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Residual mechanical characteristics and spalling resistance of fiber reinforced self-compacting concretes exposed to elevated temperatures

K.K. Sideris [*], P. Manita

Laboratory of Building Materials, Department of Civil Engineering, Democritus University of Thrace, PO Box 252, Xanthi 67100, Greece

HIGHLIGHTS

- ▶ We examined the performance at elevated temperatures of two normally vibrated concretes and six self compacted concretes.
- ▶ The strength classes of the mixtures were C25/30 and C30/37.
- ▶ Polypropylene fibres with a length of 6 and 12 mm were used to produce fibre reinforced SCC.
- ▶ The spalling tendency was increased for specimens of higher strength class irrespective of the mixture type (SCC or NVC).
- ▶ Both 6 m and 12 mm fibres had the same positive effect since all fiber reinforced SCC mixtures did not perform any spalling.

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ABSTRACT

The study presented in this paper concerns the effect that polypropylene fibres have on the properties of SCC of different strength classes when exposed to elevated temperatures. A total of six different SCC and two normal concrete mixtures were produced. The strength classes of the mixtures were C25/30 and C30/37.

The specimens produced were placed at the age of 120 days in an electrical furnace and the heat was applied with a rate of 5 °C/min. The tested temperatures were 300 °C and 600 °C. Once reached, the maximum temperature was maintained for 1 h. Then the specimens were naturally cooled down to ambient temperature in the furnace. The properties measured after heat exposures were the compressive strength, splitting tensile strength, water capillary absorption and ultrasonic pulse velocity.

It was noticed that, the spalling tendency was increased for specimens of higher strength class C30/37 irrespective of the mixture type (SCC or NVC). Such an explosive behavior was not observed when polypropylene fibers were added in the mixtures; however, in this case the residual mechanical characteristics of concretes were significantly reduced.

1. Introduction

Self-compacting Concrete (SCC) is a type of concrete developed through the last 15 years. It is widely used in different applications ranging from housing to large infrastructures, such as bridges and tunnels. SCC can spread into place under its own weight and fill restricted sections without the need of mechanical consolidation, improving this way the working environment, reducing the manpower need for casting and increasing the speed of construction and the quality of cast structures [1]. SCC is usually considered as a special type of high-performance concrete produced with higher amounts of filler materials and lower water/binder ratios as compared with other concretes. Thus porosity of SCC is usually reduced and the material is characterized by a high resistance to fluid diffusion. This fact is responsible for the superior durability usually observed on SCC [2–10]. On the other hand concrete mixtures of high diffusion resistance are usually considered as more vulnerable to fire attack [11,12]. Concrete has in general good fire resistance. Usually, its residual compressive strength is slightly reduced after fire exposure up to 300 °C [4,13–15] although some researchers reported that concrete's residual compressive strength decrease may be very important even for temperatures lower than 200 °C [16,17]. There is, however, a phenomenon that decreases the fire resistance of concrete which is named spallling. According to Khoury and Anderberg [18] spalling, in its most general form, is defined as the violent or non-violent breaking off of layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapidly rising temperatures as experienced in fires. There are four types of spalling: Explosive, surface, aggregate

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[*] Corresponding author. Tel.: +30 25410 79492.
E-mail address: kksider@civil.duth.gr (K.K. Sideris).

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and corner spalling. The most important of these is explosive spalling which occurs violently and results in serious loss of material.

The two most common explanations of the origin of spalling are internal pore pressure and thermal stress. Internal pore pressure caused by heating of water trapped in the concrete leads to tensile failure while restrained thermal expansion causes mechanical stresses which result in spalling [19]. According to Khoury and Anderberg [18], pore pressure spalling may apply by itself only for small unloaded specimens, as the specimens used in this research.

It is important to consider, when comparing different spalling theories, whether the theory deals with one-side exposure of concrete or exposure from more than one side. The mechanism of fire spalling probably depends on the type of exposure due to the fact that the stresses in the cross-section and escape routes for moisture in the pore system depend on the geometry of the elements. In multi sided exposure, where the moisture flow towards the centre of the cross-section it meets a similar flow from the opposite side, and thus the role of moisture in prompting spalling is amplified relative to that of one-sided exposure [20].

The main reason for concrete's spalling at elevated temperatures was considered to be the internal pore pressure buildup due to the vaporization of the free and chemically bound water [21]. In concrete mixtures with finer pore structure, such as HPC, this internal pressure is not released, thus leading to spalling of concrete surface [13,22–26]. Recent studies reported that pressure in itself is not the only factor impacting on the propensity of concretes to spall. Experimental results revealed that concrete spalling does not start because of pore pressure, but mostly due to internal cracking, that releases the pressure during fast heating [20,27].

