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Case study

Investigation on spalling resistance of ultra-high-strength concrete under rapid heating and rapid cooling

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ABSTRACT

Effects of the fiber type, dosage and length on the explosive spalling of ultra-high-strength concrete under rapid heating and rapid cooling were experimentally investigated. The mechanism of spalling resistance was examined by comprehensive thermal analysis, X-ray diffraction analysis, scanning electron microscopy and mercury porosimetry. The burst time is extended but the spalling is unaffected by the addition of steel fiber. The spalling resistance is improved with the addition of polypropylene (PP) fiber or PP and steel fibers. Ultra-high-strength concrete with 0.20% (vol.) PP fiber has excellent spalling resistance. The resistance to explosive spalling is enhanced with 12- or 19-mm-long PP fibers. PP fiber improves the spalling resistance mainly through the formation of tubular channels.

1. Introduction

With the expansion and densification of urban and rural construction, there are frequent building collapses due to the deterioration of building materials in fires. The fuel source of a fire affects the effect of the fire on surrounding concrete buildings. For example, the temperature of surrounding buildings rapidly rises above 1000 °C in the event of a tunnel or oil industry fire, while the temperature of surrounding buildings rapidly decreases to ambient temperature following an explosion involving a flammable and explosive gas, liquid or solid. In the case of such combustion or explosions, surrounding concrete buildings must have good resistance against rapid heating and rapid cooling. However, concrete, and especially high-strength concrete, readily undergoes explosive spalling in a fire or at high temperature [1]. In addition, with the rapid development of large and high engineering constructions in recent years, ultra-high strength concrete is more widely applied in the construction industry. There is thus a need for research on the spalling resistance of ultra-high-strength concrete under conditions of rapid heating and rapid cooling.

The explosive spalling phenomenon was put forward by Hertz [2] as early as 1984. There was serious spalling damage of 100-MPa concrete in the English–French Channel Tunnel in 1996 [3], which encouraged many countries and regions to carry out relevant research. Research on the high-temperature spalling mechanism of concrete [4,5] has considered the vapor pressure mechanism to be the primary cause. Kalifa [6] showed the feasibility of the vapor pressure mechanism by measuring the internal vapor pressure of concrete. On the basis of this mechanism, fusible organic fibers have been added to high-strength, high-performance concrete to improve the concrete's resistance to explosive spalling in a fire or at high temperature [7,8]. Doherty [9,10] studied the effects of the fiber type and length on spalling damage. In addition, Li [11,12]

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and Anson [13,14] respectively studied the effects of the aggregate and moisture content on spalling damage. Many scholars have investigated the effect of the heating speed of concrete. Chen [15] studied the spalling damage to 109-MPa concrete heated at a slow rate of 10–20 °C/min. Fellcetti [16] studied the spalling damage to 189-MPa concrete heated at the slow rate of 1 °C/min; and Durrani [17] explored the spalling damage to 89-MPa concrete heated rapidly at 30–90 °C/min. Studies of spalling damage have thus mainly focused on high-strength and high-performance concrete, while the heating rate has been relatively slow. However, there has been little research on the spalling damage to ultra-high-strength concrete, and even less under conditions of rapid heating and rapid cooling.

This paper investigates the mechanism of spalling resistance in ultra-high-strength concrete mixed with fibers of different types, dosages and lengths under the severe condition in which a specimen is put in a muffle furnace that has been preheated to 1000 °C for 10 min and then instantly placed in an environment at 25 °C.

