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THE EFFECT OF ELEVATED TEMPERATURES ON THE TENSILE PROPERTIES OF STEEL FIBER REINFORCED CONCRETE BY MEANS OF DOUBLE EDGE WEDGE SPLITTING (DEWS) TEST: PRELIMINARY RESULTS

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Abstract: The definition of the post-fire properties of steel fiber reinforced concrete (SFRC) is a current technological challenge. A study conducted using the Barcelona test (BCN) show that the puncture caused by the test may result in crushing of the porous matrix and induced frictional interaction. This influence may result in misleading conclusions regarding the properties and the behavior of the composite, which denotes that an inadequate test methodology may significantly affect results of SFRC after temperature exposure. In this context, the Double Edge Wedge Splitting (DEWS) test is a promising methodology for this type of application since a mode I fracture type is induced in the specimen, diminishing any compressive or puncture interactions with the porous matrix. Therefore, this work aims to present the results obtained for SFRC exposed to temperatures of 25 °C and 600 °C by means of DEWS test. Results show that the tensile strength of the cement matrix and the residual tensile strength at the service limit state and ultimate limit state are significantly affected. Additionally, no visible damage was caused by the interaction between the roller and the SFRC for specimens exposed to 600 °C. The present study contributes to the absent literature on the residual tensile strength of SFRC after temperature exposure, and suggests an alternative test method to be employed.

1 INTRODUCTION

The considerable specimen volume and the overestimation of the tensile strength values are obstacles related to the use of flexural test setups for the determination of the mechanical properties of SFRC – both before and after elevated temperatures. Due to this scenario, novel methodologies have been developed in substitution to the conventional flexural tests, among them the Double Edge Wedge Splitting (DEWS) test and the Barcelona (BCN) test. A recent study conducted using the Barcelona test (BCN) in specimens exposed to elevated temperature show that the puncture caused by the test may result in crushing of the porous matrix and induced frictional interaction [1].

When determining the indirect tensile strength by means of the DEWS test proposed by [2] a mode I fracture type is induced in the specimen by a compressive regime. This aids in the determination of the tensile stress-strain relationship for the composite in a more straightforward form. The residual tensile strength is determined in two distinct crack opening displacement (COD) levels: the first is related to the service limit state (SLS) with COD = 0.5 mm, while the second is related to the ultimate limit state (ULS) with COD = 2.5 mm, which are based on the *fib* Model Code considerations [3].

The DEWS test is a test idealized for open-loop conditions, which makes it viable to be conducted in most laboratories worldwide. However, there is a risk associated with this simplicity when analyzing SLS values due to the post-peak instability when evaluated SFRC with low fiber content. Additionally, this test method is capable of characterizing both softening and hardening behaviors, as well as variations associated with the orthotropy of the composite [4]. This test, however, has never before been applied to SFRC after high temperature exposure, which is the main objective of this preliminary study.

2 MATERIALS AND METHODS

2.1 Materials

A type I Portland cement (CEM I 52.5R) was used in this study. River and artificial sand were used as fine aggregates with two coarse granite aggregates (d_{max}: 19 mm and d_{max}: 9.5 mm) to increase particle packing. A superplasticizer specific for precast elements, GRACE ADVA Cast 525, was used to provide consistency to the mix. A cold-drawn hooked-end steel fiber commonly used for structural applications was used as main concrete reinforcement in the composite, Dramix 3D 80/60BG. Anti-spalling polypropylene microfibers, Neomatex FireX, were used to reduce the chances of occurring explosive spalling during fire exposure.

2.2 Composition and preparation of concrete specimens

The composition of concrete was based on the mix design of the precast segments used in the segmental lining rings for the construction of Subway Line 6 in São Paulo, which is described in Table 1. The steel fiber content adopted in this study was kept at 0.45% of total volume. The microfiber content was kept at 0.09% of total volume in order to prevent explosive spalling.

