*) investigation of temperature effects. The first group of beams was tested under increasing long-term loads while the second group of beams was tested under constant loading at increasing temperatures.

Tab. 1 gives some nominal properties of the fibres used in the present work, which are also depicted in Fig. 1, while Tab. 2 summarizes the fibre dosage in each specimen considered.

2.2 Material properties

2.2.1 Concrete properties

The mechanical properties of the concrete used in the present study were in agreement with the prescriptions of EN 14845:2006 [6]. This standard specifies four types of reference concrete with given flexural tensile strength, maximum size of the aggregate and maximum cement content. This concrete has a flexural tensile strength of 4.3 ± 0.3 MPa, in a three-point bending test. Tab. 3 gives the mix design used in the present study. Aggregates, cement, and water/cement ratio were chosen following the guidelines given by EN 14845:2006.

During the casts the slump values, the hydration temperature and the density of concrete were measured; their values are listed in Tab. 4. The superplasticizer dosage adjusted for each batch in order to obtain a slump of about 15 cm.

2.2.2 Short term FRCs properties

The short-term mechanical properties of the FRCs considered in the present study were characterized by performing three-point bending tests on 150×150×550 (height × width × length) mm notched specimens. The test procedure adopted is consistent with the guidelines given by EN 14651:2005 [7] and EN 14845:2006 [6], according to which the specimens are to be tested in the three-point bending scheme shown in Fig. 2. The specimens were notched at mid-span (the height of the notch is 25 mm), in order to control the triggering of the crack. The tests characterized the tensile behaviour of the FRC by means of force-Crack Mouth Opening Displacement (CMOD) curves, the latter being measured by a proper displacement transducer (see Fig. 2). The testing machine operates under displacement control with a constant rate of displacement (CMOD or deflection),

Tab. 3: Mix design for the concrete used in the present study.

Component	Unit	Dosage
Cement	kg/m^3	351.1
Sand (0-2 mm)	kg/m^3	113.5
Sand (0-5 mm)	kg/m^3	801.3
Gravel (8-15 mm)	kg/m^3	674.3
Gravel (15-22 mm)	kg/m^3	320.4
Water	l/m^3	174.4
Superplasticizer	l/m^3	2.68

Tab. 4: Fresh concrete properties for in the casting batches considered.

Beam code	Superplasticizer	Slump	Hydration t.	Density
	l/m^3	cm	°C	kg/m^3
MS2L	2.67	15.0	29.1	2440
SF25L	2.67	14.0	28.5	2448
MS4.8T	4.4	17.0	35.0	2460
SF35T	5.6	17.0	35.0	2450

and has sufficient stiffness to avoid unstable zones in the load-CMOD curve. During the tests, the rate of increase of the CMOD was controlled: 0.05 mm/min for CMOD ≤ 0.1 mm and 0.2 mm/min for CMOD > 0.1 mm. All the tests were terminated at CMOD = 4 mm.

The force-CMOD curves obtained from the tests are plotted in Fig. 2 which shows that, in general, even though the number of specimens is small, the short-term performances of the steel fibres are better than those of the macro-synthetic fibres, for the dosages considered. The scatter of the curves in the post peak region is higher for the specimens with the steel fibres. This is a consequence of the size of the specimen, which is small with respect to the geometry of the fibres [8-12]. It should also be noted that the scatter of the peak force values is much lower because this parameter is not dependant on the fibre content.

2.3 Long-term tests

2.3.1 Pre-cracking

Prior to the long-term tests, the beams were pre-cracked up to CMOD = 0.2 mm. This value was assumed as representative of the crack width of concrete pavements at the serviceability limit state. In order to better control the position of the crack, the beams were notched at mid-span (10 mm deep notch). The same testing-machine described in Section 2.2.2 was used, the only difference being the distance between the supports, which was equal to 800 mm in this case (see Fig. 3a). The tests were run under mid-span displacement control.