2. Experimental

2.1. Raw materials

Ordinary Portland cement with a classification of 52.5R (density: 3150 kg/m^3, specific surface area: 448 m^2/kg) was sourced from Tangshan Jidong Cement Company Limited in Hebei province, China. Silica fume (density: 2230 kg/m^3, specific surface area: 13,050 m^2/kg) was incorporated as high-strength mineral admixtures, and was supplied by Bocheng Silicon Corporation of China Limited in Gansu province, China. Silica sand in the size range of 40–300 mesh and with density of 2.87 g/cm^3 was supplied by Dajin New Material Company Limited. Quartzose sand as fine aggregates was supplied by Sand Corporation, Beijing, China. The density and fineness modulus of the fine aggregates were 2710 kg/m^3 and 2.4, respectively. Straight steel fiber coated with copper was supplied by Yutian Zhitai Steel Fiber Manufacturing Company Limited in Hebei province, China. The density, length, diameter and compressive strength of the steel fiber were respectively 7800 kg/m^3, 15 mm, 0.22 mm and 2850 MPa. Polypropylene (PP) fiber with density of 910 kg/m^3, length of 6 mm, 9 mm, 12 mm and 19 mm and equivalent diameter of 26.13 μm was supplied by Rongnaier Engineering Materials Company Limited, Beijing, China. To obtain the desired workability of the fresh concrete, polycarboxylic water-reducing agent with solid content of 24% was supplied by Basf Chemical Building Materials (China) Company Limited, Beijing, China.

2.2. Mix proportions of concrete

Mix proportions of the concrete are given in Table 1.

2.3. Experimental methods

2.3.1. Specimen preparation

Raw materials were weighed accurately to obtain the proportions given in Table 1. Solid raw materials were first mixed well for 45 s with a mixer, and liquid was then added and the mixture stirred to ensure fluidity. The total mixing time was 6 min. In the case that steel fibers were added to the mixture, the fibers were mixed in slowly after a total mixing time of approximately 3 min. Slump flow was immediately measured without vibration. The prepared pastes with an appropriate slump flow of 260 ± 20 mm were then placed, one half at a time, into a mold with dimensions of 40 mm × 40 mm × 160 mm. Two groups of specimens were thus prepared, and three specimens from each group were used in all tests. The specimens were demolded after 24 h of mixing with water. All specimens were cured in a standard curing room (relative humidity exceeding 95%, temperature of 20 °C) for 28 days. Specimens were then divided into the two groups. One group of specimens were cured in a dry air room (relative humidity of 55%–65%, temperature of 20 °C) for 14 days, at which time the spalling resistance was measured. The other group of specimens was used in the strength comparison experiment.

2.3.2. Experimental method of high temperature

A muffle furnace was heated and maintained at 1000 °C for 30 min. A specimen at room temperature was put into the preheated furnace. After 10 min, the specimen was rapidly taken out and placed in a room having a temperature of about 25 °C. As the temperature of the specimen reached approximately 100 °C, the specimen was placed in a dryer so as to isolate the air, and the specimen remained in the dryer until the strength test. The change in the environment temperature for the specimen is shown in Fig. 1.

Table 1
Mix proportions of concrete.

Water/binder ratio	Silica sand/binder ratio	High strength admixture/binder ratio	PP fiber (V%)	Steer fiber (V%)	Aggregate (V%)
0.18	0.61	20	0.20	0	10

Note: 1) The length of PP fiber was 12 mm in this study unless otherwise stated. 2) The dosage of water-reducing agent was adjusted by slump flow vibration.

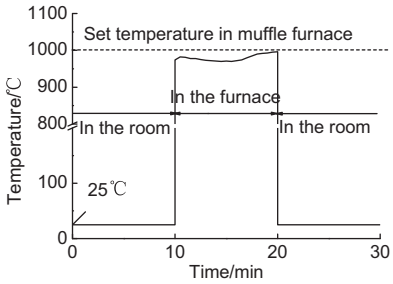

Fig. 1. Environment temperature change of specimen.

2.3.3. Methods of measuring mechanical properties

The compressive strength of concrete was measured in accordance with Method of Testing Cements—Determination of Strength (GB/T 17671-1999 (ISO 679:1989)).

2.3.4. Method of evaluating spalling damage

The degree of spalling damage was measured according to a visual evaluation, the quality loss rate and the compressive strength residual rate. Visual evaluation classified specimens as having "almost no damage", "slight damage", "moderate damage", "greater damage", "intensive damage" and "collapse", after the high-temperature test [18].

Average values for two specimens were taken for the quality loss rate and compressive strength residual rate, even if one of the specimens had experienced spalling. The quality loss rate of a specimen following exposure to a high temperature was defined as the ratio of the sum of areas of trilateral spalling debris larger than 50 mm, while the quality loss rate was taken as 100% when the specimen was scattered into small pieces without massive debris. The compressive strength was not measured when the specimen size was smaller than 40 mm × 40 mm × 40 mm.

