REZISTENȚA LA COMPRESIUNE ŞI ÎNCOVOIERE A BETOANELOR CU CONȚINUT DE PULBERI REACTIVE ŞI FIBRE HIBRIDE LA TEMPERATURI ÎNALTE

COMPRESSIVE AND TENSILE STRENGTHS OF REACTIVE POWDER CONCRETE WITH HYBRID FIBRES AT ELEVATED TEMPERATURES

WENZHONG ZHENG, BAIFU LUO*, SHUANG LU

School of Civil Engineering, Harbin Institute of Technology, Harbin, China

This paper presents the effect of temperature on mechanical properties of reactive powder concrete (RPC) at elevated temperatures. The influences of temperatures, polypropylene (PP) fibre and steel fibre content, hold time, dimension of specimens and explosive spalling were investigated. The microstructure of RPC was identified by scanning electron microscope (SEM). The experimental results show that adding 2% steel fibres and 0.2% PP fibres can prevent explosive spalling and significantly increase compressive and tensile strengths of RPC. PP fibre and steel fibre content played an important role in failures modes, explosive spalling, compressive strength and tensile strength. Cube compressive strength decreases at 100°C, increases between 200 and 500°C, and decreases beyond 600°C. Tensile strength decreases at 200°C, increases from 200 to 300°C, and decreases beyond 300°C. Pores and small channels created are beneficial for mitigating the explosive spalling at elevated temperatures.

Keywords: *elevated temperature, reactive powder concrete, mechanical properties, explosive spalling, hold time*

1. Introduction

Reactive powder concrete (RPC) is a kind of ultra-high strength, high toughness, high durability, good dimensional stability of new materials [1]. Compressive strength of RPC can be 200~800 MPa and its ductility was greater than 250 times that of conventional concrete [2,3]. RPC of superior performances has been applied widely in the civil, petroleum, nuclear power, municipal, marine and military facilities and other projects [4,5]. However, it is probable that the lower permeability of RPC prevents water vapor from escaping, causing considerable internal vapor pressure that often results in spalling. Therefore, a decrease in strength and an increase in the risk of spalling of RPC at elevated temperatures should be investigated.

Kalifa et al. [6] reported that PP fibres reduced explosive spalling at dosages as low as 0.9 kg/m^3. Polypropylene (PP) fibres melted at approximately 160–170°C; pores and small channels due to the melting PP fibres were beneficial for evaporation of water vapor to reduce the risk of explosive spalling [7]. Pressure relief inside fibre-reinforced concrete occurred at or immediately after melting of the PP fibres, and PP fibres significantly contributed towards pore pressure reduction in heated high strength concrete (HSC) [8]. For the mechanical properties of concrete with PP fibres, the experimental results are in conflict due to different experimental conditions, the cure conditions of the specimens and the heating rate [9]. The addition of 0.8~2 kg/m^3 PP fibres resulted in a decrease in compressive strength, flexural strength, splitting tensile strength and modulus of elasticity for concrete [7,9,10]. The addition of 2% of PP fibres (by mass) to high performance concrete did not have significant effect on the compressive and splitting tensile strength of concrete [11,12]. However, Ali Behnood [13] reported the addition of 2 kg/m^3 PP fibres can significantly promote the residual mechanical properties of HSC after high temperatures. Other studies showed that PP fibres improved the residual strength of concrete [14,15]. C.S. Poon [16] attributed that the addition of 0.22% PP fibres slightly improved the relative residual comressive strength of ordinary Portland cement (OPC) concretes below 600 °C, whereas OPC and PP fibres concretes had approximately the consistent relative compressive strengths at 800°C.