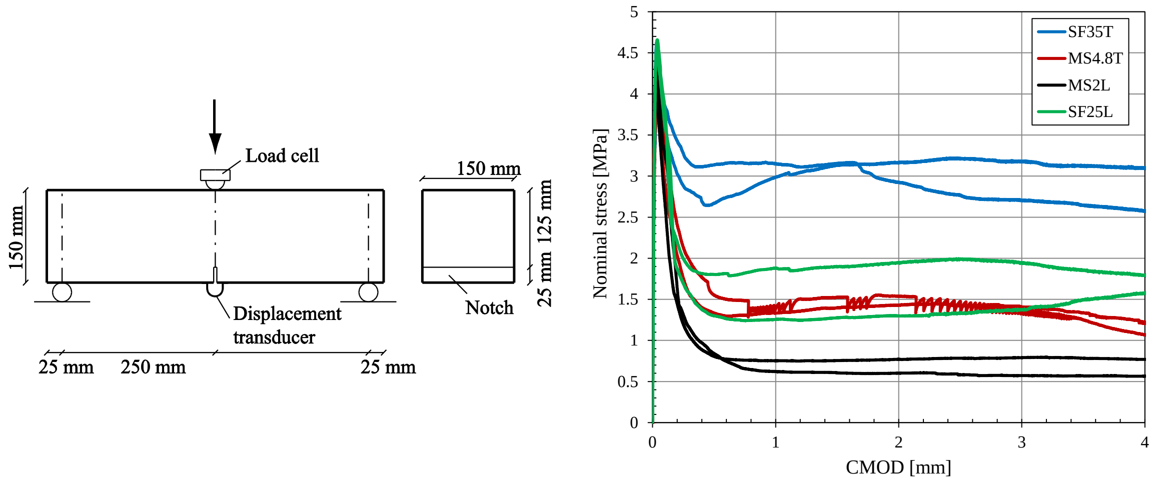

Fig. 2: Three point bending tests: experimental set-up (left) and nominal stress – CMOD curves obtained (right).

As an example, Fig. 4 shows the nominal stress - CMOD curves obtained for the mid-span cross sections of the beams SF35T and MS4.8T. The nominal stress is calculated by dividing the bending moment at mid-span by the section modulus of the net notched section. After one loading/reloading cycle, the residual strength values at CMOD = 0.2 mm, $f_{0.2}$, are: 2.30 MPa and 1.61 MPa for beams SF35T and MS4.8T, respectively. The differences are smaller as far as the residual CMOD after unloading is concerned: 0.115 mm and 0.120 mm, respectively.

These results were used to define the loading values to be applied during the long-term tests. The criterion adopted was to obtain a bending moment, and therefore a stress, at the cracked section equal to the 50% of $f_{0.2}$.

2.3.2 Experimental set-up

After the cracking phase, the long-term tests were performed using a four-point bending scheme. Fig. 3b-d shows the experimental setup. Each beam is sustained by two steel systems at the intermediate supports, thus creating a central span of 750 mm, where bending moment is constant. The dead loads were applied at the beams ends at a distance of 525 mm from the inner supports. The load is applied by using some concrete and steel blocks, laid on a steel supporting system composed of a base plate connected by two threaded rods to transverse hollow rods placed on the top of the beam. According to the system geometry, in order to induce the stresses described at the end of the previous section the load values listed in Tab. 5 were applied.

On each beam, the crack-opening at mid-span (notched section) as well as the mid-span deflection with respect to the intermediate supports were measured. The crack opening was measured by using a bridge-based displacement transducer while the deflection was measured, on both side of the beams, by using LVDT transducers. In order to evaluate the relative displacement between mid-span and the intermediate supports, two aluminium bars, supported by pins glued over the supports, on both sides of the beams were used.

