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Effect of fibre type and geometry on maximum pore pressures in fibre-reinforced high strength concrete at elevated temperatures

Mugume Rodgers Bangi *, Takashi Horiguchi

Hokkaido University, Graduate School of Engineering, Laboratory of Environmental Material, Engineering, N13-W8, Sapporo 060-8628, Hokkaido, Japan

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ABSTRACT

This paper presents results of an experimental and statistical study which investigates the effect of fibre type and geometry on the amount of maximum pore pressures measured at different depths in fibre-reinforced high strength concrete (HSC) exposed to elevated temperatures. Polypropylene, polyvinyl alcohol and steel fibres of varying lengths and diameters were used. Pore pressure measurements showed that addition of organic fibres regardless of the type significantly contributes to pore pressure reduction in heated HSC. Polypropylene fibres were more effective in mitigating maximum pore pressure development compared to polyvinyl alcohol fibres while steel fibres had a slightly low effect. Longer organic fibres of length 12 mm with smaller diameters of 18 μm showed better performance than shorter ones of length 6 mm with larger diameters of 28 and 40 μm. Based on experimental observations and using statistical analysis, a relationship to predict maximum pore pressures in heated concrete was developed.

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1. Introduction

Fire still remains one of the most serious risks for tunnels, buildings and other concrete structures especially those made of high strength concrete (HSC). Therefore, there is need for engineers to greatly take into consideration the risks associated with elevated temperatures when designing concrete structures, such as explosive spalling which has been observed by many researchers often resulting in serious deterioration of the concrete [1–4].

It has been widely shown that polypropylene (PP) fibres are very effective in mitigating spalling in HSC exposed to elevated temperatures [5–8]. Other researches have also shown that some other organic fibres such as polyvinyl alcohol (PVA) and nylon are also effective in mitigating spalling while others like cellulose [9] and polyethylene fibres [8] are not so effective. Also some natural fibres such as jute have been observed to be effective in preventing spalling [10].

The effect of fibre geometry on pressure rise and spalling mitigation in concrete exposed to elevated temperatures is also not clearly understood. It has been observed that for a given fibre content, finer PP fibres of length 12.5 mm were more effective in spalling protection during a fire compared thicker PP fibres of length 20 mm [7]. However, Young-Sun Heo et al. [9] observed that for a given fibre content, longer PP fibres of lengths 12, 19 and 30 mm were more effective in preventing spalling compared to shorter PP fibres of lengths 3 and 6 mm. A similar behavior was observed in PVA fibres where by 12 mm length fibres performed better than 6 mm length fibres in spalling prevention. Therefore, the relationship between spalling and fibre type and geometry is complex and not clearly understood. Different lengths and diameters of PP fibres have been used for spalling prevention in HSC, with the lengths ranging between 3 mm to 38 mm while the diameter ranges between 12 and 300 μm. The most common length and diameter of pp fibres used are 12 mm and 18 μm respectively [9,11–14]. In this study, 12 mm length PP fibres were used and compared with the shorter 6 mm lengths PP and PVA fibres. Also 18 μm diameter PP fibres and 16 μm diameter PVA fibres were used and compared with thicker diameter PP and PVA fibres.

The purpose of this study is to investigate the role played by fibre geometry i.e. length and diameter as well as fibre type in mitigating pressure rise in fibre-reinforced high strength concrete exposed to elevated temperatures. Also a relationship to predict relative maximum pressures in heated concrete has been developed. Pore pressures in different series of concretes containing different types and geometries of fibres have been measured at depths of 10, 30 and 50 mm from the heated surface. All fibre-reinforced concretes contained the same amount of organic fibre content of 0.9 kg/m^3 (0.1% by volume) and a heating rate of 10 °C/min was applied to all specimens.

2. Experimental procedure

2.1. Materials and mix proportions

Nine series of concretes were prepared using OPC (Ordinary Portland Cement) and crushed stone with the maximum nominal size of 13 mm. W/C of 0.5 was used for Normal Strength Concrete (NSC) while W/C of 0.3 was used for the remaining High Strength Concrete (HSC) series.

* Corresponding author. Tel.: +81 11 706 6180; fax: +81 11 706 6179.
E-mail addresses: mugume_2rb@eng.hokudai.ac.jp (M.R. Bangi), horiguti@eng.hokudai.ac.jp (T. Horiguchi).

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Some parameters of the mix proportion were kept constant for all series: water content of 170 kg/m^3 and sand to aggregate ratio (s/a) of 50%. Addition of polypropylene (PP) monofilament fibres, polyvinyl alcohol (PVA) fibres, and a combination of PP or PVA with steel fibres i.e. hybrid fibres was the main differentiation of the series. Two types of steel fibres were used in this experimental study and the fibre properties are as shown in Table 1. A polycarboxylate ether superplasticiser was used at a dosage of 0.9% of cement content to achieve the desired workability. Concrete mix proportions of all series cast are shown in Table 2. The convention for naming different series according to fibre type, fibre length and fibre diameter was used. For example HY PP 6–18 is explained as follows: HY means its hybrid concrete containing steel and organic fibres, PP 6–18 mean the organic fibre added is polypropylene (PP) with length of 6 mm and diameter of 18 μm (0.018 mm).

Cast specimens were 100 mm in diameter by 200 mm in height for strength tests and 175 mm in diameter by 100 mm in height for pore pressure tests. After casting, the specimens were covered with wet burlap under polyvinyl sheet. After 24 h, the specimens were demolded and cured under lime-saturated water at temperature of 20 ± 2 °C for 28 days for strength tests. Pore pressure specimens were also cured under the same conditions for about 3 months in order to achieve a homogenous moisture state. The initial moisture content of the pore pressure specimens was between 5% and 7% by mass.

