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High performance concrete under elevated temperatures

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HIGHLIGHTS

- Performance of HPCs under elevated temperatures.
- Use of PP fibers with air entraining admixture to decrease damage.
- Decreased spalling and increased residual strength.
- Complete disintegration of dense matrix under very high temperatures.
- Microstructural examination of cement paste–aggregate interface.

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ABSTRACT

In this study, PP fibers and air entraining admixture (AEA) were used together in an high performance concrete (HPC) mix so as to create interconnected reservoirs in concrete and to improve fire performance of HPC. For this reason, nine mixes of HPC incorporating blast furnace slag with 0.24 water-to-binder ratio and various PP and AEA contents were produced. Specimens were cast in two different sizes in order to see the effect of size and 18 series of specimens were obtained. These series subjected to elevated temperatures (300 °C, 600 °C and 900 °C) with a heating rate of 10 °C/min and after air cooling, residual mass and compressive strength of specimens were determined. The heated specimens were observed both at macro and micro scales to investigate the color changes, cracking and spalling of HPC at various temperatures. Also, thermogravimetric analyses were performed on powder samples from each nine mixes. Results showed that addition of AEA diminished the decrease in residual strength but this result was found to be irregular after 300 °C for thick specimens. The collaboration of AEA and PP fibers decreased the risk of spalling of HPC. Also, size of specimen was found to be important in deterioration of HPC.

1. Introduction

Concrete with increased strength and durability has been primarily used in special constructions such as high rise buildings, infrastructures and nuclear power plants since it became commercially available [1]. Thenceforth, some of these HPC structures exposed to severe fire conditions have exhibited poor performance. The main reason of this insufficiency of HPC at high temperatures is a result of the changes made in the composition of concrete mixes. Decrease in water to cementitious ratio, use of supplementary cementitious materials and plasticizers lead to impressive improvements such as strength, rheology of fresh concrete, impermeability and compactness. On the other hand, in most cases these changes may lead to a decrease in fire performance of HPC [2].

Lower water to cementitious materials ratio leads to lower porosity and this decreases permeability of concrete. With the increase in temperature, water in the pores of concrete evaporates and consequently pressure within the cement paste increases. Reduced permeability of HPC limits the diffusion of water vapor from the concrete pores and therefore pore pressure continues to increase until the internal stresses reach the tensile strength of concrete and eventually causes spalling [3].

Free water and moisture gradients influence the behavior of concrete at elevated temperatures and according to Hertz, they must be regarded as main reasons of spalling [4]. Meyer-Ottens treats that tensile stresses caused by steam in the closed pores of normal concrete can reach the tensile strength of concrete with more than 3% moisture by weight [5]. Hertz concluded traditional concrete with less than 3% moisture by weight will not spall and in the range of 3–4% moisture by weight has a risk of spalling, on the other hand, concrete with a dense microstructure (most of the HPC) may spall even when the moisture content is zero [4]. Due to the increased impermeability, only the crystal water arisen from

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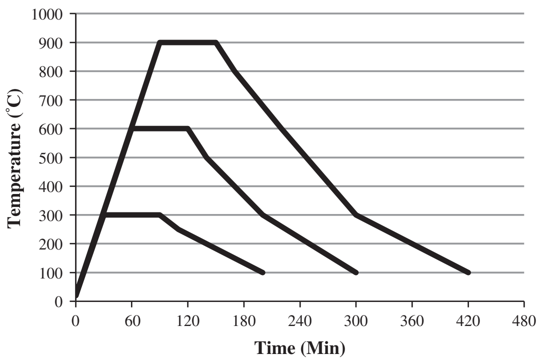

Fig. 1. Heating cycles.

dehydration of hydrates at high temperatures may cause the spalling of concrete.

Recently, many studies have focused on the contribution of different materials such as fibers and mineral admixtures to improve fire resistance of HPC [2,6,7]. Addition of PP fibers into HPC was found as an efficient way to avoid spalling of concrete. Because, PP fibers melt in concrete above 170 °C and leave micro channels in concrete and these channels form a network more permeable than cement matrix which contributes to outward migration of gases and water vapor and result in the reduction of pore pressure [7–10]. As a mineral admixture, inclusion of silica fume caused reduction in residual strength and spalling of concrete by densifiying microstructure [11,12]. On the contrary, addition of fly ash or slag showed better performance and also in some studies, strength gain observed at temperatures ranged from 200 °C to 300 °C because of tobermorite formation [13].

Furthermore, rapid heating of concrete is another factor which causes a high temperature difference between the deeper zone and the surface of a specimen and therefore explosive spalling may occur during heating [14]. Anderberg stated that during his

Table 1
Properties of cement, slag and polypropylene fibers.

Cement and slag			Polypropylene fibers	
Chemical composition	Cement (%)	Slag (%)		
SiO_2	20.17	38.37	Length (mm)	12
Al_2O_3	4.91	11.89	Diameter (μm)	32
Fe_2O_3	3.41	1.05	Specific gravity (g/cm3)	0.91
CaO	64.28	37.25	Specific surface (cm^2/g)	1340
MgO	1.18	8.13	Fiber number (fibers/kg)	110 Million
SO_3	2.84	0.38	Tensile strength (MPa)	250
Na_2O	0.13	0.28	Modulus of elasticity (GPa)	3.5
K_2O	0.96	1.28	Melting point (°C)	165
Loss on ignition	1.61	0		
Specific gravity (g/cm^3)	3.14	2.93		
Specific surface (cm^2/g)	3910	4320		

Table 2
Mix proportions.

Series	W/B	Cement (kg/m^3)	Slag (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	SP[a] (kg/m^3)	PP (dm^3/m^3)	AEA[b] (g/BA)[c]
F0A0	0.24	515	435	227	1175	15	0	0
F0A0.5	0.24	515	435	227	1175	15	0	5
F0A1	0.24	515	435	227	1175	15	0	10
F8A0	0.24	515	435	227	1175	15	8	0
F8A0.5	0.24	515	435	227	1175	15	8	5
F8A1	0.24	515	435	227	1175	15	8	10
F16A0	0.24	515	435	227	1175	15	16	0
F16A0.5	0.24	515	435	227	1175	15	16	5
F16A1	0.24	515	435	227	1175	15	16	10

[a] SP stands for superplasticizer.
[b] AEA stands for air entraining admixture.
[c] BA stands for binder amount of 1 m^3 concrete mixture in kilogram.

Table 3
The number of specimens spalled at different temperatures (out of 3 for each series).

Series	Maximum temperature			Series	Maximum temperature		
	300 °C	600 °C	900 °C		300 °C	600 °C	900 °C
T5F0A0	0	3	N.E.[a]	T10F0A0	0	3	N.E.
T5F0A0.5	0	3	N.E.	T10F0A0.5	0	3	N.E.
T5F0A1	0	3	N.E.	T10F0A1	0	3	N.E.
T5F8A0	0	2	2	T10F8A0	0	2	1
T5F8A0.5	0	0	0	T10F8A0.5	0	0	0
T5F8A1	0	0	0	T10F8A1	0	0	0
T5F16A0	0	0	0	T10F16A0	0	0	0
T5F16A0.5	0	0	0	T10F16A0.5	0	0	0
T5F16A1	0	0	0	T10F16A1	0	0	0

[a] N.E. – these specimens were not exposed to 900 °C since equivalent specimens spalled at 600 °C.