2.3.5. Microscopic experimental method

Samples of the specimen center before exposure to high temperature and the surface (0–5 mm) after exposure to high temperature were selected for comprehensive thermal analyzer (TG/DTA), X-ray diffraction (XRD), scanning electron microscopy (SEM) and mercury porosimeter (MIP) tests. The specimens were carefully cut and ground into block samples with a diameter of about 3–5 mm. Hydration was terminated using alcohol, parts of block samples were ground into powder, and all specimens were placed into a dryer. Powder specimens were used in TG/DTA and XRD tests. Thermogravimetric analysis was conducted employing a NETZSCH STA449C comprehensive thermal analyzer. XRD structural analysis was carried out using a D8 Advance Diffractometer. Specimens in the form of a flat sheet were used in SEM tests. The microscopic structure of the hydration products of a specimen was observed with a Quanta 250 FEG field emission environmental scanning electron microscope. Particle specimens were used in MIP tests. The internal porosity of specimens was tested using a mercury porosimeter.

Table 2
Relationship between the fiber type and spalling damage.

Fiber types	No fiber	Steel fiber	PP fiber	PP and steel fiber
Morphology after heated				
	Scattered into small size	Scattered, larger residual	Tiny cracks surface, complete corners	Tiny cracks surface, complete corners
Visual evaluation	Collapse	Intensive damage	Slightly damage	Slightly damage
Mass loss rate(%)	100	93.3	7.8	8.1
Compressive strength before heated (MPa)	169	198	168	198
Compressive strength residual rate (%)	0	0	70.6	97.3

3. Results and discussion

3.1. Relationship between the fiber type and spalling damage to the concrete

The addition of fusible organic fibers to high-strength, high-performance concrete is one of the most economic and feasible measures for spalling protection, and PP fiber is considered to be the most effective organic fiber [19]. In addition, steel fiber is one of the main raw materials of ultra-high-strength concretes, such as reactive powder concrete, at present. Therefore, steel fiber, PP fiber and their mixture were added to ultra-high-strength concrete. The effect of the fiber type on concrete spalling damage was investigated. The main results of the tests are summarized in Table 2.

The fiber type greatly affected the spalling damage to ultra-high-strength concrete. Specimens mixed without any fiber or with steel fiber suffered almost complete spalling, indicating poorer spalling resistance at high temperature. The classifications of spalling damage were “collapse” and “intensive damage”. Meanwhile, specimens mixed with PP fiber or PP and steel fibers remained intact and had a compressive strength residual rate exceeding 70% and a mass loss rate within 8%. This was mainly due to the ability of the PP fiber to relieve vapor pressure and the good heat conduction of the steel fiber, which allow the rapid distribution of the internal and external heat of concrete and reduce the internal stress produced by the temperature gradient. These behaviors help maintain performance under the condition of high temperature.

From the results shown in Table 2, it can be reasonably concluded that PP fiber improves the spalling resistance of concrete and steel fiber delays the spalling time. However, the steel fiber does not obviously ease the spalling phenomenon. These results are in agreement with conclusions drawn by Sideris [20], who found that steel fiber has the same effect on the spalling resistance to high temperature in the cases of high-performance concrete and ultra-high-strength concrete.

3.2. Relationship between the PP fiber dosage and concrete spalling damage

Table 3 presents the relationship between the PP fiber dosage and the spalling damage of ultra-high-strength concrete. The compressive strengths of the specimens did not change appreciably with an increase in the PP fiber dosage before heating. The concrete without PP fiber underwent spalling and scattered into small particles in a high-temperature furnace. There was a discontinuous or continuous spalling sound for the concrete with 0.10% PP fiber and one of the specimens spalled into pieces in the furnace. As the dosage of PP fiber increased to 0.15%, there was an occasional spalling sound and one of the specimens suddenly spalled into pieces after being taken out of the furnace. There was no spalling sound for the concrete with at least 0.20% PP fiber. This illustrates that ultra-high-strength concrete has appreciable spalling resistance to high temperature when the dosage of PP fiber in the concrete reaches 0.20%.