2.2. Experimental set-up

All specimens tested during the pore pressure measurement experiment were 175 mm in diameter and 100 mm in height. Thermal load was applied on one face of the concrete specimen by means of a computer-controlled radiant heater placed 10 mm above it. The heater of power 500 watts exposes the whole surface of the specimen and generates maximum temperature of up to 600 °C. Ceramic fibre was used to heat-insulate the lateral faces of the specimens to ensure quasi-unidirectional thermal load upon it. For each series, two specimens were tested and if the results were different and inconsistent, then more specimens were tested in order to obtain consistent results.

A heating rate of 10 °C/min was applied in the experiment whereby the specimen was set under the heating device and temperature increased gradually at a rate of 10 °C/min until it reaches the maximum temperature of 600 °C. Then this maximum temperature was maintained for 3 h. Then the heated specimens were left to cool down naturally.

All specimens were instrumented with pressure gauges that allow pore pressure measurements. The gauges were made of a disk of porous sintered metal (Ø 12 mm × 4 mm) with evenly distributed pores of diameter 2 μm which was encapsulated into a metal cup that was brazed to a metal tube with inner diameter of 1.5 mm. The free end of the tube then stuck out at the rear face of the specimen. Three gauges were placed with in the central zone of the specimen at 10, 30 and 50 mm respectively, from the heated face. A porous sintered metal is used because it would be able to collect moisture vapour in an evenly manner due to its evenly distributed pores which lead to stable pressure measurements. K-type of thermocouples of diameter 0.65 mm having a covering material of glass fibre was attached on the sides of the gauges which were used to measure the temperature inside the heated specimens. An additional thermocouple was placed on the heated surface of the specimen to measure and monitor the build up of temperature. The set-up of the experimental test is shown in Fig. 1.

After casting, specimens were cured inside a lime-saturated curing tank for about 3 months in order for a homogenous moisture state to be achieved. Prior to heating, all gauges were filled with silicon oil having a flash point of 315 °C and a thermal expansion of 0.00095 cc/cc/°C. A syringe was used to fill the gauges with oil from the top of the gauge and then a very thin wire is used to continuously insert oil into the gauge until it is filled to ensure that no air bubbles were trapped inside the gauge. Then the filled gauges are carefully connected to the pressure transducers which are in turn connected to the data logger.

Table 1
Characteristics of fibres.

	Polypropylene	Polyvinyl alcohol	Steel (S13)	Steel (S30)
Diameter (mm)	0.018, 0.028	0.016, 0.040	0.16	0.60
Length (mm)	6, 12	6	13	30
Shape	Filament	Filament	Straight	Indent
Density (gr/cm^3)	0.9	1.3	7.8	7.8
T_{melt} (°C)	160–170	200–230	1370	1370
$T_{vapourize}$ (°C)	341	–	–	–

Table 2
Mixture proportions.

Series	W/C (%)	s/a (%)	Fibre vol. (%)			W	C	S	G	SPAE*1 (%×C)
			PP/PVA	(S30)	(S13)	(kg/m^3)				
Plain NSC	50	50	–	–	–	170	340	893	867	0.9
Plain HSC	30		–				567	795	771	
PP 6–18			0.1							
PP 12–18										
PP 12–28										
PVA 6–16										
PVA 6–40										
HY(PP 6–18)				0.4	0.1			788	764	
HY(PVA 6–40)				0.4	0.1			788	764	

SPAE*1: Super plasticiser and air entraining agent.

3. Results and discussions

3.1. General observations

Fresh and hardened properties of all the series of concrete measured at room temperature are shown in Table 3. It was observed that PP series had a higher air content compared with PVA and HY series. This is probably because of their poor bonding properties with concrete resulting in air voids. It was also generally observed that addition of organic fibres reduced the workability of concrete which may have been caused by intertwining of the fibres during mixing hence a reduction in slump. Furthermore, a reduction in compressive strength was observed in all fibre-reinforced HSC series compared with Plain HSC probably because of addition of fibres which led to more interfacial transition zones (ITZs) which in turn affected the compressive strength.

The thermal behavior of heated HSC is shown in Fig. 2. All other concrete series tested showed a similar behavior during heat exposure. It has been observed in past studies [5] that fibres had a low effect on the thermal properties of concrete and that the thermal diffusivity of concrete is mainly influenced by the aggregate type used [15]. Thus, since the same type of aggregates was used for all series in this experiment, a similar thermal behavior of all series confirms that aggregates are the main influence on thermal diffusivity of concrete.

Fig. 3 shows the pressure rise with time inside both Plain NSC and Plain HSC. The two series did not have any fibres added in their mixes. A higher maximum pore pressure of 5.0 MPa was observed in Plain HSC at a depth of 30 mm while a lower maximum pore pressure of 2.1 MPa was observed in Plain NSC at a depth of 10 mm. This confirmed the effect of permeability already discussed by Bentz [16] on pore development inside heated concrete. NSC which is less dense than HSC has a higher permeability and porosity due to its higher water cement ratio. This result in higher moisture vapour escape during heating hence better pore pressure relief and subsequently lower pore pressures being measured in NSC compared to HSC. Therefore, the transport properties of concrete significantly influence the build-up of pore pressure and consequently the likelihood of spalling in heated concrete. However, a

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