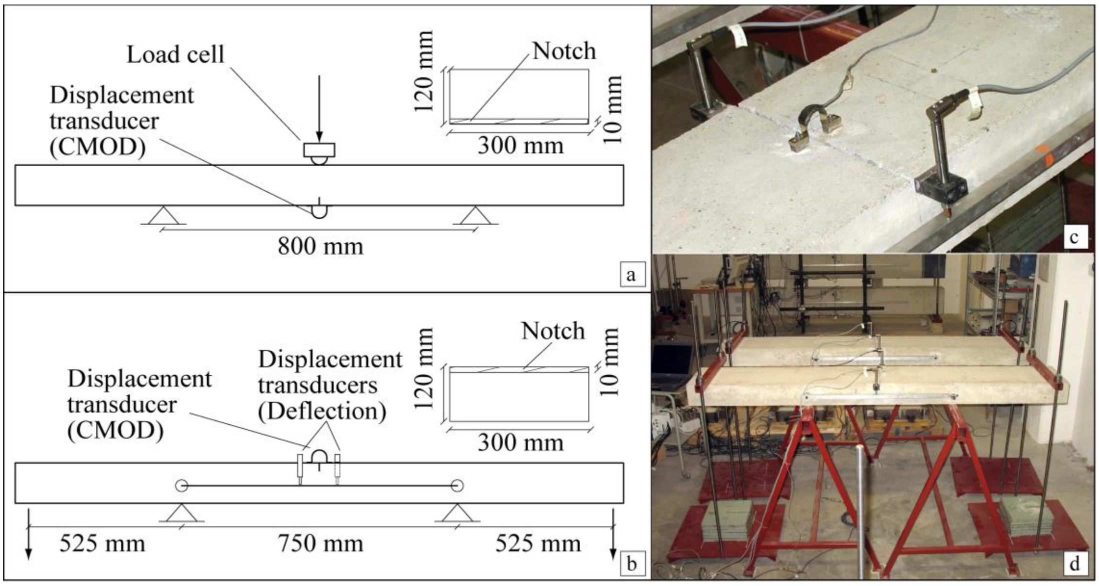

Fig. 3: Experimental setup for pre-cracking tests (a) and experimental setup for long term tests (b-d).

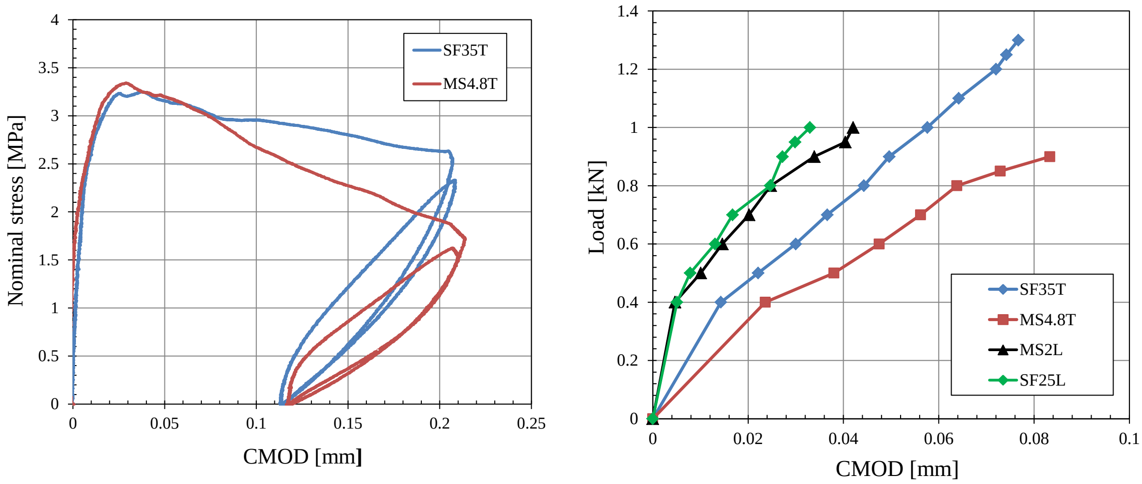

Fig. 4: Nominal stress – CMOD curves derived from the pre-cracking tests of beams SF35T and MS4.8T (left) and load – CMOD curves during the loading phase at the beginning of long-term tests.

For the entire duration of the test on the beams SF25L and MS2L the their were kept in a climate controlled room, at 20 °C and RH 60%; on the other hand the temperature was increased in two steps during the test on beams SF35T and MS4.8T.

3. Long-term test results

3.1 Loading

As described in Section 2.3.2, the loads used in the long-term tests were applied using steel and concrete weights (see Fig. 3b-d). As an example, Fig. 4 shows the force-CMOD curves recorded during the loading phase. Those curves are clearly not-continuous because the

*Tab. 5:*Loads applied on the beams during the long-term tests.

