THE EFFECT OF HIGH TEMPERATURES ON STEEL FIBER REINFORCED CONCRETE

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Keywords: high temperatures, concrete, steel fibers, mechanical properties, DEWS.

Abstract. *High temperatures in concrete structures, caused by fires, result in a reduction in the concrete's tensile strength, that can lead to the collapse of the structure. The employment of steel fibers, that act in the post-cracking stage, contribute to the increase in residual strength, increasing the tenacity and safety of the structures. To assess the mechanical properties of low-strength concrete, usually used in São Paulo city's structures, reinforced with fibers (FRC), cubic specimens were used and subjected to two different temperatures. The assessment of properties occurred through the DEWS (Double Edge Wedge Splitting) testing, which, according to recent studies, showed good results when applied to high-strength concretes. Therefore, it is possible to check whether low-strength concrete is affected by high temperature to the same extent as high-strength concrete.*

1. INTRODUCTION

The fiber reinforced concrete (FRC) is increasingly used in the construction industry, especially in tunnel lining and prefabricated parts. From 2013, with the publication of the fib Model Code 2010 [1], occurred the diversification in the use of fibers as structural reinforcement of concrete, and the establishment of essential parameters for the design of structures with this composite. However, the technical standards and articles published related to the subject are still scarce, making evident the need to carry out studies and researches that contemplate the wide field of application of the FRC.

Fires in civil structures cause huge damages and risks, due to the chemical and physical changes suffered by structural materials at high temperatures. In this regard, the fibers contribute to provide a pseudo-ductile behavior the matrix and increase the residual tensile strength, since the steel macrofibers function as bridges that "sew" the imminent cracks, caused, among other factors, due to the drop in resistance suffered by the cementitious matrix and additional thermal efforts.

The mechanical characterization of the FRC must be made taking into account the post-peak stress behavior of the stress-strain curve, which matches with the rupture of the concrete matrix, because it is at this stage that the fibers start to act as a reinforcement of the matrix.

Usually, the mechanical behavior assessment of the FRC is done through the flexion test of prismatic specimens, however, this test tends to overestimate the values of the FRC's residual tensile strength, since it is a flexion test and not a tensile test, thus, it provides results against the safety of the structures. In addition to the low reliability of the results, there is an experimental difficulty with the method, since the specimens have large dimensions and weight, making handling difficult, especially after being degraded and weakened by high temperatures.

Thus, new tests are gaining space in the field of FRC's mechanical characterization, such as the Double Punching test and the DEWS (Double Edge Wedge Splitting) indirect tensile test [2]. However, while the Double Punching test provides obstacles in the analysis of the results due to the complex rupture area and the matrix crushing, already deteriorated by the temperature [3], the DEWS test proved to be efficient in the characterization of specimens after submission to high temperatures and direct fire [4].

Another fact is that even the few articles published based on studies related to the behavior of the FRC after exposure to high temperatures, these refer to cementitious matrices with high resistance characteristic values. In this current study, the analysis of the mechanical behavior of an FRC of low characteristic strength was performed, and the values of concrete used are the same as those in the construction industry in São Paulo city, with characteristic compressive strength f_{ck} = 25 MPa. Consequently, it was possible to evaluate the loss of strength caused by high temperature and compare it with the results obtained for high strength concretes.

2. EXPERIMENTAL PROGRAM

2.1. Materials

A high initial strength cement CP-V was used as a binder. Artificial sand and gravel 1 served as fine and coarse aggregate, respectively. A water/cement (w/c) ratio of 0.58 was adopted. Superplasticizer additive was also used to improve the workability of the concrete, in a content of 2.05 L/m³ of concrete. Finally, short cold-drawn, hooked end steel fibers model Wirand Maccaferri FS3N, specified in Tab. 1 were used in a content of 25 kg/m³ of concrete (Tab. 2).

Table 1 – Properties of the steel fibers.

Steel Fiber	**Value**
Length (mm)	33
Diameter (mm)	0.75
Length/Diameter (L/D) ratio	44
Tensile strength (MPa)	> 1100
Rupture deformation (%)	< 4
Young modulus (GPa)	210

Table 2 – SFRC composition.

Materials	**Dosage (kg/m³)**
Portland cement	305
Artificial sand	1250
Granite coarse aggregate D_{max} = 19 mm	1370
Water	177
Superplasticizer	2.05
Steel macrofibre	25

2.2. Preparation of specimens

A plant produced 4 m³ of concrete without fibers, which composition is the one typically used in construction in São Paulo city. The transport to the Technological Hall laboratory of Polytechnic School of University of São Paulo was carried out by a concrete mixer truck with a capacity of 8 m³.