HSC with 1% steel fibres had a higher residual compressive strength, flexural strength and elastic modulus than normal strength concrete (NSC); steel fibres can inhibit the spread of cracking [17]. Concrete with steel fibres had also a higher compressive strength at elevated temperatures than ordinary concrete without steel fibres. Steel fibres could increase the ultimate strain of concrete and improve its ductility [18]. The residual compressive strength of RPC with 1%–3%

* Autor corespondent/*Corresponding author,*
e-mail: zhengwenzhong@hit.edu.cn (Wenzhong Zheng), luobaifu@gmail.com (Baifu Luo).

steel fibres content increases after heating at temperatures ranging from 200 to 300 °C, but significantly decreases when temperatures exceed 300 °C [19]. Adding hybrid fibers in HSC (both steel and polypropylene fibers) had also been recommended to optimize the solutions for spalling mitigation [20,21]. However, experimental results regarding the influence of temperature on RPC (superior strength concrete) are limited.

The aim of this paper is initiated to determine relationships between compressive strength with temperature, fibre content, dimension of specimens and hold time. Tensile strength is also investigated as temperature and fibre content vary. Mechanical properties of RPC including compressive and tensile strength are measured at 20, 100, 200, 300, 400, 500, 600, 700 and 800 °C. The compressive strengths with a hold time of 0, 1 and 3 h are measured at 200, 400, 600 and 800 °C. Explosive spalling and failure modes of RPC were taken into consideration. Furthermore, differences in compressive and tensile strengths of NSC, HSC and RPC are compared. Pores changes in microstructure from 20 to 800 °C reveal mechanical properties from a macro perspective.

2. Experimental detail

2.1. Materials and mixing

Cement: In this study, Chinese Standard P.O 42.5N Portland cement was used. Silica fume (SF): SiO_2 content reached 94.5% and specific surface area was 20780 m^2/kg; Slag: Slag used was locally available 'Jing Gang' slag and specific surface area was 4750 cm^2/g. Quartz: The fine sand were with maximum nominal sizes of 0.2 mm and coarse sand were with maximum nominal sizes of 0.35 mm, which were mixed in a ratio of 1:1. Superplasticizer (SP): Polycarboxylate was used as a superplasticizer in RPC mixes. Steel fibres: Grade 60 brass-coated steel fibres of diameters (0.22 mm) were used in preparing specimens. Polypropylene (PP) fibre: Fibre length was 18~20 mm, the average diameter was 45 μm, density was 0.91 kg/cm^3 and melting temperature was 165 °C. The proportion of steel fibres (or PP fibres) added was reported to concrete volume. The mix proportions are summarized in Table 1.

2.2. Sample preparation for strength tests

A total number of 87 groups of three specimens (36 groups of cube specimens, 36 groups of dumbbell-shaped specimens and 15 groups of prism specimens) were prepared in research. As the test results reproduced well represents the average results of three tests. Cube (70.7 × 70.7 × 70.7 mm), prism (70.7 × 70.7 × 220 mm) and dumbbell-shaped specimens (shown in Figure 1) were prepared.

The cement, silica fume, slag, quartz sand and superplasticize were first mixed for about 3 min at low speed in a tilting drum mixer. Water was added and re-mixed for about 6 min. Subsequently, PP fibres and steel fibres were added and additional mixing was applied for about 6 min. The specimens were kept in the steel molds for 24 h at 20 °C. After that RPC specimens were removed from the steel molds and immersed in accelerated curing curing box at 90 °C for 3 days. The specimens, which were subjected to heat treatment, were kept in the laboratory air at a temperature of 20 °C and a relative humidity of 75% before testing.

2.3 Tests setup

To measure mechanical properties of RPC at elevated temperature, test furnace, temperature controller, tensile fixtures and testing machine were used. Tensile fixture was added to the RPC specimens to transmit loads from the testing machine to the specimen and serves as a heat insulator to protect the test equipment (Figure 1). Compressive strength and tensile strength tests were carried out on the concrete using machine with a 1000 kN and 600 kN capacity, respectively. The specimens were measured according to GB/T 50081-2002 in China. Tensile fixtures and test furnace were put in their proper places to ensure that tensile fixtures and specimen were axial in vertical direction (Figure 2). The clearance between tensile fixtures and the furnace was filled with a ceramic fibre insulator to restrict heat loss through air circulation.