Beam	Load during long-time test (kN)
MS2L	1.0
SF25L	1.0
MS4.8T	0.9
SF35T	1.3

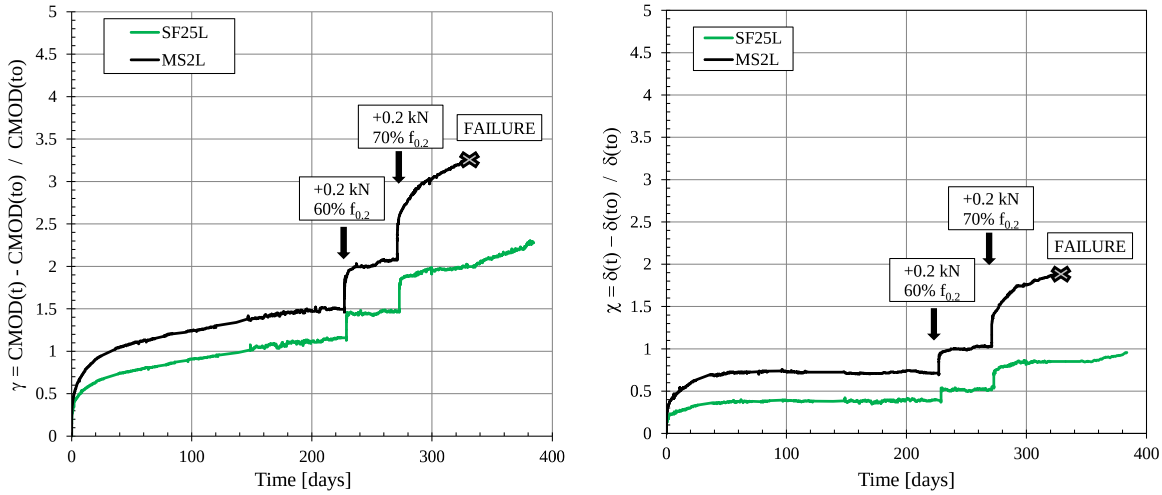

*Fig. 5:*Relative CMOD increase over time (left) and relative mid-span deflection increase over time (right) measured during the long-term tests of beams SF25L and MS2L.

loading was applied in discrete steps. At the end of loading the CMOD values measured on the beams of the two groups were similar: 0.033 mm and 0.042 mm for SF25L and MS2L (loaded with 1.0 kN), respectively, and 0.077 mm and 0.083 mm, for SF35T and MS4.8T (loaded with 1.3 kN and 0.9 kN), respectively. These loads were then kept constant during the long-term tests.

3.2 Loading-level effects (beams MS2L and SF25L)

In order to better understand the results of the long-term tests the CMOD and mid-span deflection increases over time will be reported in terms of coefficient of viscosity, defined as:

$$\gamma = \frac{CMOD(t) - CMOD(t_0)}{CMOD(t_0)}, \tag{1}$$

as far as CMOD is concerned, and as:

$$\chi = \frac{\delta(t) - \delta(t_0)}{\delta(t_0)}. \tag{2}$$

as far as the mid-span deflection, δ, is concerned. In equations (1) and (2) t is the generic time instant and t_0 is the time at the end of the loading phase (see Fig. 4). The curves calculated by using Eq. (1) and Eq. (2) are plotted in Fig. 5. The creep deformations, in terms of CMOD and mid-span deflection, had a large increase during the first days of the

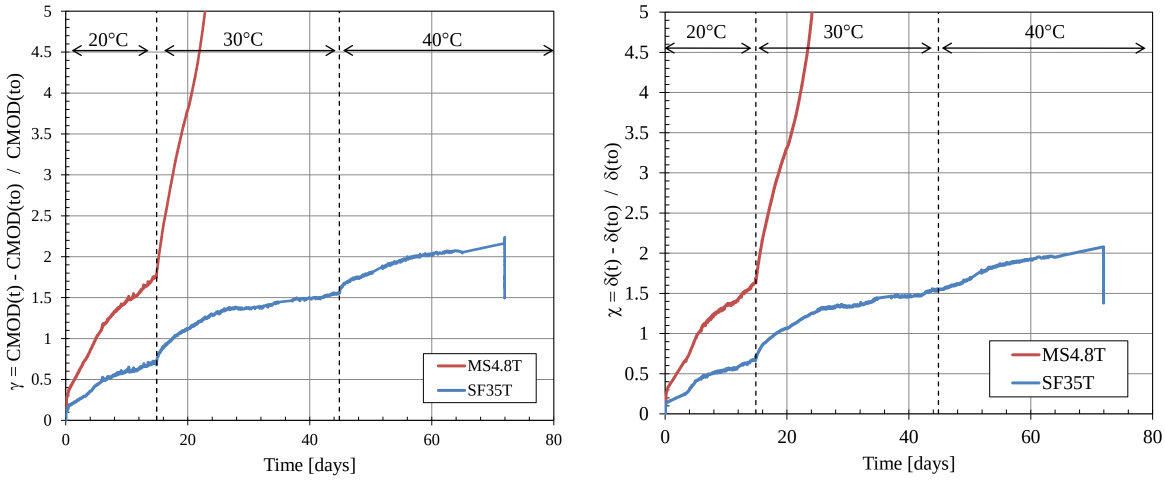

Fig. 6: Relative CMOD increase over time (left) and relative mid-span deflection increase over time (right) measured during the long-term tests of beams SF35T and MS4.8T.

