Construction and Building Materials 165 (2018) 723–734

Contents lists available at ScienceDirect

Construction and Building Materials

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

Temperature effects on failure behavior of self-compacting high strength plain and fiber reinforced concrete

Hernán Xargay [a,b], Paula Folino [a,*], Luciano Sambataro [a], Guillermo Etse [a]

[a] Universidad de Buenos Aires, Facultad de Ingeniería (FIUBA), Laboratorio de Métodos Numéricos en Ingeniería (LMNI), Instituto INTECIN (UBA-CONICET), Buenos Aires, Argentina
[b] Comisión Nacional de Energía Atómica (CNEA), Departamento ICES, Buenos Aires, Argentina

HIGHLIGHTS

- Experimental results of Self-Compacting HSC after thermal treatment are reported in this paper.
- Plain and Fiber Reinforced Concrete with steel and polypropylene fibers are considered.
- Results of uniaxial compression, splitting tensile and three point bending tests are included.
- Experimental tests on samples exposed to 300 °C and 600 °C, in residual state, are included.
- A detailed analysis of failure features for different load scenarios is addressed.

ARTICLE INFO

Article history:
Received 22 September 2017
Received in revised form 14 December 2017
Accepted 20 December 2017

Keywords:
Self-compacting concrete
High-strength concrete
Fiber reinforced concrete
High temperature
Failure behavior
Volumetric strains

ABSTRACT

This work analyzes the effect of temperature on the mechanical behavior up to failure of self-compacting high strength concrete specimens when subjected to three different stress paths, corresponding to the uniaxial compression, splitting tensile and three point bending tests. The experiments were performed under residual conditions. In addition to the room temperature case, two different temperatures were considered in the preliminary heating phase in electrical furnace, namely, 300 °C and 600 °C. Both, plain concrete and fiber reinforced concrete were used, with a hybrid combination of steel and polypropylene fibers in the last case. Thirty days after the thermal treatment, concrete specimens were subjected to the mechanical tests up to failure. A relevant conclusion in this work is that the addition of fibers to the cementitious matrix improves concrete fracture energy release capacity not only under room temperature condition, but also under moderate and high temperature. This evidence which is valid for all different considered tests, is a consequence of the fiber contribution to the overall sample integrity much beyond peak. The work includes a detailed analysis of failure processes under the different considered load scenarios, the evolution of volumetric strains under uniaxial compression, SEM images of thermally treated plain concrete and the discussion of the degradation caused by temperature on the different mechanical properties.

1. Introduction

Self-compacting high strength concrete (SCHSC) is a material with outstanding performances both in early age and mature stages due to its inherent higher flow-ability and strength capability. The addition of steel fibers strongly contributes to improve the ductility during the post-cracking phase and to reduce the brittle failure mode potentials which is clearly the highest shortcomings of concrete materials. As a consequence, there is an increasing use of self-compacting, high-strength and fiber reinforced concrete in the construction industry, particularly related to high responsibility structures such as tunnels, tall buildings, nuclear power plants, bridges, etc.

One of the most critical action that concrete materials may suffer is temperature. This is a consequence of the severe changes in their chemical, physical and mechanical features which lead to dramatic degradations and loss of bearing capacities of the involved structures. The experimental evidence demonstrates that concrete main mechanical features such as the elastic properties are affected at temperatures above 100 °C. However, the most

* Corresponding author.
E-mail address: pfolino@fi.uba.ar (P. Folino).

https://doi.org/10.1016/j.conbuildmat.2017.12.137
0950-0618/

relevant chemical changes and degradations take place above 300 °C (See a.o. Khoury [1]).

In the literature, several works can be found focused on self-compacting concrete (SCC), high strength concrete (HSC) and fiber reinforced concrete (FRC), belonging all of them to the so-called high performance concretes (HPC). Regarding SCC, most of the related studies in the literature are mainly focused on fresh properties, mix proportioning and constitutive materials. Moreover, generally these works take into account moderate compressive strengths, up to 60 MPa. Regarding their conclusions and observations, no relevant one have been reported on the mechanical property differences between normal strength concrete (NSC) and SCC in hardened state, but only in fresh one [2]. Actually, and related to hardened state, only a difference in the initial elastic Young's modulus (E_0) was mentioned: it was found that E_0 can be up to 40% lower in NSC. When HSC of over 90 MPa is considered instead, the difference in E_0 reduces to less than 5% being the one corresponding to SCC the higher one [3]. Other works were advocated to study and optimize the microstructure properties of SCC, based on concrete composition [4].

Related to the mechanical behavior of HSC, some remarkable conclusions can be obtained from the available bibliography [5–9]: the initial elastic stiffness tends to increase with the concrete compressive strength, the ratio between tensile and compressive strengths decreases as the compressive strength increases and, the ductility in post-peak regime significantly decreases under increasing compressive strength.

The effects of adding steel fibers, or of a hybrid combination of fibers to the cement matrix have been extensively discussed in the literature. The addition of fibers clearly improves the ductility in concrete post-peak behavior, while it does not substantially contribute to increase the compressive strength (see a.o. [10–13,8,14–18]).