Kimura [21] found that a dosage of 0.15% 12-mm-long PP fibers inhibit spalling damage to 68-MPa high-strength concrete, while Munehiro [22] found that a PP fiber dosage exceeding 0.20% can inhibit spalling damage to 147-MPa ultra-high-strength concrete. The present study found that a PP fiber dosage of 0.20% had an appreciable effect. Comparison of the present results with the previous research results shows that the inhibition of spalling damage by PP fiber is related to the strength of the concrete and the high-temperature system.

Table 3
Relationship between the PP fiber dosage and spalling damage.

PP fiber dosage (%)	0	0.10	0.15	0.20	0.25	0.30
Morphology after heated						
	Scattered into small size	One spalling into pieces in furnace	One spalling outside the furnace	Tiny cracks, complete corners	Tiny cracks, complete corners	Tiny cracks, complete corners
Visual evaluation	Collapse	Intensive damage	Intensive damage	Slightly damage	Slightly damage	Slightly damage
Mass loss rate (%)	100	20.5	18.1	7.8	7.7	7.4
Compressive strength before heated (MPa)	169	163	167	168	163	160
Compressive strength residual rate(%)	0	34.9	35.1	70.6	72.7	73.3

Table 4
Relationship between the PP fiber length and spalling damage.

PP fiber length(mm)	6	9	12	19
Morphology after heated				
	Spalling into pieces	Spalling into pieces	Tiny cracks, complete corners	Tiny cracks, complete corners
Visual evaluation	Intensive damage	Collapse	Slightly damage	Slightly damage
Mass loss rate(%)	92.7	100	7.8	7.8
Compressive strength before heated (MPa)	165	170	168	171
Compressive strength residual rate (%)	0	0	70.6	93.7

3.3. Relationship between the PP fiber length and concrete spalling damage

To evaluate the relationship between the PP fiber length and spalling damage of ultra-high-strength concrete, the spalling resistances of ultra-high-strength concretes with different lengths of PP fiber were determined. The test results are given in Table 4. The compressive strengths of the concretes did not appreciably change with an increase in PP fiber length before heating. However, after heating, the PP fiber length strongly affected the spalling resistance of the concretes. There was spalling damage to concretes with PP fiber lengths of 6 and 9 mm. The spalling resistance to high temperature of the concretes with PP fiber lengths of 12 and 19 mm was excellent and the compressive strength residual rate increased with the PP fiber length. These results are in accordance with results obtained by Bentz [23] for high-performance concrete, which indicated that the spalling resistance of a long fiber is more effective than that of a short fiber. In the present experimental range, the addition of PP fiber with length of 12 mm to concrete effectively inhibits the spalling damage to specimens.

3.4. Mechanism analysis

3.4.1. TG/DTA analysis

Fig. 2 shows the TG/DTA curve of an ultra-high-strength concrete specimen. There is one obvious endothermic peak and two unobvious endothermic peaks in the DTA curve of the ultra-high-strength concrete specimen. The obvious endothermic peak at around 90–200 °C is attributed to the dehydration of the hydrated calcium silicate and hydrated calcium sulfoaluminate followed by the evaporation of water in capillary pores. At the same time, PP fiber that melts within 165–173 °C is present only in small volumes, and its peak is not enough to affect the DTA curve. The endothermic peak located at 420–450 °C originates from the decomposition of $Ca(OH)_2$. The endothermic peak at around 650–750 °C is due to the decomposition of $CaCO_3$ crystals. However, Li [24] found a significant weight loss for a general concrete specimen with a water/binder ratio of 0.25, which is caused by the decomposition of $Ca(OH)_2$ with weight loss of 1.83%. Nevertheless, the weight loss is only 0.32%, as shown in Fig. 2. This weight loss is mainly due to the pozzolanic reaction between the large amount of active SiO_2 in the high-strength admixture and $Ca(OH)_2$ generated by cement hydration, forming the C-S-H gel and reducing $Ca(OH)_2$ and $CaCO_3$.

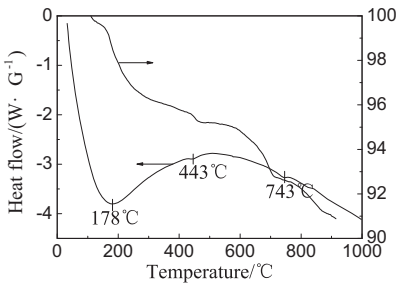

Fig. 2. TG/DTA curves of specimens.