The received concrete was submitted to the Slump test, before the addition of fibers, in its fresh state. A reduction of 30 mm was found, as the specified was 80 ± 10 mm, 70 liters of water were added to the mixture. Again, the Slump test was performed, this time the reduction measured was 85 mm. The slump test was carried out with an aluminum plate with dimensions 500 x 500 mm and a cone trunk (Abrams cone) of the same material, with 300 mm high, an upper internal diameter of 100 mm and a lower internal diameter of 200 mm. The cone trunk was positioned in the center of the plate, previously to avoid loss of water to the environment, and to reduce the influence of friction. With the mixer in motion, 19.2 kg of steel macrofibers were added in a volume of 768 L of concrete, resulting in a fiber-reinforced concrete with a content of 25 kg/m³.

The molding of the cubes of dimensions 100 x 100 x 100 mm took place in a steel prismatic shapes with capacity for four specimens (Fig. 1). Wooden wedges with a 45° opening and 20 mm high were glued in the center of the sides, in order to avoid the step of sawing the wedges after the concrete cured. To test the compressive strength, cylinders of 100 mm in diameter and 200 mm in height were molded into steel forms. All forms were greased with a layer of mineral oil to assist in the forms stripping. After filling with fresh FRC, the filled forms were taken to the vibrating table for approximately 60 seconds. 12 cubic specimens and four cylindrical specimens were produced. After molding, the specimens were covered with plastic canvas and remained at room temperature for 48 hours, when the stripping took place. Then, water was then sprayed in the filled forms with a hose and again it was covered with canvas at room temperature. This process took place for 60 days until the cure was.

Figure 1 – Steel mold for specimens used in DEWS test.

2.3. Compressive strength testing

At the age of 28 days, the cylindrical specimens were subjected to the compressive strength test in a Shimadzu UH-2000kNXR press with a load capacity of 2000 kN. The compression rate used was constant at 0.5 MPa/s.

2.4. Heating procedure

With a dry saw, grooves of 5 mm deep and 2 mm thick were made in the vertices of the wedges of each cubic specimen to induce a type I fracture. The 12 specimens were then separated into three groups of four. The first group remained at room temperature in order to establish a reference for the degradation of the composite due to the high temperature. The second group was exposed to a temperature of 300 °C for eight hours in an industrial electric oven GENGA Inforgel model GCRSP, this was the time necessary for the interior of the specimen to reach the desired temperature. Finally, the third group was exposed to a temperature of 600 °C for four hours in the same oven.

2.5. DEWS test

After heating the specimens, steel plates with dimensions 0.9 x 15 x 100 mm were fixed with the assistance of a pasty plastic mass based on polyester resin on the surfaces molded by the wedges at 45°, in order to serve as support the steel rollers responsible for transferring the load from the press to the specimens. The rollers used had a diameter of 30 mm and a length of 170 mm. In order to avoid friction between the rollers and the sheets during the test, after the drying of the plastic mass, the surfaces of all sheets were sanded. Before the rollers were accommodated in the test, powdered graphite was added in contact with the plates.

The DEWS test (Fig.2) was performed according to the simplified methodology proposed by Borges et al. [5]. An electromechanical press EMIC model DL 10000 was used, with an open system for speed control and frame stiffness of 42 kN/mm. A loading speed of 0.12 mm/min was used to evaluate the FRC's tensile strength and tensile strength after cracking. Also, to measure the crack opening, two clamp extensometers were attached to opposite faces of the cube at medium height, perpendicular to the rupture plane, with the assistance of elastomeric rings. In this way, the crack opening value corresponds to the arithmetic mean of the two measurements.

Figure 2 – Setup of the DEWS test.

3. RESULTS

During the heating of the specimens, spalling did not occur in any of the specimens in either of the two temperatures. During the DEWS test, there was no sign of crushing of the matrix by the rollers or any other damage. These facts indicate that the results are representative of the behavior of the FRC after being subjected to high temperatures and proves that the DEWS test constitutes an efficient and reliable methodology for the evaluation of the residual tensile strength of the FRC after being exposed to high temperatures. After 28 days, it was verified that the average compressive strength of the FRC at ambient temperature was 28 MPa with a standard deviation of 0.90 MPa, confirming that the concrete tested falls into the category C25.

The tensile strength curves as a function of the crack opening (COD), for each of the specimens, at temperatures of 25 ° C, 300 ° C and 600 ° C are shown in Fig. 3. The average value curves tensile strength for each of the three temperatures as a function of the crack opening (COD), obtained by arithmetic mean, are contained in Fig.4 (a).