The incidence of temperature on the mechanical behavior of plain concrete, including the case of SCC, was extensively evaluated by many different researches. A detailed description and discussion on the bibliography related to experimental studies on NSC and HSC subjected to high temperature is provided in Ripani et al. [19]. Thereby is also detailed the subtantial changes on the main mechanical properties of concrete, including cohesion, stiffness, and strength, above the threshold temperature of 300 °C. Related to the temperature effects on SCC, we refer to the works by Persson [20], Persson [21] Liu et al. [22], Khazaal [23] and Aslani and Samali [24], while concerning temperature effects on HSC, with and without fibers, to the contributions by Phan and Carino [25], Noumowe [26], Giaccio and Zerbino [27], Kodur and Phan [28], Khaliq and Kodur [29] and Heap et al. [30]. It is generally accepted that the addition of polypropylene fibers reduces spalling potentials in concrete under the action of extreme high temperatures. The main reason is the modification of the mortar pore structure that takes place above 170 °C when the polypropylene fibers melt, which allows the relaxation of the pore pressure. It is also widely accept that the addition of steel fibers leads to an increase of tensile strength and post-peak ductility of concrete under both, room temperature and high temperature [28], while no improvement on the concrete spalling behavior was observed. Due to the involved complexity, scarce are the papers related to experimental tests on structural components in real scale, made of plain and reinforced concrete, and subjected to high temperature or fire, see a.o. Caner and Böncü [31], Yasuda et al. [32] and Yan et al. [33].

Despite the significant potentials of fiber reinforced concrete and moreover of fiber reinforced HPC in civil constructions, there is still a lack of a clear and deep understanding about the effects of high temperature on its mechanical behavior up to failure. This is even more critical in case of self-compacting, high-strength fiber reinforced concrete.

In this work, the results of an experimental campaign aimed at studying the high temperature effects on the mechanical behavior up to failure of SCHSC, with and without the addition of a hybrid combination of steel and polypropylene fibers is presented. The experimental investigations were developed at the Laboratory of Materials and Structures of the University of Buenos Aires (UBA), in collaboration with the Argentinean National Commission of Atomic Energy (CNEA). Three types of test set-ups were followed: uniaxial compression test (UC), splitting tensile test (ST) and three point bending test (TPB). The concrete samples were firstly subjected to a heating process followed by a cooling phase and only then were subjected to the different experimental set-ups. After a detailed description of the experimental campaign, the obtained results in terms of residual strengths, SEM images, overall response behavior in pre and post-peak regimes, and of the failure mechanism are extensively discussed. Finally, the conclusions are presented which provide a new light for more clearly understand the mechanical and failure features of fiber reinforced SCHSC under high temperature.

2. Experimental program

Plain and fiber reinforced concrete specimens were elaborated in the frame of the experimental campaign. For the latter, a hybrid combination of industrial steel macro-fibers and polypropylene micro-fibers was utilized. The following nomenclature will be used along the paper.

- SCHSC: plain self-compacting high-strength concrete
- SCFRHSC: self-compacting fiber reinforced high-strength concrete.

2.1. Materials and mix proportioning

Concrete mixture proportions are listed in Table 1. Target cylindrical 28 days compressive strength was 80 MPa. The mixture was firstly designed for the SCHSC and then, the same cement matrix was adopted for both SCHSC and SCFRHSC.

A combination of siliceous river and granitic crushed sands was used as fine aggregates, with fineness modulus of $FM = 1.77$ and $FM = 3.52$, respectively, while coarse aggregates consisted on granitic crushed stone with $FM = 5.69$. Same content of fine and coarse aggregates was adopted, distributed as follows: 18% of natural sand, 32% of crushed sand and 50% of coarse aggregates. The fineness modulus of the resulting mixture of aggregates was $FM = 4.29$, and its particle size distribution obtained from the sieve analysis can be observed in Fig. 1. Water absorption properties and density of aggregates are presented in Table 2. A nominal maximum coarse aggregate size $\Phi_{max} = 9.50$ mm was considered.

High strength cement -similar to Type III, ASTM- was employed, mixed with mineral and chemical admixtures. Blast furnace slag

Table 1
Concrete mixes.

		SCHSC	SCFRHSC
Cement (c)	[kg/m^3]	429.8	425.5
Blast furnace slag (s)	[kg/m^3]	183.9	182.4
Water (w)	[kg/m^3]	214.6	212.8
Fine Aggregates	[kg/m^3]	780.8	774.2
Coarse Aggregates	[kg/m^3]	783.7	777.1
Superplastizicer	[kg/m^3]	3.1	3.1
Steel macro-fibers	[kg/m^3]	0.0	60.0
Polypropylene micro-fibers	[kg/m^3]	0.0	0.90
Water/binder ratio (w/b)*	[–]	0.35	0.35

* binder b includes cement and slag contents ($b = c + s$)