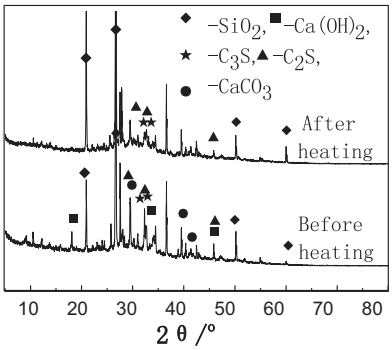

Fig. 3. XRD curves of specimens.

3.4.2. XRD analysis

Fig. 3 shows the XRD patterns of ultra-high-strength concrete before and after heating. The peaks of SiO_2, C_3S, C_2S, $Ca(OH)_2$ and $CaCO_3$ are observed in the concrete before heating. However, the peaks of $Ca(OH)_2$ and $CaCO_3$ are weak, in accordance with the TG/DTA curve. After heating, the peak of $Ca(OH)_2$ in the specimen almost disappears, suggesting the decomposition of $Ca(OH)_2$ after heating.

3.4.3. SEM analysis

Fig. 4(a) shows SEM images of concrete with 0.20% PP fiber before heating. The particles and clusters of C-S-H gel, which is the main product of hydration, are observed and the C-S-H gel is cemented together. No particles of $Ca(OH)_2$ can be observed. There are no obvious pores between the cement and aggregate and the matrix and interface structure are compact. Before heating, the hydration products are firmly attached to PP fiber, as shown in Fig. 4(b). This illustrates that the PP fiber and hydration products have a good bonding effect. Beyond a high temperature of 1000 °C, a large number of tubular channels that are formed by the fusion volatilization of PP fiber and a certain number of micro cracks that are formed by the dehydration of hydrated calcium silicate gel appear in the interior of the matrix, as shown in Fig. 4(c) and (d).

The specimen has high compressive strength of 168 MPa in terms of its macro performance. However, the concrete readily undergoes spalling damage under heating owing to its ultra-high strength and ultra-compactness. The concrete without PP fiber undergoes spalling into small pieces (shown in Table 2). However, the concrete with 0.20% PP fiber has no spalling damage after heating at 1000 °C. This is because both tubular channels and micro-cracks promote the extension of water vapor channels to an external space, thus relieving the internal vapor pressure and improving the spalling resistance.

3.4.4. MIP analysis

Fig. 5 shows the pore size distribution of a specimen before and after heating. Before heating, there are two significant characteristic peaks at 17 and 5 nm, the most probable pore size is small, and the total pore volume is 0.0391 cm^3/g. After heating, the most probable pore size increases to 55 nm, while at the same time, a small number of large pores of 16 and 68 μm appear, and the total pore volume increases to 0.0695 cm^3/g. The 16-μm pores may be formed by 20-μm PP fibers, which have an equivalent diameter of 26.13 μm when melted (see Fig. 4(d)). A high temperature can therefore increase the total porosity, destroy hole grading, generate water vapor channels, relieve internal vapor pressure, and prevent concrete from spalling. This conclusion was confirmed by SEM.

The results of TG/DTA, XRD, SEM and MIP analyses reveal that, before heating, the hydration products of concrete are cemented together to form particle clusters with good cementation between PP fiber and cement. The overall structure is

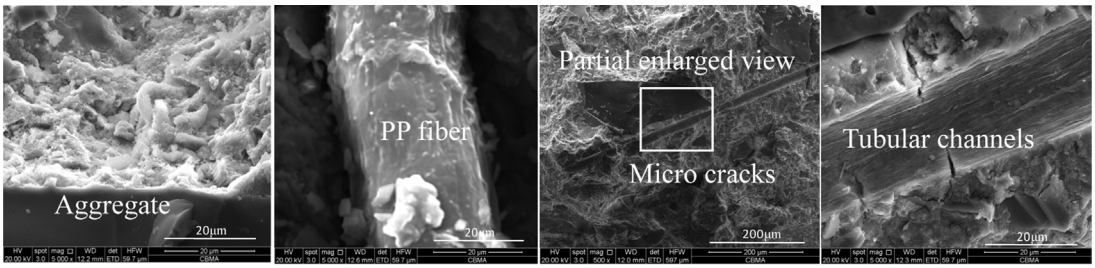

Fig. 4. SEM images of concrete before and after heating.

