FIRE BEHAVIOUR OF A FIBRE REINFORCED CONCRETE TUNNEL SEGMENTS

Adérito Alves[1], João Paulo Rodrigues [2*], Joaquim Barros[3], Lúcio Lourenço[4] & Simão Santos[5]

[1]MSc Student, University of Coimbra, ajga@dec.uc.pt
[2] Assistant Professor, University of Coimbra, jpaulocr@dec.uc.pt
[3] Associate Professor, University of Minho, barros@civil.uminho.pt
[4] PhD Student, University of Minho, lucio@civil.uminho.pt
[5] MSc Student, University of Minho, simaopfsantos@civil.uminho.pt

Keywords: High strength concrete, steel fibres, polypropylene high temperatures

INTRODUCTION

In spite of the efforts of the technical and scientific communities in terms of understanding the behaviour of reinforced concrete structures when submitted to high temperatures, such is the case of a fire, severe damages, even impressive structural collapses continue to occur due to fire action Tunnel linings is one of the infrastructures more prone to fire accidents. Depending on several conditions, such is the case of concrete properties and temperature level and duration, the damages induced on the concrete lining can be so significant that can compromise the local, or even, the structural stability, resulting impacts in terms of human and economic losses that can be catastrophic [1].

The Universities of Coimbra and Minho, at Portugal, are developing a Fibre Reinforced Concrete of Enhanced Fire Resistance (FRCEFR) of enough resistance for some structural applications, such is the case of pre-casting concrete segments for tunnel lining. This FRCEFR is reinforced with a fibrous system that was designed to assure the necessary ductility and to improve the fire resistance of medium high strength concretes.

This fibrous system is composed by two types of fibres: a polypropylene fibre that under the action of the fire allows the creation of a system of micro-channels into the concrete microstructure, from where the water vapour can be escaped, reducing the possibility of spalling [2]; and a steel fibre that has the two main functions: increase the concrete post-cracking resistance of hardened concrete, increase the integrity of concrete when submitted to high temperatures [3].

EXPERIMENTAL TESTS

A mix design program was done with the objective of finding the composition that accomplishes the requirements in terms of fire resistance and concrete ductility, taking into account the economic restrictions for the concrete production and the concrete technological practices indicated by a contractor associated to this project.

To assess the compressive strength of the designed fibrous compositions when submitted to high temperatures, as well as, after have been exposed to high temperatures, series of compression tests were carried out.

Tunnel segments are, in general, reinforced with high percentage of steel bars, in order to attend not only to known load conditions, but also to unpredicted effects. The time consume deserved by steel reinforcement preparation and installation has significant impact on the final cost of this structural element. Previous research has indicated that steel fibres can totally or partially replace conventional steel bars with technical and economic advantages [4]. To evaluate the possibilities of steel fibres replace partially or totally the reinforcement ratio currently used in this type of application, tunnel segments were manufactured by the developed FRCEFR and submitted to fire tests. After have been submitted to fire, the tunnel segments were tested under bending, up to its failure, in order to determine its residual flexural resistance.

Compression tests at high temperatures

Core cylinders of 75 mm diameter and 225 mm height were extracted from a FRCEFR slab, and were submitted to direct compression force in a test equipment that can, simultaneously, apply high temperatures to the specimen (see Figure 1). These specimens were instrumented with thermocouples at pre-established places inside of the specimen, according to the recommendations of RILEM [5].

Figure 1 Compression tests at high temperatures

The specimens, under constant load, were heated up in an electric oven, with a heating rate of 3 K/min until a desired level of temperature was reached. An interval of time was waited for homogenization of the temperature in the specimen, after which the compression test was carried out.

For the assessment of the residual compressive strength, other specimens were tested. These specimens were heated up to a certain level of temperature and then cooled down to the room's temperature. During the heating and cooling process the specimens were subjected to a constant compression load. The compression test for the evaluation of the residual compressive strength was carried out at room temperature.

Four levels of temperature (300, 500, 700 and 900 ºC) and three stress levels (0,3f_{cd}, 0,7f_{cd} and f_{cd}) were selected for this experimental program, where f_{cd} is the concrete design compressive strength. Three specimens were tested for each combination of the analyzed parameters.