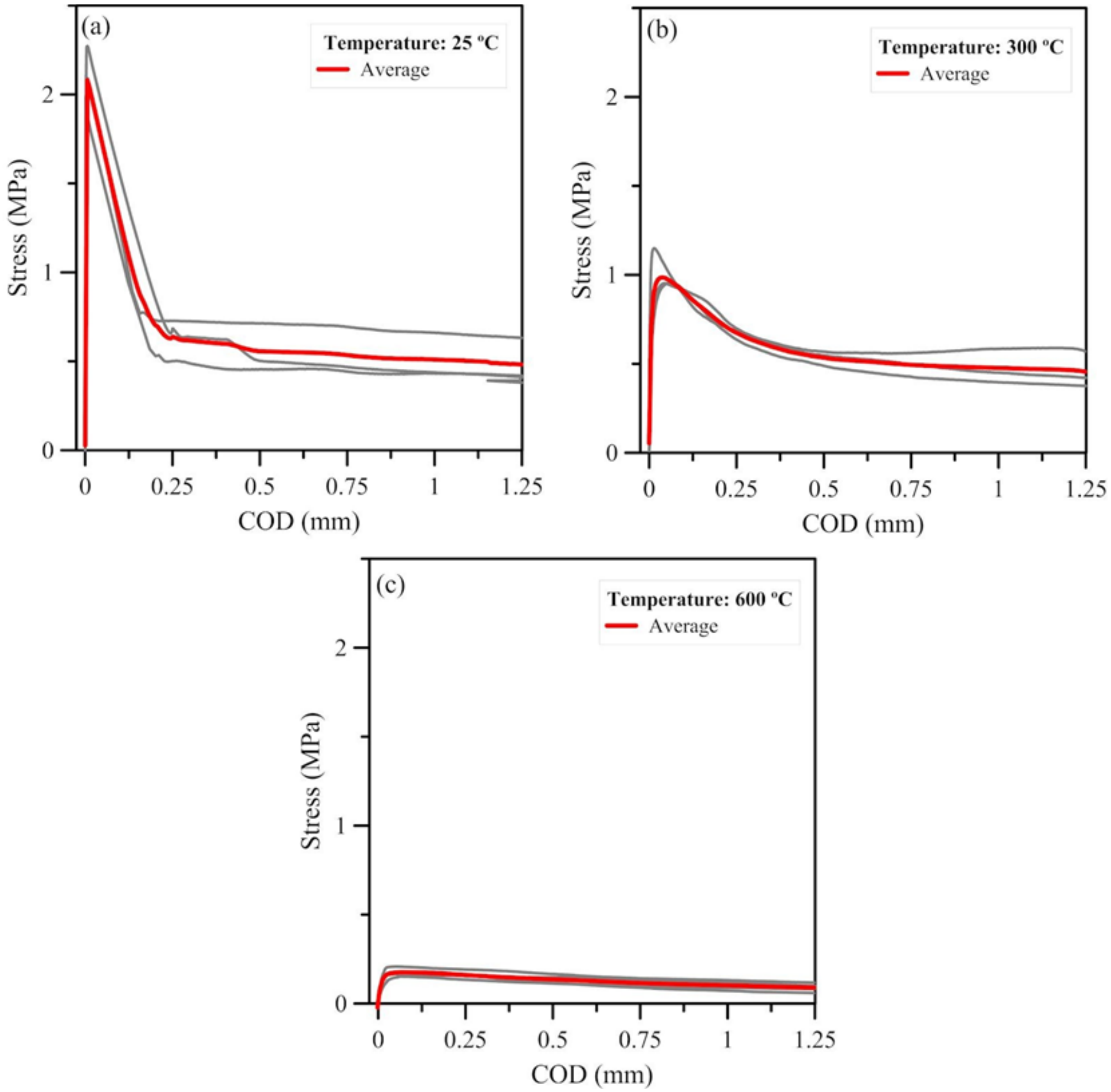

Figure 3 – Stres-COD results by DEWS test: (a) 25 °C, (b) 300 °C, (c) 600 °C.

Figure 4 (b) presents the graphs with average values of the maximum tensile strength (ftc) and residual strength corresponding to the 0.5 mm (ft,0.5) and 1.25 mm (ft,1.25) openings. These last two characterize the service limit state (SLS) and the ultimate limit state (ULS) respectively. Based on Tab. 3, it is noted that the maximum tensile strength (ftc) was reduced by 50.96% at 300°C and 93.75% at 600°C when compared to the resistance at room temperature. Residual tensile strengths were also affected.

At the crack opening of 0.5 mm (SLS), there was an apparent increase in the average resistance of 4.69% at a temperature of 300°C, however, it appears that this increase is encompassed by the standard deviation, while for the temperature of 600°C there was a significant reduction of 75.00%. At the 1.25 mm crack opening (ULS) and temperatures of 300°C and 600°C, the reductions were 6.12% and 81.63%, respectively, when compared to room temperature.

