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Impact of melting and burnout of polypropylene fibre on air permeability and mechanical properties of high-strength concrete

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ABSTRACT

This study intends to investigate the impact of high temperature, melting and burnout of Polypropylene Fibre (PP fibre) on mechanical properties, pore size distribution and air permeability of high strength concrete. The specimens were high-strength concrete with 120 MPa strength produced with a water-binder ratio of 20%. To examine the effects of melting and burnout of the PP fibre, the experiment was conducted using two mixtures. One mixture contained 1.5 kg/m^3 of PP fibre, while the other did not contain any PP fibre. Heating temperatures were set to room temperature (RT), 120, 200, 300 and 400 °C, considering the temperatures for the melting and burnout of the PP fibre. After heating and cooling, compression tests were carried out on the concrete specimens to measure the modulus of elasticity and Poisson's ratio. Pore size distribution was measured using the fragments created by the compression tests. Air permeability was estimated by measuring the pore size distribution. It was found that melting and burnout of the fibre did not affect the compressive strength and modulus of elasticity but the Poisson's ratio of the specimens containing fibres increased at 400 °C. The effect of melting and burnout of fibre on pore volume and air permeability is quite small. If it is assumed that micro-cracks affected the air permeability, it is expected that high strength concrete with a large fibre content should create many micro-cracks at high temperature, leading to an increase of air permeability.

1. Introduction

In high-strength concrete, it is well known that including organic fibres in the mix is effective in reducing the occurrence of explosive spalling. Previous studies reported the heating test results of concrete with verious types of organic fibres, as well as the amount and length of fibres [1–4]. Explosive spalling was found to be reduced if 3 kg/m^3 of PP fibre was mixed into a loaded column specimen, and 1.5 kg/m^3 in small specimens without loading [1,2]. The effect of blended organic fibres (PP fibre and another fibre) has also been reported [3,4]. From the relationship between the fibre melting point and the residual weight ratio, they stated that the melting of fibres could reduce the degree of spalling due to an increase in the void fraction and a reduction of the pore pressure [3,4]. Mechanical properties of concrete, such as residual strength, tensile splitting strength, and flexural strength after heating may also change by including fibres [5,6]. The change may be related to the thermal stress for onset of spalling [7]. Related to the pore pressure rise theory [8], the results of measured water vapor pressure inside concrete at high temperatures have been reported as well as air permeability and pore size distribution in specimens after heating and cooling [9–11].

Especially, Kalifa established from experimental measurements that the maximum pore pressure is reduced as the PP fibre content is increased and that the air permeability of concrete after heating and cooling is increased as the PP fibre content is increased [11]. The maximum pore pressure inside the concrete decreased to half from 4 MPa to 2 MPa by including the PP fibre. However, it turned out that the increase of air permeability for the PP fibre specimen was about 25 times at temperatures in the range 200–300 °C and about 8 times at 400 °C.In addition, considering the melting temperature (171 °C) and burnout temperature (350 °C) of PP fibre, it is difficult to say that the increase in air permeability in the range of temperatures between 200 °C and 300 °C is due to the effect of the fibre melting. As the air permeability was measured using a specimen after heating and cooling, micro-cracks might have developed during cooling phase.

For this reason, this study intends to investigate the impact of the mixing, melting and burnout of fibre on compressive strength and other mechanical properties of concrete. Air permeability was also

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Nomenclature

d_{350}	Mean pore diameter in the range 0.003–350 μm (μm)
d_{20}	Mean pore diameter in the range 0.01–20 μm (μm)
Greek	
ε_{VC}	Strain in axial direction (dimensionless)
ε_{HC}	Strain in circumferential direction (dimensionless)
ϕ_{350}	Pore volume with pore diameters 0.003–350 μm (ml)
ϕ_{20}	Pore volume with pore diameters 0.01–20 μm (ml)
κ_{dry}	Air permeability in dry condition (m^2)
κ_{RT}	Air permeability at room temperature (m^2)
κ_T	Air permeability at high temperature, T (m^2)
υ	Poisson's ratio (dimensionless)

investigated and was calculated from the pore size distribution rather than by direct measurement.

2. Experimental method

2.1. Specimen, concrete mixing and curing conditions

For measuring the mechanical properties, cylindrical specimens (ϕ100×200 mm high) after heating and cooling were used. Mortar fragments were gathered from the concrete specimens after compression in order to measure the pore size distribution.

