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Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: Spalling, transfer and mechanical properties

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HIGHLIGHTS

- Ten different concretes with polypropylene and/or steel fibres are exposed to ISO 834 fire.
- Plain concrete (f_c = 70 MPa) did not show spalling contrary to steel fibres (60 kg/m^3) concretes.
- Polypropylene fibres prevent any macroscopic damage of steel fibre concretes during ISO fire.
- SEM observation and MIP analysis show that steel fibres reduce the crack opening during heating.
- At 900 °C steel fibres have more favorable effect on the residual mechanical performances.

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ABSTRACT

In this study different mixtures of high strength concretes (70 MPa) were prepared with different natures of aggregates, moisture content, length and dosage of polypropylene fibres (PPF) and steel fibres (SF) and subjected to the standard ISO 834 fire. Concretes with 60 kg/m^3 of SF show spalling while plain concrete (without fibres) and concrete with 0.75 kg/m^3 of PPF and 60 kg/m^3 of SF did not spall. Microstructure, thermal, hydric and mechanical properties of concretes were investigated. PPF increase the porosity and permeability of concretes. Steel fibres control crack development which reduce the stress relaxation phenomenon and the size of new pores.

1. Introduction

High strength concrete (HSC) contributes to a high durability and strength of a structure, compared to normal strength concrete (NSC). But the HSC is more sensitive to spalling because of his high density matrix and small permeability. The fires in Channel tunnel (1996 and 2008) showed significant damages. High strength concrete linings were severely damaged by spalling and main reinforcement rebars were exposed [1]. Several researchers have shown that concrete thermal sensitivity could be the product of vapour pressure build-up mechanisms [2] and/or the restrained thermal dilatation mechanisms [1]. The first is connected with the increase of water vapour pressure in the porous concrete network during heating. When temperature increases in a concrete structure, water vapour pressure is continuously forming in a zone close to surface. The pressure gradient then guides vapour not only out of the concrete structure but also to the colder parts of the concrete, where the steam condensates. The accumulation of the steam in the colder layers generates the fully saturated regions also called “moisture clog”. This one restricts the ulterior movement of steam towards the colder region and when the moisture pressure exceeds the tensile strength of the concrete, piece of concrete presents spalling. The second is associated with dilatation/shrinkage gradients inside the concrete, which lead to high compressive

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stresses near the surface caused by the restriction of the colder inner part of the concrete. As a result, a tension stress is formed in the boundary between the heated surface and the colder inner part of the concrete element. According to this theory, biaxial thermal stresses parallel to the heated surface show concrete spalling. Furthermore, the parameters such as water content, porosity, permeability, type of aggregates, heating rate, etc. have an influence on concrete thermal stability [3].

Authors [4–7] have shown that the behaviour of concrete at high temperature can be improved by adding polypropylene fibres (with a ratio varying from 0.5 kg/m^3 –3 kg/m^3). The melting (160 °C–170 °C) and vaporization (350 °C) of polypropylene fibres generates not only new pores, but also creates microcracks at the tip of fibres connecting the already existing pores [8]. Ozawa and Morimoto [9] carried out permeability tests on high strength concretes (72 MPa) including 0.15% by volume of PPF. Results showed the residual permeability increased 12 times after heating the PPF concrete to 500 °C compared to the reference concrete. Thus the improvement of permeability increasing reduces the likelihood of explosive spalling [10].

According to Rivaz [11], steel fibres can significantly decrease spalling sensitivity and improve also the residual bending strength of the concrete by using the minimum SF amount of 25 kg/m^3. An important mechanical contribution was noticed by Lau and Anson [12] up to 1000 °C. Chen and Liu [13] showed that 47 kg/m^3 of SF only delay the time when spalling of HSC (80 MPa) occurs. Nevertheless the literature results are contradictory. The studies of [14,15] have presented the important spalling sensitivity of HSC (90–110 MPa) containing 100 kg/m^3 of SF. The heating rate varied from 0.1 to 10 °C/min.

The mix of the polypropylene and steel fibres can limit the spalling sensitivity and enhance the residual mechanical properties of the concrete simultaneously. Poon et al. [16] heated HSC with 2 kg/m^3 of PPF and 78 kg/m^3 of SF with 2.5 °C/min heating rate to 600 °C and 800 °C. It was noticed that the concrete containing a cocktail of fibres maintained about 45% of its compressive strength after the heating up to 600 °C, and after it was reduced to 23% at 800 °C. The modulus of elasticity was also improved by 5% comparing to reference concretes. Peng et al. [14] noticed a higher fracture energy of the two concretes containing a cocktail of fibres (0.6 kg/m^3 PPF × 40 kg/m^3 SF and 0.3 kg/m^3 PPF × 70 kg/m^3 SF) after the heating at 400 °C at 10 °C/min than before heating. This increase was significantly greater than that of concretes without fibres. They suggest that steel fibres may improve concrete resistance against the explosive spalling and have a complementary action to polypropylenes fibres.