The results of residual resistance show that at 300°C the cement matrix is already deteriorated, due to factors such as cement dehydration, changes in the distribution of pores [6] and efforts of thermal origin. However, the fibers and the fiber-matrix interface, which are mainly active in the post-cracking stage, have not yet suffered major damages [7]. Thus, there are no drastic reductions in post-cracking strength. At a temperature of 600°C, the steel fibers are already beginning to undergo degradation and consequently, the residual resistance is affected more severely. Although studies of this type are scarce, the results observed in this study are consistent with the results obtained by Serafini et al.[8]. In addition, it can be seen that the tensile strength, both in the matrix and in the post-cracking properties, follows a linear trend of reduction, that was also evidenced in the study by Serafini et al. [8].

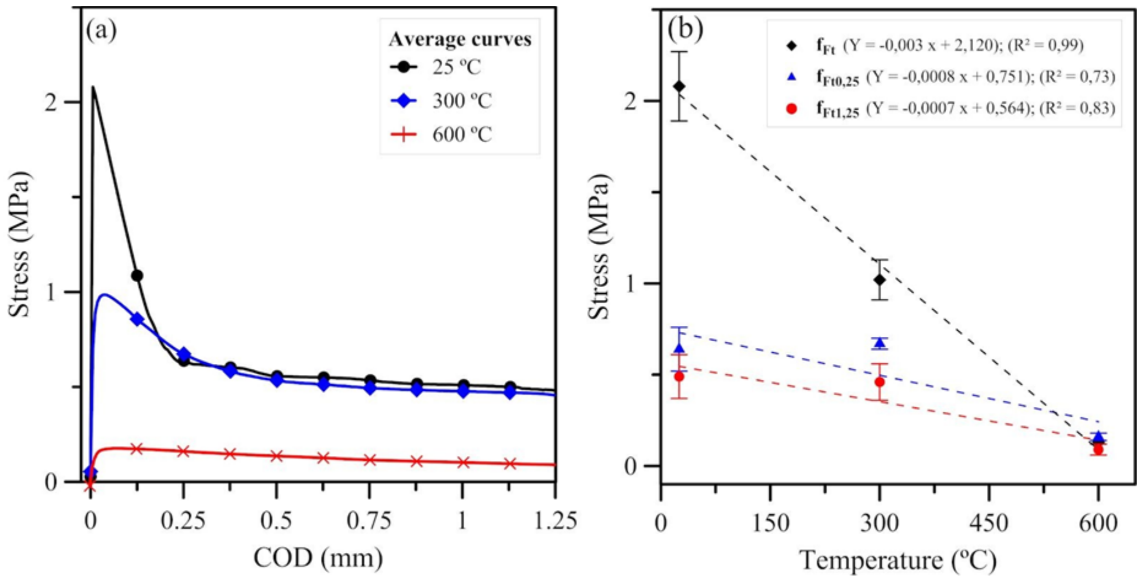

Figure 4 – DEWS test: (a) stress-COD average results and (b) tensile and post-crack tensile strength results.

Table 3 – Average results in terms of tensile and post-crack tensile strength for SFRC.

Target temperature (°C)	f_{tc} (MPa)	$f_{t0.25}$ (MPa)	$f_{t1.25}$ (MPa)
25	2.08 (± 0.19)	0.64 (± 0.12)	0.49 (± 0.12)
300	1.02 (± 0.11)	0.67 (± 0.03)	0.46 (± 0.10)
600	0.13 (± 0.01)	0.16 (± 0.02)	0.09 (± 0.03)

4. CONCLUSIONS

The following conclusions were drawn with the results obtained in this study:

- No crushing was observed in the region of contact between the rollers and the matrix at any of the temperatures.

- The DEWS test proved to be efficient for characterizing the tensile strength after cracking of the FRC of low characteristic resistance, as well as for high-strength concretes, demonstrated in the literature.

- A type I crack is induced by the DEWS test, allowing direct and simple analysis of the residual resistance values of the FRC.

- The tensile strength of the matrix was reduced by 50.96% and 93.75% at temperatures of 300 °C and 600 °C, respectively when compared to room temperature. In SLS (COD = 0.5 mm), the residual resistance did not suffer a significant reduction for the temperature of 300 °C and suffered a reduction of 75% for the temperature of 600 °C. For the characterization of the ULS (COD = 1.25 mm), the residual resistance at temperatures of 300 °C and 600 °C, suffered a reduction of 6.12% and 81.63%, respectively.

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