Table 4 – Dosage of materials to produce one cubic meter of macro-synthetic fiber reinforced concrete

Materials	Dosage (kg/m³)
Portland cement	400
Silica fume	22
Water	165
Siliceous river sand	403
Artificial granite sand	269
Coarse aggregate - d_{max}:19 mm	770
Coarse aggregate - d_{max}:9.5 mm	330
Superplasticizer	3
Micro-synthetic fiber – antispalling	0.80
Hooked-end steel fiber	35

Silica fume was used as supplementary cementitious material at a content of 5.5% of the cement mass, and water to cementitious materials ratio (w/cm) was kept constant at 0.39. All aggregates were oven dried at 100 °C for 14 h before concrete production.

Concrete was prepared in a conventional concrete mixer with capacity of 300 L in a room at (25 ± 1) °C. First, cement, silica fume, coarse aggregates, and a third of total water and superplasticizer were pre-mixed and then added to the mixer and homogenized for 3 min. Then fine aggregates and a third of water mixed with superplasticizer were added and homogenized for the same time period. At last, the remaining one third of water and superplasticizer were added and macro- and micro-synthetic fibers were slowly added during 3 min of mixture. The composition was, then, mixed for 6 min. The SFRC presented a specific weight equal to (2430 ± 52) kg/m^3 and a slump value of (4 ± 1) cm (average obtained from three determinations).

Concrete was cast in polypropylene molds in one layer consolidated in a vibrating table with a frequency of 60 Hz for 60 s. A total of 9 prismatic specimens with dimensions of 150x150x550 mm (width x height x length) and 5 cylindrical specimens with diameter of 150mm and height of 300mm were produced. Specimens were cured in a saturated room for 72 h, and then stored at room temperature until the age of 150 days to better simulate *in situ* humidity and curing conditions. Cylindrical specimens were cured for 28 days only in order to assess the compressive strength of the composite.

Prismatic specimens were, later on, cut in cubes of 150x150 mm and for DEWS test. Two triangular grooves with an inclination of 45° were cut along two opposite sides of the cubes, respecting the casting orientation. After that, two notches with 5 mm depth and 2 mm width were cut starting in the groove vertices toward the center of the cubes. This procedure aims to induce cracks on the vertical plane of cubical specimens. Two steel plates measuring 0.9 x 15 x 150 mm (thickness x width x length) were attached to the groove surfaces using body filler as glue. The steel plates are used to reduce frictional interaction between the roller and the specimen during test.

2.4 Compressive strength test

The compressive strength tests were performed on a Shimadzu UH-2000kNA with 2000kN load capacity. Tests were conducted according to the Brazilian standards [5] stress controlled at a rate of 0.5MPa/s. The compressive strength tests were conducted when concrete reached an age of 28 days for specimens at room temperature and exposed to 600 °C. Strain was calculated using piston displacement results divided by the specimen's height.

2.5 Heating procedure

An industrial INFORGEL GENGA electric oven, model GCR.SP, with maximum temperature of 600 °C was used to heat cylindrical specimens. Specimens were heated for the target temperature of 600 °C at a heating rate of (12 ± 2) °C/min. After reaching the target temperature, a sustained thermal load of 120 min was employed. After the heating was finished, the chamber was kept closed and cooling until the room temperature, and lasted for 24 h. The cooling rate was not controlled.

2.6 Double edge wedge splitting test

The DEWS test was conducted using an open-loop universal testing machine, EMIC DL 10000. Cubical specimens were evaluated regarding the tensile strength and post-crack tensile strength following the simplified procedure presented by [4] and is summarized here for the convenience of the reader. The crack opening displacement (COD) was measured by two transducers positioned in opposite sides and middle height of the cubical specimens. The tests were conducted using a COD opening displacement rate of 0.12 mm/min. A total of 10 cubical specimens were evaluated in this preliminary test, being five specimens tested for room temperature and five specimens for the target temperature of 600 °C. Figure 1 shows the test setup adopted.