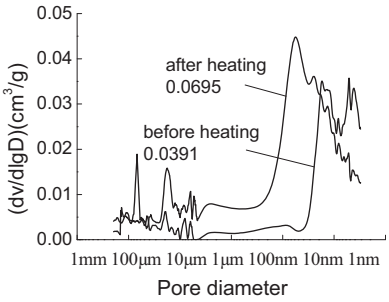

Fig. 5. Pore size distribution curves of specimen before and after heating.

compact with low total porosity, which leads to explosive spalling. After heating, however, almost all the PP fiber melts from the external to the internal of samples and forms tubular channels. Additionally, the dehydration of hydrated calcium silicate gel increases the capillary porosity. Both behaviors relieve internal vapor pressure and prevent specimen spalling.

A certain amount of PP fiber is needed in concrete to improve spalling resistance. When the PP fiber dosage is 0.10%, explosive spalling occurs in the high-temperature furnace, which indicates that the tubular channels formed by the melting of PP fiber are insufficient to advance water vapor channels from the internal to external space, and the internal vapor pressure of the concrete is not relieved. When the PP fiber dosage reaches 0.15%, tubular channels from the external to the internal grow, resulting in the internal vapor pressure of the concrete being lower than the concrete's strength, and specimens therefore do not spall in the high-temperature furnace. Once placed in an environment at room temperature, the concrete contracts sharply under the dual effects of the internal vapor pressure and external contraction and explosive spalling occurs. When the PP fiber dosage reaches 0.20%, the internal vapor pressure of the concrete is relieved, and the explosive spalling phenomenon does not occur.

The PP fiber dosage has an important effect on the spalling resistance of concrete, and the length of the fiber has a certain impact. In the cases of 6- and 9-mm fiber samples, tubular channels from the external to internal formed by the melting of PP fiber are not enough, water vapor pressure cannot be relieved, and spalling thus occurs in the high-temperature furnace. Only when the PP fiber length reaches 12 mm is the internal vapor pressure relieved and explosive spalling prevented.

4. Conclusions

The effects of the type, dosage and length of fibers on the spalling resistance of ultra-high-strength concrete with highest compressive strength of 198 MPa under the condition of rapid heating and rapid cooling were demonstrated. The mechanism of the spalling resistance of ultra-high-strength concrete mixed with PP fiber was discussed. The main conclusions drawn from this study are as follows.

(1) Steel fiber can delay the spalling time but does not obviously ease the spalling phenomenon. PP fiber can improve the spalling resistance of concrete.
(2) The PP fiber dosage affects the spalling resistance of concrete. The degree of explosive spalling is related to the PP fiber dosage. The spalling resistance is poor when the dosage is lower than 0.20%. Meanwhile, the spalling resistance is best for a PP fiber dosage of 0.20% or more, in which case the compressive strength residual rate exceeds 70% and the mass loss rate is within 8%.
(3) The PP fiber length affects the spalling resistance of the concrete specimen. Specimens with PP fiber lengths of 6 and 9 mm undergo appreciable explosive spalling, while specimens with PP fiber length of 12 and 19 mm have appreciable spalling resistance at high temperature. The compressive strength residual rates are more than 70% and mass loss rates are within 8%.
(4) PP fiber improves the spalling resistance of ultra-high-strength concrete mainly through the formation of tubular channels from the external to internal via the melting of PP fiber. Additionally, there is an increase in capillary porosity due to the dehydration of hydration products. The combination of these behaviors relieves internal vapor pressure and prevents specimen spalling.

