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Experimental tests on the effect of temperature on the long-term behaviour of macrosynthetic Fibre Reinforced Concretes

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HIGHLIGHTS

- We investigate the effect of temperature (20–50 °C) on the behaviour of MSFRCs.
- We consider cracked beams in bending with no rebars.
- The short term strength can decrease by 20%.
- Creep failures under serviceability loads may be triggered by temperature.

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ABSTRACT

This paper presents the experimental results of short- and long-term tests on cracked MSFRC elements at different temperatures. Various factors affecting the long-term behaviour of MSFRCs have been identified in the literature but the effect of temperature has never been investigated. Short term three-point bending tests were carried out at 20 °C and 40 °C. Four-point long-term tests under sustained loads were performed at increasing temperatures (20–50 °C). Temperature reduced the short-term residual strength of some of the MSRFCs analyzed. It also had a strong effect on long-term deformations producing, in some cases, creep-failure. These findings suggest that temperature should always be considered as an important factor when designing MSFRC elements.

1. Introduction

In the last few years the usage of Fibre Reinforced Concretes (FRCs) in the construction industry has significantly increased, supported by research advances and by new standards. These materials, in fact, feature important advantages if compared to concrete with traditional reinforcement [1,2]. In fact, the significant residual tensile strength in post-cracking regime, and the enhanced capacity to absorb strain energy, given by the bridging mechanism of fibres across crack-surfaces, lead to important improvements in terms of serviceability behaviour over plain concrete. The main advantages of the inclusion of fibres in structural concrete include: durability improvements by crack-width and permeability reduction; potential cost-savings when fibres substitute steel-reinforcing bars; and the mitigation of damage due to shrinkage and early age cracking. For these reasons, FRCs have were used for tunnel linings, bridge decks, airport pavements, slabs on grounds, industrial floors, dams, pipes, and marine structures [3–7].

Many studies and experimental tests have contributed to a better characterization of FRCs, in particular of Steel Fibre Reinforced Concretes (SFRCs), and have allowed to gain a better understanding of the instantaneous behaviour of this composite material and to specify minimum performance requirements. The state of the art is well known and lots of international standards provide clear guidance and criteria to use safely SFRC [8–13]. Structural Macro-Synthetic Fibre Reinforced Concretes (MSFRCs) appeared more recently on the market and, even if their behaviour has not been studied as deeply as for SFRCs, their behaviour under short-term loads is already well known [14].

Nevertheless, a proper knowledge of the actual long-term behaviour of SFRCs and MSFRCs has not yet been achieved and the literature on the topic is still very limited, in particular as far as MSFRCs are concerned. Kurtz et al. [15] tested the long-term performance of cracked beams made of concrete reinforced with polypropylene and nylon short-fibres (19 mm long). Creep failure occurred when the stress level was higher than a certain

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percentage of the failure load under short-term monotonic testing, measured using the Average Residual Strength (ARS) as defined by ASTM C1399 [16]. In particular, the maximum sustainable stress for the polypropylene was 24.9% of the ARS while for nylon this percentage was 38.3%. Furthermore, the authors observed that even low levels of load that did not produce creep failure produced substantial creep deformations. Bernard [17] investigated the time dependent behaviour of cracked FRC round panels reinforced with either steel (1 fibre type considered) or MS fibres (2 fibres types considered). The load applied during long-term tests was defined according to the actual residual tensile-strength measured in the pre-cracking tests, during which all the specimens tested exhibited a softening behaviour. Long-to-short-term load ratios spanning from 18% to 85% were considered. Bernard found that post-crack creep coefficients were relatively insensitive to load ratio for the SFRC and for one of the two MSFRCs while for the second MSFRC the creep coefficient was sensitive to the load ratio. He also noticed that the magnitude of this sensitivity depended on how the load ratio was defined. In particular he highlighted that the load resistance at the maximum deformation sustained in the short-term might not be representative of the load resistance exhibited across the range of deformations suffered during the process of creep, if initial loading is terminated in a region of rapid strain softening. Bernard concluded that for narrow initial crack widths and load ratios up to 50% of static capacity, one of the MSFRCs tested exhibited a behaviour similar to the SFRC. A wider range of creep coefficients was observed on the second MSFRC. MacKay [18] described the results of experimental tests comparing the behaviour of one SFRC and one MSFRC under long terms loads. Beams were pre-cracked according to ASTM C1399 [16], therefore the actual crack opening width was not measured, up to a maximum deflection of 0.2 mm, and then tested in bending under long-term loads. They concluded that at similar loading levels, cracked MSFRCs could experience creep coefficients larger than SFRCs by a factor two. No control over the creep testing-environment was used, and thus fluctuations in temperature and relative humidity may have caused variability in the flexural creep data. Kusterle [19] tested one SFRC and three different MSFRCs. For each mix six beams were cast and tested in four point bending. The beams were pre-cracked up to a mid-span deflection of 1.75 mm. A sustained load ranging from 50% to 60% of the strength at 1.75 mm was applied. Kusterle concluded that MSFRCs had large long-term deformations and that a maximum load level of 50% seemed to be the maximum for obtaining good long-term performance. SFRCS were able to sustain larger loads (60%). They failed when the load level was increased to 75–80%.