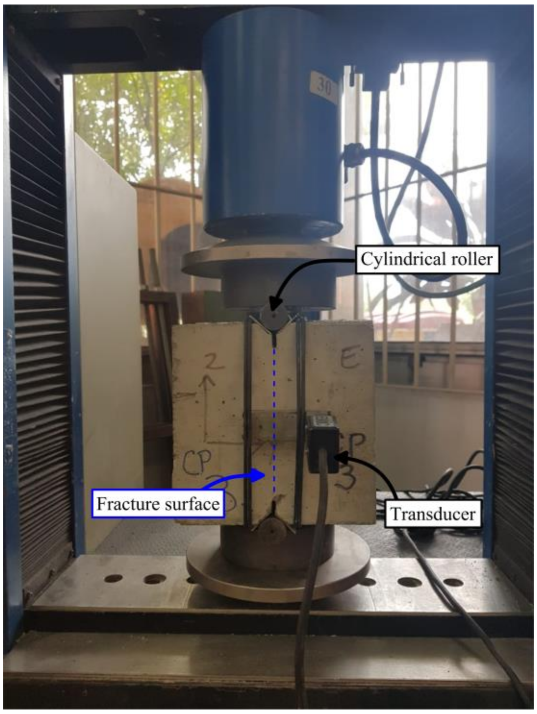

Figure 1: The test setup adopted.

3 RESULTS AND DISCUSSION

3.1 Compressive properties of SFRC

Figure 2 shows the stress-strain results obtained.

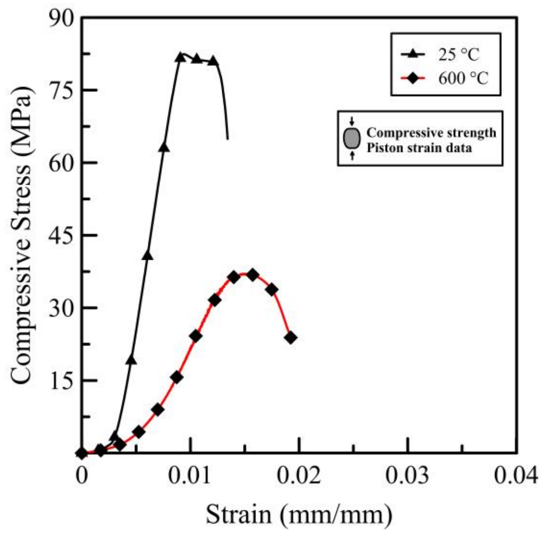

Figure 2: The average stress-strain results obtained

The average compressive strength of SFRC at room temperature was 82.6 MPa with a standard deviation of 1.38 MPa. This denotes that the composite may be considered a high strength concrete of class C80. After temperature exposure of 600 °C the composite shown an average compressive strength of 37.45 with a standard deviation of 1.08 MPa. This denotes a compressive strength loss of 54.66 %. Changes in the elastic properties can also be seen by analyzing the changes in the slope of the stress-strain curves.

3.2 Tensile properties of SFRC

Figure 3 shows the stress-COD results and the tensile and post-crack tensile strength of the composite. The average results can be found in Table 2. Standard deviation values are provided in parenthesis.

The composite tensile strength values after temperature exposure of 600 °C were 82.5% lower than the value reached at room temperature (3.78 MPa). This reduction value is in line with the classical literature [6] and also with recent results found in literature [7, 8] for a similar class of concrete tested in comparable conditions.

For the temperature of 25 °C, an instability region can be observed after the matrix cracks and may be attributed to the considerable gap between the matrix tensile strength and the SLS residual tensile strength. The use of an open-loop system is another factor that influenced the occurrence of post-crack instability for room temperature results. For results after temperature exposure of 600 °C, however, the reduced gap between matrix tensile strength and SLS tensile strength diminished the negative effects of instability.