Fire resistance of concrete tunnel segments

Tunnel segments of distinct volumentric percentage of steel fibres and different steel reinforcement ratio were submitted to fire test and, after have been cooled, their residual flexural resistance was assessed carrying out three point bending tests. The tunnel segments had dimensions of 1.2 x 2.4 x 0.35m^3 and were provided with thermocouples to measure the temperature variation at pre-selected points inside the specimen.

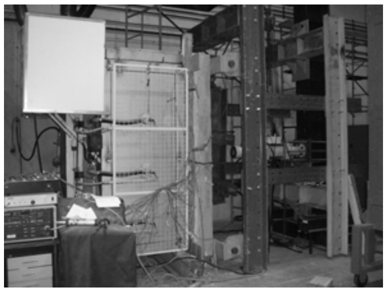

Figure 2 Experimental set-up for the fire resistance tests

Four tunnel segments were manufactured: a reference specimen of high strength concrete without fibres and with 81 kg/m^3 of conventional reinforcement (*Specimen 1*). This specimen is similar to the ones used in the construction of tunnels in Portugal; a second one, with 75 kg/m^3 of steel fibres and without steel bars reinforcement (*Specimen 2*); a third specimen with 45 kg/m^3 of steel fibres and 51 kg/m^3 of steel bars reinforcement (specimen *Specimen 3*); and finally, a fourth specimen with 60 kg/m^3 of steel fibres and 35 kg/m^3 of steel bars reinforcement (*Specimen 4*). The percentage of polypropilene fibres was maintained constant and equal to 2 kg/m^3 in specimens 2, 3 and 4.

Figure 3 Bending tests

These specimens, supported in an external structure, were tested in a fire resistance furnace capable of follow the ISO 834 curve. During the fire resistance test, the elements were subjected to a constant load of 174 kN, applied to its mid span and orthogonally to the middle surface of the specimen. (see Figure 2) This load was estimating taking into account the load conditions that tunnel segments are submitted in service.

Bending tests to assess the residual flexural resistance of tunnel segments

The tunnel segments that did not collapse during fire test were, after cooled in the laboratory environment, tested under a three load configuration in order to evaluate its residual flexural resistance. The elements were tested under displacement control at a displacement rate of 0,001 mm/sec (see Figure 3).

RESULTS

Compression tests at high temperatures

Figure 4 depicts a typical relationship between the applied force and the measured displacement for a FRCEFR specimen submitted to a stress level of $0,3f_{cd}$ and a maximum temperature of 300ºC.
On the compression tests, the increase of load level and maximum temperature of exposure conducts to a small resistance. For the series of 900ºC, it was not possible to obtain results because all the specimens collapsed during the heating phase for a temperature of around 700ºC.

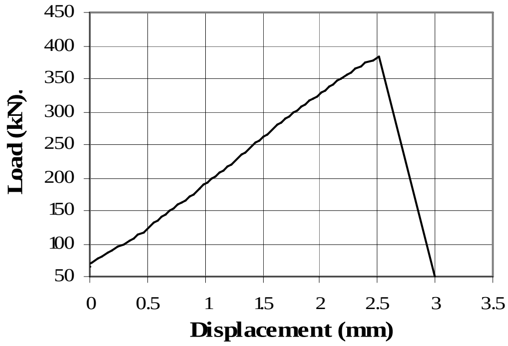

Figure 4 Force versus displacement relationship for a FRCEFR specimen submitted to a 300ºC and $0.3f_{cd}$

Fire resistance of concrete tunnel segments

In general, the tunnel segments behaved well during the fire resistance tests, except for *Specimen 2* that only includes fibres. After 10min of fire exposure a macro-crack occurred at the face turned to the fire, at the loaded cross section. The crack opening has increased up to the flexural collapse of the Specimen that occurred after 110 min the fire test initiation. A post-analyze of the flexural tensile stress introduced by the resultant line load of 174 kN indicated that this load exceeds the load corresponding to crack initiation of the cement based matrix of the FRCEFR used in the fabrication of this Specimen.

The other elements resisted completely for more than 240min without reaching the maximum deflection or speed of deformation indicated in EN 1363-1 for fire resistance tests. [6].