Zerbino and Barragán [20] studied the creep behaviour of SFRC cracked beams subjected to long-term loading. The beams were pre-cracked up to crack openings spanning from 0.2 to 3.5 mm. The SFRCs tested showed hardening behaviour. For small crack-openings at the beginning of long-term tests stable responses were obtained during 18 months, even when applying stress levels equal to the final stress level reached at the end of the initial cracking tests. A stable response could be observed for a pre-crack of 0.5 mm. However for load ratios of 0.96 relatively high crack-opening rates were found, indicating the possibility of the initiation of creep failure. When the loads were further increased, a quick failure was observed in these cases. When creep rupture took place, a three-stage creep response was observed. García-Taengua et al. [21] tested 31 SFRC specimens in four point bending [22] in order to investigate the effects of various parameters on creep in cracked conditions by means of multiple linear regression. They concluded that the load-ratio had an effect on flexural creep response and that the extent of this effect depends on fibre slenderness and fibre dosage. Zhao et al. [23,24] carried out an experimental program to investigate the long-term behaviour of SFRCS under uniaxial tensile loads by testing cylindrical specimens, pre-cracked up to either 0.05 or 0.2 mm crack openings. Two loading levels were considered: 30% and 60% of the peak strength measured during pre-cracking. The time-dependent crack opening observed was almost at the same level of instantaneous crack opening after 3 months loading at around 30% of cracking strength. It should be noticed that specimens showed either hardening or very limited softening. They also concluded that the damage due to debonding at the fibre/matrix interface was not increasing with creep deformation at the loading level of 30%, even though the irreversible part almost doubled during the creep loading. Babafemi and Boshoff [25] investigated the time-dependent behaviour of MSFRC under long-term uniaxial tensile loading. Prismatic specimens were pre-cracked up to 0.5 mm using a displacement control machine. Only one MSFRC was considered. It showed a typical softening behaviour during the pre-cracking tests. Babafemi and Boshoff observed that the MSFRC showed significant crack widening over time under sustained uniaxial tensile loads. Even at loads as a low as 30% of the post-peak resistance, the time-dependent crack widening did not stabilize after 8 months. Tensile creep failure occurred within 10 days for specimens loaded at 60% of the post-peak resistance and within less than a day for a 70% loaded specimen. Average fibre counts on the cracked face of MSFRC were found to influence the time-dependent behaviour. Higher fibre counts resulted in lower time-dependent CMOD and vice versa. Babafemi and Boshoff also performed single fibre long-term pull-out tests observing that specimens loaded at 50% of the quasi-static capacity pulled out over time. No tests were done at lower loads. Time-dependent crack widening under sustained loading was identified to be caused by two mechanisms: time-dependent fibre pull-out and time-dependent fibre creep.

The most important factors, identified in the literature, affecting the long-term deformations of cracked FRCs, are therefore: the load ratio, the crack opening at the beginning of the long-term loading, and hardening/softening behaviour of the material. The extent to which the aforementioned factors affect the performances of FRCs is still not completely clear and further experimental investigations are indeed needed. Furthermore the literature on the topic clearly suggests that MSFRCs and SFRCS have different behaviours, mainly because of different features of the concrete-fibre bond and of creep of MS fibres.

Recently we found, that temperature may play a fundamental role on the long-term behaviour of MSFRC, leading in some cases to creep failure [26]. The effect of temperature seems less relevant on SFRC [26].

The present experimental study extends those findings by investigating the effect of moderate temperature variations (20–50 °C) on the long- and short-term behaviour of cracked MSFRCs structural elements. The experimental campaign described in the present paper was carried out in two phases; at first we studied the effect of temperature on the short-term behaviour of notched MSFRC prisms by performing three-point bending tests at 20 °C and 40 °C, then we analyzed the long-term behaviour of cracked beams under sustained loads at increasing temperatures. The results of the tests carried out showed that even small temperature variations can influence long term deformations to a very large extent and in some cases lead to tertiary creep failure of structural elements.

2. Materials and methods

2.1. Summary of the experimental program

The experimental campaign was implemented in two phases: (a) short-term tests, and (b) long-term tests.