Table 1 shows the mix proportions of the concrete specimens. Two mix proportions, PP0 and PP1.5 were used. The mixes had the same water-binder ratio and sand/aggregate ratio etc, but differed in the PP fibre content with PP0 containing no fibres and PP1.5 containing 1.5 kg/m^3. The fibre length was 12–19 mm. The fibre content was selected based on previous heating experiments which demonstrated a reduction in explosive spalling [12]. The specimens were cured indoors. The age of specimens was 2 years for measuring the mechanical properties, and 2 or 4 years for measuring pore size distribution. The specimens used in measuring the pore size distribution were produced from the same mixture, but were tested at different times. As a result, the specimens for pore size distribution have two different material ages.

Table 2 shows the mechanical properties of the constituent materials. Table 3 shows the tensile strength and melting temperature of the PP fibre.

2.2. Heating conditions

The specimens were heated and then cooled to room temperature in the time patterns shown in Table 4. The heating temperature was selected considering the melting point and burnout temperature of the PP fibre. To measure mechanical properties, heating temperatures were set to three conditions; room temperature (non-heating, hereafter RT), 200 and 400 °C. To measure the pore size distribution, the heating temperatures were set to RT, 120, 200, 300 and 400 °C.

The heating temperature is shown in Fig. 1. The rate of temperature rise may affect the evolution of internal cracks due to the temperature gradient. Therefore, the rate was selected to be as low as possible at 0.5 °C/min. After reaching the target temperature, a constant temperature was maintained for the duration of 24 h so that a uniform temperature was achieved towards the center of the specimen. Finally the specimens were cooled in the furnace to room temperature.

2.3. Compression test for the measurement of mechanical properties

Using the cylinder specimens, the residual strength, modulus of elasticity and Poisson's ratio were measured in a uni-axial compression test. The strain gauges were attached to the specimen after heating and cooling as shown in Fig. 2. To measure Poisson's ratio, two strain gauges were attached to the side surface in both an axial direction and a circumferential direction. The length of the strain gauge was 60 mm.

From the measured stress-strain curve, the secant modulus of elasticity was calculated from the gradient between two points corresponding with 5% and 1/3 of the maximum stress. The modulus of elasticity was averaged between ε_{VC1} and ε_{VC2} which were measured by two strain gauges in the axial direction. Poisson's ratio was calculated by Eq. (1) using the measured value of four strain gauges attached in the axial direction ε_{VC1} and ε_{VC2} and the circumferential direction ε_{HC1} and ε_{HC2} at the axial stress corresponding with 5% and 1/3 of the maximum stress.

$$\upsilon = \frac{\frac{\varepsilon_{HC1}+\varepsilon_{HC2}}{2}}{\frac{\varepsilon_{VC1}+\varepsilon_{VC2}}{2}} \quad (1)$$

2.4. Methods for measuring pore size distribution and calculating air permeability

Pore size distribution was measured by mercury intrusion porosimetry. Measured pore size ranges between 0.003–350 μm. To calculate the air permeability, an empirical equation was used. Air permeability of dry concrete κ_{dry} can be correlated with a variable $\phi_{20}{d_{20}}^2$ as shown in Fig. 3, where ϕ_{20} and d_{20} are the parameters obtained from the pore size distribution 0.01–20 μm. The correlation was extended to include pore diameters up to 0.003–350 μm, ϕ_{350} and mean diameter d_{350} [13]. As a result, the following formula was applied:

$$\kappa_{dry} = 0.0683\phi_{350}{d_{350}}^2 \quad (2)$$

It should be noted that the formula is applicable to air permeability of absolute dry conditions at RT and that no effect of cracking is considered.

3. Results of compression tests

3.1. Stress-strain relationships

Stress-strain relationships have been reported for various concretes with and without PP fibres after heating and cooling or at high temperatures [16]. However, there are few studies measuring mechan-

Table 1
Mix proportions of cement mortar or concrete.

Specimens	W/B (wt%)	S/Agg. (vol%)	SF/B (wt)	Unit water (kg/m^3)	Mass per unit volume (kg/m^3)					
					Binder (B)	C	SF	S	G	PP
PP0	20	43	0.10	170	849	765	85	555	751	0
PP1.5	20	43	0.10	170	849	764	85	555	750	1.5