Spalling behavior of certain concretes under fire conditions is a reason for inhibiting their use in structures where increased fire resistance is required for safety reasons, such as high rise buildings and tunnels. A lot of research has been carried out in order to model the spalling tendency of HPC and to propose some alternative solutions such as different mixture proportions or use of materials that provide a passive or active protection against spalling. Among the proposed solutions, the addition of polypropylene fibres seems to be an effective one [28–33]. It was reported [34] that polypropylene melts at 160–168 °C whereas HPC spalls when the air temperature ranges between 190 and 250 °C. Melting of polypropylene fibres creates an additional pathway for release of internal vapor stresses at higher temperatures. Eurocode 2 [35] recommends including more than 2 kg/m^3 of monofilament polypropylene fibres in HSC to reduce spalling but the size of the fibres is not specified. Many researchers reported that concrete spalling may be avoided when adding even smaller amount of fibres [32,36–38].

Recent research [39] has shown that for the same w/powder ratio, the porosity and pore size distribution of SCC are very similar to these of high performance concrete. This means that when self-compacting concrete is exposed to elevated temperatures, it might have the same risk (i.e. explosive spalling) as high performance concrete. But the phase composition of SCC and HPC is different as observed by SEM and DTA/TGA measurements. In the case of limestone as filler in SCC concrete, the limestone particles are almost not decomposed up to a temperature of 700 °C and the weight loss of SCC is much smaller than that of HPC before this temperature [40].

In this paper the mechanical characteristics of eight self-compacting and normally vibrated concretes subjected to elevated temperatures up to 600 °C were experimentally investigated. The initial effort was to produce self-compacting concretes with cement and water content as close as possible to the quantities used for the production of NVC mixtures of the same strength class. Polypropylene fibres with length of 6 mm and 12 mm were added in four SCC.

2. Experimental program

2.1. Materials

Eight different concrete mixtures – six self-compacting concretes (SCCs) and two normally vibrated concretes (NVCs) were produced. The concretes belong to two strength classes, C25/30 and C30/37, according to EN206-1 [41]. Concretes were prepared using two classes of Blended Portland Cement, i.e. CEM II A-M/42.5N and CEM II A-M/32.5N according to European standard EN 197-1 [42]. The initial effort was to keep the cement dosage and water content stable among SCC and NVC of the same strength class. The coarse aggregates consisted of crushed granite with maximum size of 16 mm. The fine aggregates used were natural river sand and crushed limestone sand. All SCC mixtures were produced with crushed limestone sand only in order to increase the content of fine materials. Limestone filler was also added in SCC mixtures. SCCs were prepared and tested in fresh condition according to the specifications of EFNARC [43]. Chemical composition of cements and limestone filler are presented in Table 1. Polypropylene fibres (PPFs) with a length of 6 mm and 12 mm at a dosage of 1 kg/m^3 were also used to produce fibre reinforced SCC of both strength classes. Physical and mechanical properties of PP fibres are presented in Table 2. A high range water reducing carboxylic ether polymer admixture was added at different dosages in order to achieve a slump of 190–200 mm in the case of NVCs, or to achieve self compactibility in the case of SCCs. The proportions as well as the properties of fresh mixtures are presented for all concretes prepared in Table 3.

2.2. Mechanical tests and type of specimens

The specimens prepared were 150 mm (edge) cubes and 150 × 300 mm cylinders. Six 150 mm cubes for each mixture were cured in a curing chamber (T = 20 °C, RH = 98%) and used for measuring the 28 days compressive strength and the water capillary absorption. All other specimens (150 mm cubes and 150 × 300 mm cylinders) were used for heat tests. They were initially cured for the first 14 days in the curing chamber. From this age onwards they were placed in the laboratory air environment (relative humidity = 50–60% and temperature = 20 ± 2 °C) where they remained until the test age.

2.3. Heat testing

At the age of 120 days specimens were placed in an electrical furnace with heat applied at a rate of 5 °C/min until the desired

Table 1
Chemical composition of cement and limestone filler.

	CEM II/A-M 42.5 N	CEM II/A-M 32.5 N	Limestone filler
SiO_2	22.71	23.85	17.79
Al_2O_3	6.06	5.22	1.57
Fe_2O_3	3.43	4.13	1.62
CaO	58.87	58.2	44.24
MgO	1.67	3.2	4.04
SO_3	2.65	3.3	3.02
K_2O	1.18	0.68	–
Na_2O	0.43	0.32	–
TiO_2	0.28	0.24	0.17
P_2O_5	0.09	0.06	0.02
SrO	0.03	0.03	–
Cr_2O_3	0.01	0.02	–
ZnO	0.01	0.01	–
SG (g/cm^3)	3.15	3.10	2.65
Blaine (cm^2/g)	4050	3760	2739