All the presented results depend on experimental conditions and mix design parameters like fibre content, water/cement ratio, which explains the contradictory results from the literature. Thus, it is necessary to improve the fundamental understanding of the steel and polypropylene fibres action regarding the concrete behaviour at high temperature. The aim of this study is to relate physical concrete characteristics to the spalling resistance in order to achieve meaningful performance criteria regardless of mixture proportions.

This paper put at the disposal new experimental results to improve the understanding of the behaviour of high strength fibre concretes at high temperature. The study is realised in two stages. Firstly, this paper supplies new results on the spalling behaviour of ten formulations with the addition of PPF and/or SF submitted to two hours ISO 834 fire. Two types of aggregate were tested: calcareous and siliceous-calcareous aggregates. Secondly, three formulations from the previous study, showing opposite spalling behaviour, were chosen for the characterisation under low heating rate (0.5 °C/min): concrete without fibres (Cref(C)), SF concrete (CS 60) and concrete containing a cocktail of fibres (CPPS 0.75-60). The evolution of physical, thermal and microstructural parameters with temperature were investigated in order to explain the observed difference in spalling sensitivity. In addition, the impact of fibres on the post fire behaviour was studied by measuring of residual mechanical properties. Specimens were subjected to six heating-cooling cycles from the room temperature to 200 °C, 300 °C, 500 °C, 600 °C, 750 °C and 900 °C.

2. Experimental schedule

2.1. Materials

Portland cement CEM I 52.5 N was used in this study. Two types of aggregates were used: a limestone aggregate (C) composed of calcareous (87–91%) and eventually quartz (9–13%); and a siliceous-calcareous aggregate (X) composed of flints (70–75%), calcium carbonate (20–25%) and feldspaths (5%). The aggregates fractions were 0/4 mm (sand) and 4/10 mm (gravel). Monofilaments cylindrical polypropylene fibres of Duomix M12 and Krampeharex and high carbon galvanized steel fibres Dramix RC-80/30-CP with hooked ends were used. Table 1 specify the properties of PPF and SF.

The superplasticizer (polycarboxylate-based Cimfluid 2002) was used to adjust the workability of the concrete mixes. The superplasticizer density was 1.1 kg/m^3 with dry extract of 35%.

2.2. Mixture proportions designs

Four series of high strength concrete mixes were studied: concrete mixes without fibres (Cref(C) and Cref(X)), concrete mixes with polypropylene fibres (CPP 0.75 and CPP 1.5), concrete mixes with steel fibres (CS 60) and concretes mixes with polypropylene and steel fibres (CPPS 0.75-30, CPPS 1.5-30, CPPS 0.75-60 and CPPS 1.5-30(X)). The first number (0.75 or 1.5) indicates the mass (kg) of polypropylene fibres and the second number (30 or 60) indicates the mass (kg) of steel fibres. The letters (C) or (X) indicate a limestone or a siliceous-calcareous aggregates respectively. Two mixes with siliceous-calcareous aggregates were made: Cref(X) and CPPS 1.5-30 (X), the other mixes include only calcareous aggregates. All the mixes contain 475 kg/m^3 of cement with a water/cement (W/C) ratio of 0.38. The slump of concretes without fibres ranged from 160 to 210 mm and that of fibre concretes from 100 to 150 mm [17]. Concrete mix proportions are provided in Table 2.

In order to carry out ISO 834 fire tests, 132 cylindrical specimens 150 × 300 mm (diameter × height) (11–12 per mixture) were made. For low heating rate test, 40 cylindrical specimens and 16 prismatic specimens (100 × 100 × 400 mm) were made.

2.3. Curing conditions

Three curing conditions were investigated in order to test different moisture contents:

Mode 1: it is the "non-drying concrete" condition according to RILEM (200-HTC) [18]. Specimens were kept in their moulds the first seven days in order to avoid any water evaporation and, then in sealed plastic bags at 20 ± 2 °C with a damp cloth to maintain a humidity-saturated atmosphere, at least during 90 days, until the heating. The average moisture content by weight of 15 specimens was 4.7% with the standard deviation (SD) of 0.2% before heating.

Mode 2: it is the "drying concrete" condition according to RILEM (200-HTC). Specimens were kept in their moulds the first seven days and then in climate chamber at a temperature of 20 ± 2 °C with relative humidity of 50 ± 5% at least during 90 days. Only one concrete (Cref(C) «drying») was stored under this mode and