2.4 Heating regimes

Designed target temperatures were 20 °C,

Table 1

Mixture of RPC test

Mix	W/B	Binder (kg/m^3)			Quartz sand (kg/m^3)	SP (kg/m^3)	Steel fibres (% vol.)	PP fibres (% vol.)
		Cement	Silica fume	Slag				
RPC0	0.2	816.87	245.06	122.53	980.25	47.38	-	-
HRPC1	0.2	799.72	239.91	119.96	959.66	46.38	2	0.1
HRPC2	0.2	798.90	239.67	119.83	958.68	46.34	2	0.2
HRPC3	0.2	807.07	242.12	121.06	968.48	46.81	1	0.2

Note: The proportion of PP fibres and steel fibres added was measured by concrete volume.

Fig. 1- Dimensions of dumbbell-shaped specimens and tensile fixtures.

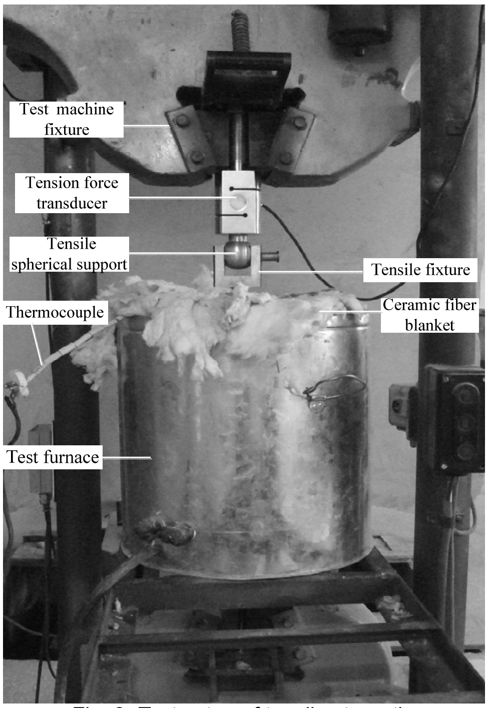


Fig. 2- Test setup of tensile strength.

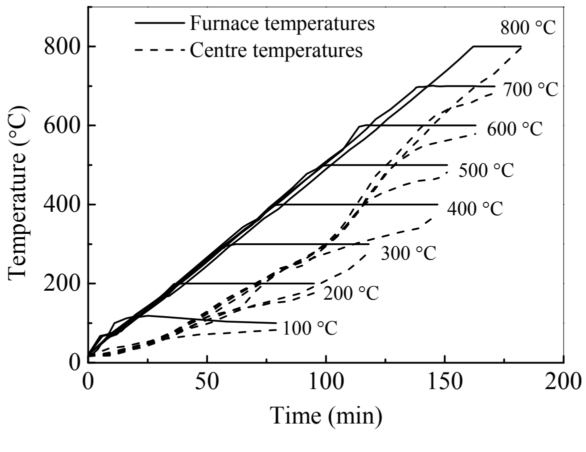


Fig. 3- Furnace and centre temperatures of specimens.

100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C and 800 °C. All specimens were heated at a constant rate of 5 °C/min. The furnace and centre temperatures of the RPC cubes in this study are shown in Figure 3. All specimens were heated and maintained according to the heating regimes presented in Figure 3. Three test methods, commonly referred to as stressed, unstressed, and unstressed residual strength tests, have been used to study the effect of high temperature on mechanical properties of concrete under axial compression [22]. In unstressed tests, specimens are heated under initial stress and loaded to failure at the desired elevated temperature. In this study, unstressed tests were adopted from 20 to 800 °C.

3. Results and Discussion

3.1. Phenomena of test and failure modes of RPC

Specimens of RPC had little white mist appeared in the temperature range of 100~200 °C. When the central temperature of the specimens was raised to 335~341 °C, a little persistent white smoke accompanied. About 3 minutes later, white smoke significantly reduced. After 5~10 minutes, the white smoke had disappeared. Explosive spalling for RPC0 ocurred at 400 °C. When furnace temperature was at 257 °C, a slight sound generated for HRPC2; a big sound generated for HRPC2 at 364 °C, 372 °C and 379 °C; a big sound generated for HRPC3 at 394 °C, 398 °C, 397 °C, 402 °C, 407 °C, 415 °C and 429 °C.