test and the become almost steady after 200 days since the beginning of the test. The MSFRC beam showed larger deformations in this phase. The load value was then increased by 0.2 kN after 227 and 271 days since the beginning of the test, as indicated in Fig. 4. Each one of these increments corresponds to an increase of the initial long-term load of 10% with respect to $f_{0.2}$ (see Section 2.3.1), thus leading to a total value of applied load equal to 60% and 70% of the residual strength previously indicated. Until the second load increment, both curves show a steady-state viscous behaviour. This type of behaviour changed for the beams MS2L after the application of the second load increment, which produced a large increase in the slope of the curve and 328 days after beginning of the test it led to the failure of the beam. On the contrary the beam SF25L maintained its strength and showed a steady viscous behaviour even after the second load increment. At the end of the test this beam was unloaded and tested to failure in three-point bending. The comparison of the so obtained nominal stress – CMOD curve with those obtained from the specimens described in Section 2.2.2 suggested that the long term loading had no noticeable effect on the strength of the beam.

3.3 Temperature effect (beams MS4.8T and SF35T)

In order to evaluate the effect of temperature on the long-term behaviour of cracked FRC elements under flexure, these tests have been performed inside a climate chamber where the temperature was kept constant for prescribed time intervals at increasingly higher values; in particular, the tests started with a temperature of 20° C, which was maintained constant for the first 15 days; after that, the temperature was increased up to 30° C and maintained for further 30 days; finally, the temperature was raised to 40° C for the last 27 days. The increase over time of the coefficient of viscosity in terms of CMOD and mid-span deflection (defined in the previous Section) are given in Fig. 6.

During the test, the MSFRC beam failed under constant loading while the SFRC beam reached the end of the test, when it was unloaded. After the first increase of temperature, from 20° C to 30° C, the beam MS4.8T showed a sudden increase of the rate of crack opening and deflection; after further few days (about 10 days) of constant loading a "tertiary creep" behaviour was observed, leading to the failure of beam MS4.8T. The other beam, SF35, was kept under loading and after 45 days since the beginning of the test the temperature was raised to 40° C, until the end of the long-term test. After 72 days since the beginning of the test the beam SF35T was unloaded, cooled down to 20 °C and tested up to failure in a three point-bending scheme. The comparison of the so obtained nominal stress – CMOD curve with those obtained from the prisms described in Section 2.2.2 suggested that the long-term loading and the temperature increases had no noticeable effect on the strength of the beam.

4. Conclusions

In the present study the long-term behaviour (in terms of delayed crack opening and mid-span deflection) of two SFCR and two MSFRC beams was investigated. All the beams considered were pre-cracked up to a crack opening equal to 0.2 mm, in order to represent serviceability limit state conditions and then tested under long-term loads that were defined as a fraction of the strength showed by the beams during the pre-cracking phase. In particular two different test procedures were developed: one to investigate the effects of loading level and one to investigate the effects of temperature.

One MSFRC and one SFRC beam were tested in a climate controlled chamber with constant temperature and humidity under long-term loads that were increased to three different levels during the tests. The behaviour of the two beams was completely different during the test, in fact the MSFRC beams showed an unstable “tertiary creep” after the second load increment that lead to its failure. On the other had the SFRC beam maintained a steady viscous behaviour even after this load increment and did not reach failure.

The two remaining beams were tested in different environmental conditions. In this case, in fact, the load was constant for the entire duration of the test but the temperature in the climate controlled room was set to three different levels: 20°C, 30°C and 40°C. Each temperature was kept constant for ad different time span. The MSFRC and SFRC beams had a different behaviour also during this test. In fact when the temperature was increased to 30°C the MSFRC beam showed “tertiary creep” and after a few days reached failure under constant loading. The SFRC beams did not reach failure even after the temperature was set to 40 °C.

Even though this is a first attempt in understanding the long-term behaviour of FRCs, the results obtained in the present experimental campaign suggest that creep deformations may be extremely important especially as far as MSFRCs are concerned. Furthermore temperature may have significant effects on viscous deformations of these materials and therefore it may be advisable to take into account in design.

Acknowledgements

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