Construction and Building Materials 159 (2018) 73–82

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of high temperature on the mechanical properties of hybrid fibre reinforced normal and high strength concrete

F.B. Varona *, F.J. Baeza, D. Bru, S. Ivorra

Department of Civil Engineering, University of Alicante, Alicante, Spain

HIGHLIGHTS

- Synergy of polypropylene & steel fibres has similar evolution at high temperature.
- Higher aspect ratio steel fibres could be more prone to lose bond to the matrix.
- Steel fibres in HSC may not provide the same ductility at high temperature.
- Design equations for properties at high temperatures have been proposed.

ARTICLE INFO

Article history:
Received 23 August 2017
Received in revised form 27 October 2017
Accepted 30 October 2017

Keywords:
High strength concrete
High temperature
Residual properties
Steel fibre
Polypropylene fibre
Hybrid fibre

ABSTRACT

The current version of the European standard for concrete structures gives tabulated data for the evolution of the mechanical properties of normal strength concrete subjected to elevated temperatures. However, the standard acknowledges the lack of sufficient data for the case of high strength concrete with limestone aggregate and there are no provisions for fibre reinforced concrete at high temperatures. This paper presents the experimental results obtained on six batches of normal and high strength fibre reinforced concrete made with limestone aggregates and tested after exposure to high temperatures. These results gave a good correlation with previous researches and equations were obtained to describe the evolution of the compressive strength and the flexural strength at elevated temperatures. Ductility was also measured in the flexural strength tests and results suggested that the use of steel fibres with higher aspect ratio may lead to lower ductility after exposure to temperatures higher than 650 °C.

1. Introduction

Within the context of the most usual construction materials for building and civil infrastructures, concrete stands out because of its excellent behaviour when exposed to high temperatures and fire condition. All the variables that assess this performance are defined in International Standards [1,2] which also include some advices to fulfil the structural requirements in these cases, such as minimum concrete covers for each particular fire resistance, simplified methods for the determination of the structural resistance of each type of section, or even some basis for advanced numerical modelling methods. Reinforced concrete became a structural material during the second half of 19th century. One of the main reasons was actually its good behaviour during accidental fires, especially when compared to the other usual construction material of that age, e.g. cast iron. Even today concrete presents better fire performance than modern structural steel. Two appropriate examples of this assertion are the Windsor Tower fire in Madrid in 2005 and the Grenfell Tower fire in London in 2017.

In the 1970′s concrete research focus shifted towards the structural behaviour of the material under high temperatures [3–6], because of the development of nuclear power plants, whose reactors were initially and currently made in concrete. In the late 1980′s the focus was turned towards high strength concrete (HSC), with a more compact microstructure than normal strength concrete (NSC) [7–12]. This dense internal structure makes HSC more sensitive to the splitting of the concrete cover in the hottest elements. One of the causes of structural spalling, as this phenomenon is known, is the thermal gradients and the thermal incompatibility of the different components of the reinforced concrete elements: the cement paste, the aggregates, the steel rebars and tendons, which have different coefficients of thermal expansion. Another cause of spalling is the dehydration of the C-S-H gel and the portlandite, which generates water steam and provokes an increase of the pore pressure within the concrete. Spalling is one of the greatest concerns when dealing with concrete structures exposed to fire. In this regard, notable fire catastrophes can be

---

* Corresponding author.
E-mail address: borja.varona@ua.es (F.B. Varona).

https://doi.org/10.1016/j.conbuildmat.2017.10.129

mentioned, such as fire in the Eurotunnel of the English Channel in 1996, the Tauern tunnel in 1999 (Austria) and the Mont Blanc tunnel in 1999 (France) [13–16]. In these examples, the thermal exposure in a confined environment, and with a high combustible charge, caused a fast temperature rise, which led to severe concrete damage and explosive spalling. Thus, the structural section is rapidly reduced and inner layers become exposed, hence the structural safety may be compromised for the design load values.

In the last two decades research has been focused on studying the influence of the addition of fibres to the concrete subjected to high temperatures. Polypropylene fibres, which melt at approximately 170 °C, have been proven adequate to control the spalling of concrete; their melting creates an additional capillary pore network inside the concrete, which allows the release of the water steam generated by dehydration reactions [17,18]. Thus, the main objective of polypropylene fibres is not the structural reinforcement but the improvement of the fire resistance of concrete. Instead, steel fibres can be used in order to increase the residual strength of concrete after exposure to elevated temperatures [19,20]. However, some research [21] argues that the benefit of adding steel fibres may not be so obvious, since they contribute to speeding up the heating of the concrete and may be prone to producing internal micro-cracking because of thermal incompatibility with the concrete matrix. Recent researches [21–23] have studied hybrid fibre reinforced concrete, which incorporates both polypropylene and steel fibres. Experimental results suggest a synergy between both types of fibre in enhancing the mechanical properties of concrete subjected to high temperatures.

There are three different types of tests for concrete at high temperatures: in stressed tests specimens are prestressed to a certain fraction of their ultimate load and then are exposed to high temperature until failure, either at a constant load or after loading at high temperature [9,24–27]; in unstressed tests specimens are heated and then tested at high temperature [4,5,7,19,28]; and finally in residual tests specimens are heated to maximum temperature and then cooled and tested at ambient temperature [17,21,29–31].

The current version of the European standard for concrete structures [2] gives tabulated data for the evolution of the mechanical properties of NSC subjected to elevated temperatures, accounting for the case of quartz aggregates and for the case of calcareous aggregates. However, the standard acknowledges the lack of sufficient data for the case of high strength concrete (HSC), making no distinction between the use of different types of aggregate. Furthermore, this standard gives no provisions for fibre-reinforced concrete at high temperatures.

