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Study of temperature effect on macro-synthetic fiber reinforced concretes by means of Barcelona tests: An approach focused on tunnels assessment

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HIGHLIGHTS

- MSFRC loses residual tensile strength and energy density with rising temperature.
- Temperatures of 400 °C and 570 °C are critical to the MSFRC mechanical performance.
- Up to 100 °C the residual mechanical behavior of the macro fibers is not affected.
- The specimen surface degradation caused by temperature affect BCN test result.

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ABSTRACT

This paper presents an experimental investigation on the applicability of the Barcelona (BCN) test to evaluate the mechanical properties of a macro-synthetic fiber reinforced concrete (MSFRC) submitted to high temperature environments (up to 600 °C). BCN tests demonstrated that the MSFRC gradually loses tensile strength an energy consumption density with increasing temperature. Temperatures of 400 °C and 570 °C shown to be critical to the MSFRC mechanical performance. The residual mechanical behavior of the macro-synthetic fibers was not affected by the temperature up to 100 °C. For higher temperatures, the reinforcement showed that may lose part of its crystallinity compromising the MSFRC post-cracking performance. The constitutive model used to determine the stress-strain curves of the MSFRC was capable to reproduce the composite behavior after the event of a fire.

1. Introduction

It is well known that a properly dosed concrete composite reinforced with macro-synthetic fibers (i.e.: MSFRC) may be suitable for structural applications, presenting ductility under compression and great energy absorption capacity under tension [1–4]. Different from other fiber reinforced composites (e.g.: steel fiber reinforced concretes), the mechanical behavior of a MSFRC is majorly dependent on the frictional bond stablished between the fiber and matrix at the interfacial transition zone [5]. Such characteristic led the macro-synthetic fibers to evolve in terms geometry, anchorage and surface treatment.

In high temperature environments, however, the behavior of a MSFRC is dependent on the thermal gradient established in the element, as well as on the mechanical and physical changes occurred on both: fibers and matrix. This topic represent one of the main unresolved and challenging issues regarding the performance of this composite that still concern the scientific community and the construction sector. The effect of fire exposure and elevated temperatures on the mechanical behavior of a MSFRC is particularly interesting to the case of underground tunnel structures, which frequently employ this type of material.

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Once heated, a Portland cement concrete will experience several chemo-physical transformations: release of free and chemically combined water, decomposition of the calcium silicate hydrates (CSH), dehydration of portlandite and decomposition of carbonated phases. As a result, the concrete exhibits reduction of the tensile and compressive strength, cracking, loss of the bond between the aggregates and the cement paste, deterioration of the hardened cement paste and, in some cases, spalling [6]. The addition of micro synthetic fibers (in particular the polypropylene fibers) may reduce the chance of concrete spalling [7] while macro fibers (e.g. steel, polypropylene), may guarantee residual load-bearing capacity of the structure [8–10].

Such load-bearing capacity will depend on the type of fibers used, but certainly it will contribute to reducing the risk of a tunnel collapse. This aspect is particularly relevant considering the high costs associated to the reconstruction or repairing of a collapsed tunnel [11–12] and the historic sequence of catastrophic events occurred in such structures submitted to fire loading [10].

Table 1 presents relevant data of previous studies on the effects of high temperature on FRC, including the used type of fiber, the temperatures reached and the tests performed. The notation used to distinguish the material of the fiber is: C for carbon, S for steel, PP for polypropylene and PE for polyethylene. The symbol + is applied for hybrid reinforcement (when more than one type of fiber is used in one mix).

The data presented in Table 1 reveals that previous studies focus on the evaluation of the mechanical properties such as residual strengths or toughness indexes. However, the microstructure of matrix and the damage suffered by the fiber, which are relevant parameters to understand the composite mechanical behavior at high temperatures, are not evaluated.

This paper presents a comprehensive study of the effects of high temperature on MSFRC: from the mechanical performance to the microstructure point of view. The goal was to establish the pattern of the degradation of the specimen along its central axis and, then, correlate it with the loss of mechanical strength.