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References

[1] S.Y.N. Chan, G.F. Peng, M. Anson, Comparison between high-strength concrete and normal-strength concrete subjected to high temperature, Mater. Struct. 29 (1) (1996) 616–619.
[2] C.J. Kirkaland, The fire in the channel tunnel, Tunneling and Underground Space Technology 17 (2) (2002) 129–132.
[3] Chen Qiang, The influence of high temperature on explosive spalling behavior and mechanical properties of reactive powder concrete, Ph.D. Thesis, Beijing Jiaotong University at China, 2010.
[4] Z.P. Baoant, Analysis of pore pressure, thermal stresses and fracture in rapidly heated concrete, Proceedings of International Workshop on Fire Performance of High-Strength Concrete (NIST Special Publication 919), Gaithersburg: NIST, 1997, pp. 155–164.
[5] T.Z. Harmarthy, Effect of Moisture on the Fire Endurance of Building Elements, ASTM publication STP, Philadelphia, 1965, pp. 74–95.
[6] P. Kalifa, F.D. Menneteau, D. Quenard, Spalling and pore pressure in HPC at high temperature, Cem. Concr. Res. 30 (2000) 1–13.
[7] S. Ishikawa, Explosion preventive structure of high-strength concrete method. JP2002-206295.
[8] L. Sarvaranta, E. Mikkola, Fibre motar composites under fire conditions: effects of ageing and moisture content of specimens, Mater. Struct. 27 (1994) 532–538.
[9] P. Doherty, F. Ali, A. Nadjai, et al., Explosive spalling of concrete columns with steel and polypropylene fibres subjected to severe fire, J. Struct. Fire Eng. 3 (1) (2012) 95–104.
[10] A. Bilodeau, V.K.R. Kodur, G.C. Hoff, Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire, Cem. Concr. Compos. 26 (2) (2004) 163–174.
[11] Li Jincheng, Research progress of HSC/HPC high temperature cracking mechanism, Shanxi Archit. 37 (25) (2011) 108–111.
[12] Y. Andrtberg, Spalling phenomena of HPC and OC, Proceedings of International Workshop on Fire Performance of High-Strength Concrete (NIST Special Publication 919), Gaithersburg: NIST, 1997, pp. 69–73.
[13] M. Anson, Fire behavior of high-performance concrete made with silica fume at various moisture contents, ACI Mater. J. 96 (3) (1999) 405–409.
[14] Bian Songhua, Peng Gaifei, Zhao Zhangli, Yi Quanxin, Effects of moisture contents and fibers on properties of high performance concrete at high temperatures, J. Build. Mater. 8 (3) (2005) 321–327.
[15] R. Felicetti, P.G. Gambarova, M.P.N. Sora, G.A. Khoury, Mechanical behaviour of HPC and UHPC indirect tension at high temperature and after cooling. 5th RILEM Symp. Fibre-Reinforced Concretes (FRC) – BEFIB (2000) 749–760.
[16] A.J. Durrani, C. Castillo, Effect of transient high temperature on high strength concrete, ACI Mater. J. 35 (1) (1990) 47–53.
[17] H. Momose, F. Sakuramoto, K. Yanagita, Experimental Study on Fire Resistance of Ultra-high Strength Concrete with Design Strength of 150N/mm^2 Mixed with Polypropylene Fiber, 25(1, Japan Concrete Institute, 2003, pp. 995–1000.
[18] K. Pierre, C. Gregoire, G. Christophe, High-temperature behavior of HPC with polypropylene fibres from spalling to microstructure, Cem. Concr. Res. 31 (2001) 1487–1499.
[19] L. Sarvaranta, E. Mikkola, Fibre motar composites under fire conditions: effects of ageing and moisture content of specimens, Mater. Struct. 27 (1994) 532–538.
[20] K.K. Sideris, P. Manita, A. Papageorgiou, E. Chaniotakis, Mechanical characteristic of high performance fiber reinforced concretes at elevated temperatures, ACI Special Publication 212-60 (2006) 973–988.
[21] K. Kimura, M. Ozawa, K. Rokugo, H. Morimoto, Relationship between internal vapor pressure and explosive spalling of fiber reinforced concrete, Proceedings of the Japan Concrete Institute 30 (1) (2008) 339–344.
[22] U. Munehiro, K. Shigemi, Study on Fire Resistance of Reinforced Concrete Columns with Ultra High Strength Material, 32, Technical Research Institute, Toda Corp., 2006, pp. 1–13.
[23] D.P. Bentz, Fibers: percolation, and spalling of high performance concrete, ACI Mater. J. 97 (3) (2000) 351–359.
[24] Li Qinghai, Research on the thermal expansion performance of cement-based materials, Ph.D. Thesis, China Building Materials Academy at China, 2007.