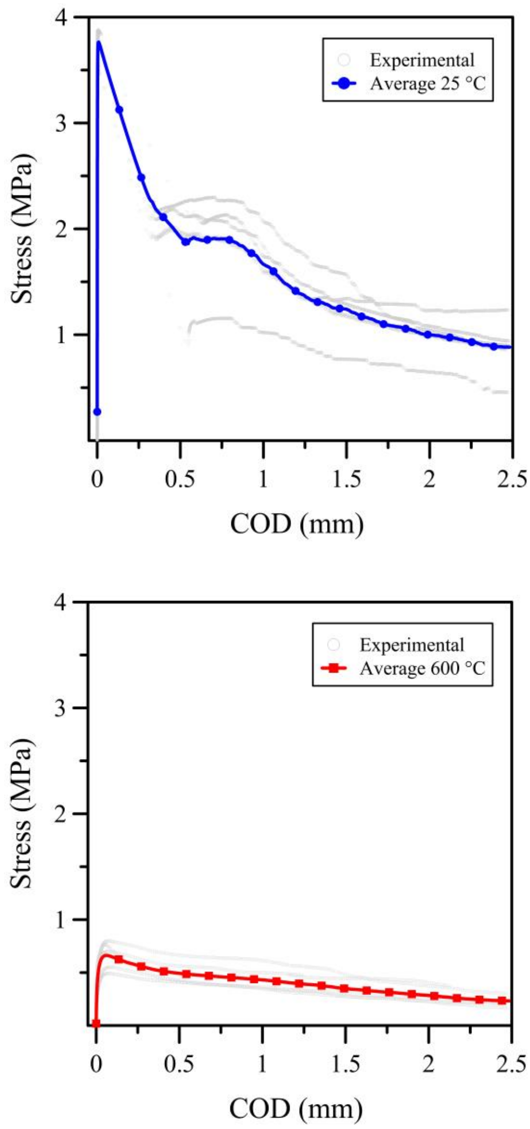

Figure 3: The stress-COD results for DEWS test.

The post-crack tensile strength values at SLS (COD = 0.5 mm) after exposure to 600 °C was 74.3% lower than the value reached at room temperature (1.93 MPa). The post-crack tensile strength values at ULS (COD = 2.5 mm) after exposure to 600 °C was 72.2% lower than the value reached at room temperature (0.88 MPa).

Table 2 – Average results in terms of tensile and post-crack tensile strength for SFRC

Temperature (°C)	f_{tc} (MPa)	$f_{t0.5}$ (MPa)	$f_{t2.5}$ (MPa)
25	3.78 (± 0.16)	1.93 (± 0.50)	0.88 (± 0.27)
600	0.66 (± 0.13)	0.50 (± 0.11)	0.24 (± 0.07)

Although a reduction trend was observed, further studies need to be conducted for intermediate temperatures in order to isolate variables, such as cracking, porosity and microstructural changes, and to better characterize the behavior of SFRC after temperature exposure.

3.2 Visual evaluation of the test

Figure 4 illustrates the interaction between roller and the cubic specimen exposed to 600 °C after the DEWS test was conducted.

Figure 4: The roller-specimen interaction after DEWS test.

No visible damage, such as crushing, was caused by the interaction between the roller and the SFRC for temperatures up to 600 °C. This denotes that the DEWS test is a viable methodological option for the assessment of the post-crack tensile properties of SFRC after temperature exposure.

The considerable variation in post-crack results, however, may be a limitation of DEWS test for post-heat applications. This may be especially true when applied to SFRC that exhibits a strain-softening behavior due to reduced post-crack load values. Even with those considerations, the average curves can be obtained and the behavior of the composite can be analyzed.

Further studies are required in order to verify the suitability of DEWS test in more severe conditions of heating rate, temperature of exposure, and cooling conditions, as well as in strain-hardening SFRC.

12 CONCLUSIONS

The following conclusions can be drawn from the present study:

- The compressive strength of the composite reduced by 54.66% after exposure to 600 °C.
- The composite tensile strength values after temperature exposure of 600 °C were 82.5% lower than the value reached at room temperature.
- The post-crack tensile strength values at SLS (COD = 0.5 mm) reduced by 74.3% and in ULS (COD = 2.5 mm) by 72.2% when compared to room temperature.
- No visible damage, such as crushing, was caused by the interaction between the roller and the SFRC for temperatures up to 600 °C.
- Even though limited comparable data can be found in literature, the DEWS test has shown, preliminary, to be a viable methodological option for the assessment of the post-crack tensile properties of SFRC after temperature exposure.

One of the main advantages of DEWS is that it generates a pure type I fracture that simplify the determination of constitutive equations from the results, without the need to estimate uncertain parameters as in other test methodologies. Some limitations may be imposed when the gap between the matrix tensile strength and the SLS tensile strength is elevated. This gap generates a instability region when using an equipment with open-loop system. Even though this instability may affect SLS results for room temperature results, the instability seems to reduce for SFRC after temperature exposure of 600 °C due to the deterioration of the matrix and, consequently, the reduction in the previously mentioned gap. For room temperature specimens, the negative effects of instability may be diminished by using closed-loop systems.

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