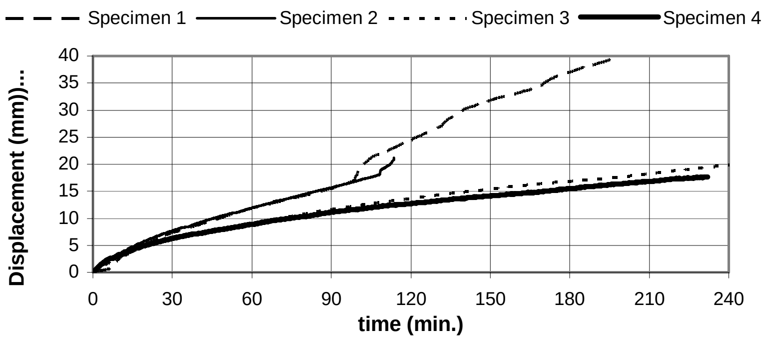

Figure 5 Evolution of mid span displacements in the specimens during fire resistance tests

Figure 5 presents a synthesis of the results obtained in the fire resistance tests with tunnel segments. *Specimen 1* was the first to be tested and, due to deficient functioning of the supports, the test was interrupted at 200min. A significant increase of the deflection rate is observed after 100min of fire exposition, which may be justified by an excessive deformation of the supports. This fact was solved for the subsequent tests.

Specimen 3 and *4* presented the smallest deflection rates, which indicates that a reinforcement in terms of steel fibres and bars placed in the contourn of the specimen are good reinforcement solution in terms of retaining the stiffness of the structural element under fire conditions.

Bending tests to assess the residual the residual resistance of tunnel segments

The force-deflection curves obtained from the bending tests with the tunnel segments after have been submitted to the fire conditions imposed by the ISO 834 curve are represented in Figure 6 .

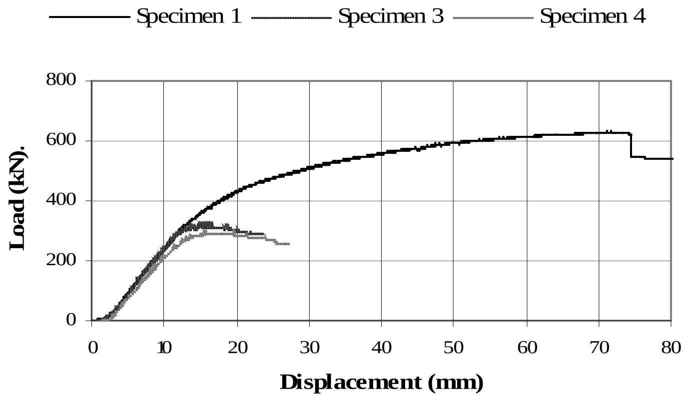

Figure 6 Experimental load versus mid span displacement for the tunnel segments after have been exposed to ISO 834 curve

The obtained results shown that *Specimen 1* presented the largest residual flexural resistance. The others specimens presented similar load carrying capacity. As already mentioned, *Specimen 2* was not tested since it collapsed in the fire resistance test.

CONCLUSIONS

The specimens with polypropylene fibres presented less spalling than the specimens without fibres. The existence of these type of fibres in the concrete allowed the creation of channels through which the water steam, generated through the heating of the specimen, can escape.

Partial replacement of conventional reinforcement by steel fibres is a possible solution in terms of fire resistance. However, in terms of residual load carrying capacity after specimens have been submitted to fire conditions imposed by ISO 834 curve, the reinforcement solution based on steel bars (81 kg/m^3) was superior to those based on hybrid reinforcement (45 kg/m^3 of steel fibres and 51 kg/m^3 of steel bars; 60 kg/m^3 of steel fibres and 35 kg/m^3 of steel bars)

REFERENCES

[1] Khoury G. A.- *Spalling Review*, Fire Safety Design, work package 4, 2005.

[2] Rivaz B., *Les performances techniques des bétons renforcés des fibres métalliques es polymères*, Tunnels et Ouvrages Souterrains, nº 198, 2006, pp. 367-371.

[3] Borot. G., Larive C. & Feron C.- *Apports des essais incendie pour la détermination de la tenue au feu des structures*, Tunnels et Ouvrages Souterrains, nº 198, 2006, pp. 365-366.

[4] - Casanova, P., 'Bétons renforcés de fibres métalliques du matériau à la structure', PhD Thesis, LCPC, Paris, France, (996) 203 pgs.

[5] RILEM TC 129-MHT. - *Test methods for mechanical properties of concrete at high temperatures*, Materials and Structures, vol. 33, May 2000, pp224-228.

[6] CEN, EN 1363-1; *Fire Resistance Tests – part 1: General Requirements,* August 1999.