The integrated analysis of the mechanical behavior with the characterization of the damage that occurred in the microstructure provide a unique and novel insight into the effects of high temperatures on the performance of MSFRC. Furthermore, the study also sheds light into the applicability of the Barcelona test to evaluate the post-heating residual strength of the material. In fact, this test is one of the few in the literature that can be performed on FRC specimens drilled from real structures that have been exposed to a fire.

2. Experimental campaign

The experimental campaign begins with the manufacturing and curing process employed to the studied MSFRC. Mechanical tests were performed to assess the composite behavior before and after heating. The MSFRC was evaluated with respect to the residual tensile strength through the Barcelona test [17]. Pre and post heating compressive strength and elastic modulus, were also determined. These evaluations provide conditions to assess the influence of temperature on the behavior of the composite.

In order to obtain a better understanding of the effect of the temperature variation in the materials structure, tests were performed to characterize their structures. The integrity of the fibers before and after heat treatment was evaluated through direct tensile tests and Differential Scanning Calorimetry (DSC). The fiber-matrix interfaces were assessed in all target temperatures by means of a Scanning Electron Microscope (SEM). Such isolated investigations (pre and post heating), represent key points while studying the residual performance of a real structure. Finally, a well detailed explanation is given about the materials characterization, which involves SEM, thermogravimetry (TG), differential scanning calorimetry (DSC) and XRD analysis applied for both: MSRFC, paste and macro-synthetic fibers.

2.1. MSFRC manufacturing and curing

The concrete used in this research was developed using the same materials and mix-design specified to the concrete matrix used to produce the tunnel segments of the "Metro Line 6″ under construction in the city of São Paulo, Brazil. The matrix was designed with a High Early Strength Portland Cement (CP V - ARI RS), silica fume, two coarse aggregates (d_{max}:19 mm and d_{max}:9.5 mm), artificial (d_{max}:4.8 mm) and river sand (d_{max}:2 mm) and a polycarboxylate-based superplasticizer (ADVA 525, Grace Company). The matrix composition is summarized in Table 2.

The concrete matrix was reinforced with macro-synthetic fibers (BarChip48) commercialized in Brazil by the EPC Group (Elasto Plastic Concrete). The real tunnel has adopted steel fibers combined with conventional reinforcement to produce the pre-cast segments. Polypropylene micro-fibers, from the Brazilian company Neomatex, were also employed in the mixture in order to inhibit explosive spalling at elevated temperatures respecting the segments specification. The dosage and properties (supplied by the manufacturers) of both synthetic fibers can be found, respectively, in Tables 2 and 3.

Preliminary tests were carried out in order to define the reference matrix with the desired macro fiber content (8 kg/m^3) and slump value (~8 cm). The composite was prepared in a conventional concrete mixer (300 l capacity) at a room temperature of 24 °C ± 1 °C.

First, all aggregates were homogenized by dry mixing for 60 s prior to the addition of cementitious materials (+60 s of dry mixing). Water and superplasticizer were then slowly added to the mixture, which was subsequently blended for 8 min. Both fibers were manually incorporated into the mixture (+5 min of blending). The concrete mixture was cast in the steel molds 150 × 300 mm (diameter x height) in two equal layers. The concrete consolidation was carried out through a vibratory table (60 Hz) during 30 s.

The MSFRC was cured in a wide electric oven at 40 °C during 24 h before demolding. Before heating process, the specimens were sealed using a PVC film. After thermal cure, cylinders were cut into two equal pieces (half of the height) in order to generated

Table 1
Summary of previous studies on the effect of temperature on FRC.

Reference	Fiber	Temperature (°C)	Specimen (mm)	Tests
Chen and Liu [13]	C, S, PP, C + S, C + PP, S + PP	200, 400, 600, 800	100 × 100 × 100	Compression and splitting
Peng et al. [14]	S + PP	400, 600, 800	100 × 100 × 100	Compression
			300 × 100 × 100	Bending and explosive spalling
Sukontasukkul et al. [8]	S, PP, PE	400, 600, 800	350 × 100 × 100	Bending
Colombo et al. [15]	S	200, 400, 600, 800	500 × 75 × 60	Bending
Choumanidis et al. [16]	S, PP, S + PP	280	150 × Ø150	Barcelona test

*C = Carbon; PP = Polypropylene; S = Steel; PE = Polyethylene.