This paper presents the experimental results obtained on six batches of normal and high strength fibre reinforced concretes subjected to high temperatures up to 825 °C. The mechanical properties studied are the compressive strength, the tensile splitting strength, the dynamic modulus of elasticity and the flexural strength and ductility after natural cooling, i.e. residual mechanical properties. According to the existing literature [32], residual properties are always lower than their high temperature counterparts, hence these results would be conservative. The main objective is assessing the influence of hybrid fibre content with a low volume fraction on the evolution of the mechanical properties of concrete subjected to elevated temperatures, especially for high strength concretes made with limestone aggregates.

2. Experimental procedure

2.1. Materials and specimen preparation

Six different fibre reinforced concrete (FRC) batches were prepared, divided in two different types of concrete: three of them were designed to obtain normal strength concrete (NSC), while the other three were high strength concretes (HSC). Table 1 includes the dosages of this two reference concretes, NSC and HSC. Limestone aggregates were used for both coarse and fine fractions; CEM II/B-M (S-L) 42.5R according to UNE-EN 197-1:2001 was used for NSC, while a combination of silica fume and CEM I 52.5R was used for HSC. In order to obtain an adequate workability of the fresh mix, different water reducing agents were used and even combined: in NSC Chryso Plast Delta 21 (type A) was used, while in HSC a mixture of Sikament 165 (type B) and Sika Viscocrete 5980 (type C) was included. Moreover, polypropylene (PP) fibres (according to Eurocode 2 [2]) were used to avoid integrity problems due to explosive spalling when samples were exposed to temperatures higher than 400–500 °C (as observed in previous research even for normal strength concretes [17]). In this case, PP fibres melt at around 170 °C generating a capillary pore network to reduce pore pressure when cement hydration products decomposed at high temperatures. Therefore PP fibres were not used as structural reinforcement, but to guarantee concrete performance after high temperature exposure. On the other hand, two different steel fibres (with diameters of 0.35 mm and 0.75 mm respectively) were used to prepare FRC. Table 2 summarises the main properties of these three fibre types. To sum up the following six concrete types were prepared:

- NSC-0: control NSC, with PP fibres.
- NSC-1: hybrid fibre reinforced NSC, with PP fibres plus type 1 steel fibres.
- NSC-2: hybrid fibre reinforced NSC, with PP fibres plus type 2 steel fibres.
- HSC-0: control HSC, with PP fibres.
- HSC-1: hybrid fibre reinforced HSC, with PP fibres plus type 1steel fibres.
- HSC-2: hybrid fibre reinforced HSC, with PP fibres plus type 2 steel fibres.

The preparation process comprised the following phases: first, all aggregates, water and cement materials were mixed; afterwards, water reducing agents and fibres (PP and steel if necessary) were added; finally, concrete was poured into the moulds and kept for 24 h, when they were demoulded and conserved in ambient controlled room (20 °C and RH >95%) until 28 days age. High temperature tests were made at 60 days age for a proper concrete curing process. For each different concrete 45 specimens were prepared and tested: 15 cubic specimens with dimensions 15 × 15 × 15 cm were used for compressive strength tests and elastic modulus measures, 15 cylinders, with a diameter of 15 cm and a height of 30 cm were used for tensile splitting strength tests, and 15 prismatic 15×15×60 cm specimens were used for bending tests.

2.2. Testing

The objective of this work is aimed at the evaluation of the mechanical properties of FRC after high temperature exposure. For this purpose the following tests were made under five different conditions (28 days ambient temperature, 60 days ambient temperature, 60 days 450 °C, 60 days 650 °C, 60 days 825 °C): compressive strength tests according to UNE-EN 12390–3:2009; tensile strength tests according to UNE-EN 12390–6:2009; bending strength tests according to UNE-EN 14651:2007 + A1:2008 (Fig. 1); finally, densities and dynamic elastic moduli were measured in the same samples prior to compressive strength tests. A non-destructive test based on ultrasounds velocity pass was used for elastic modulus assessment. These tests were made using a Proceq Pundit Lab Plus device and two Olympus Panametrics transducers, which were located at the centre of two opposite faces of each sample. Two perpendicular directions were measured on each specimen, and those samples that had to be exposed to high temperatures were measured prior and after the heating process. This technique has been successfully used to evaluate mechanical performance loss of construction materials [33], and the registered signal is analysed to determine the propagation velocity of P-waves (V_p) and S-waves (V_s), which can be directly related to the elastic modulus $E_{c,dyn}$ and Poisson coefficient $\nu_{c,dyn}$ using Eqs. (1) and (2).

$$E_{c,dyn} = \rho \cdot V_p^2 \cdot (1 - 2 \cdot \nu_{c,dyn}) \cdot \frac{1 + \nu_{c,dyn}}{1 - \nu_{c,dyn}} \qquad (1)$$

Table 1

Concrete dosages for normal (NSC) and high strength (HSC) concretes.

Material	NSC	HSC
CEM II/B-M (S-L) 42.5R	290 kg/m^3	–
CEM I 52.5R	–	450 kg/m^3
Silica fume	–	45 kg/m^3
w/c ratio	0.6	0.35
Fine aggregate (0–4 mm)	800 kg/m^3	865 kg/m^3
Coarse aggregate (5–11 mm)	1090 kg/m^3	865 kg/m^3
Water reducing agent type A	3.2 kg/m^3	–
Water reducing agent type B	–	4.95 kg/m^3
Water reducing agent type C	–	9.9 kg/m^3
PP fibres	1.5 kg/m^3	2.5 kg/m^3
Steel fibres*	20 kg/m^3	20 kg/m^3

[*] Only in hybrid fibre reinforced NSC and HSC.