Color changes, surface characteristics variation and porosity of the cube specimens with fibres at different temperatures are listed in Table 2. As the temperature increased, porosity, number and width of cracks increased. It is due to physical and chemical processes and composition of hydration products depending on temperature. Furthermore, specimens of RPC with different steel fibres (or PP fibres) content did not significantly differ in appearance after exposure to the same temperature. Therefore, color changes, width and numbers of cracks, surface flaking, unfilled corner flaking and porosity were associated with maximum temperatures of exposure.

Specimens with hybrid fibres had no obvious cracks observed below 400 °C. Cracks were initiated on RPC surfaces in temperature range of 500 and 600 °C. More cracks were observed on RPC surfaces between 700 and 800 °C. Specimens had no obvious penetrating inside cracks for 20 to 800 °C. The RPC's failure modes were improved as steel fibre content increased, but the width of the cracks increased with increasing steel fibre content. Failure modes of RPC were improved as PP fibre content increased. Failure modes of RPC with hybrid fibres are ductile failure and cube specimens suffer more serious thermal damage than dumbbell-shaped specimens.

3.2. Cube compressive strength of RPC with hybrid fibres

Figure 4 depicts the compressive strength of RPC with hybrid fibres versus temperature. The compressive strength of RPC0 decreases sharply at 100 °C and continuously decreases till 400 °C. Compressive strengths of HRPC1, HRPC2 and HRPC3 also decrease at 100 °C. The values of cube compressive strength of HRPC1, HRPC2 and HRPC3 at temperatures of 100 °C are 111.46, 108.54, 107.29 MPa, what represent 69.0%, 67.4% and 67.3%, respectively, of the original strength at 20 °C.

The strength loss at 100 °C was attributed to a reduction of the cohesion of Van der Waal forces between the C–S–H layers. This reduces the surface energy of C–S–H and leads to the formation of siloxane bonds (Si–O–Si) that presents weaker bonding strength [23]. Compressive strengths of HRPC1, HRPC2 and HRPC3 between 200 and 600 °C increase comparing to that under 100 °C. The increase in strength between 200 and 600 °C is attributed to the phenomenon called "dry hardening" due to the evaporation of water [24,25]. Furthermore, the silanol groups lose a part of bond water, which induces the creation of shorter and stronger siloxane bonds (Si–O–Si) with probably larger surface energies that contribute to the increase in strength [23]. Compressive strengths of HRPC1, HRPC2 and HRPC3 at 700 and 800 °C decrease in comparison with that at 600 °C. Compressive strength of HRPC2 was 63.75 MPa at 800 °C, what represent 39.6% of the original strength at 20 °C. Performance of RPC with hybrid fibres has greatly degenerated and the expansion deformation is as well as at 800 °C. Quartz transforming from α to β form caused volume expansion of RPC at about 573 °C [26]. Furthermore, the decomposition of the C–S–H gel is another cause of the severe deterioration [27].

Figure 4 indicates also the relationship between compressive strength of RPC and hybrid fibres content at elevated temperature. Cube compressive strength of HRPC2 is lower than cube compressive strength of HRPC1 below 300 °C, but is higher than that of HRPC1 beyond 300 °C. The air content and pore size distribution of RPC is changed due to addition of PP fibres, therefore, RPC with more PP fibre content has lower compressive strength below 300 °C. Compressive strength of RPC increases between 300 and 800 °C as PP fibre content increase. PP fibres has melted before 300 °C, what result in leaving a large number of pores, sublimed and creating a network of micro-channels in interior RPC, which serves as a way for the release of water vapour to the outside. Vapor pressure is relieved by water vapor migrating, therefore, reducing internal thermal damage and spalling. Cube compressive strength of HRPC2 is higher than that of HRPC3 below 400 °C, but is lower than that of HRPC3 beyond 400 °C. A high steel fibre content results in greater expansion and a great number of cracks due to thermal expansion between the cement and steel fibres [19].

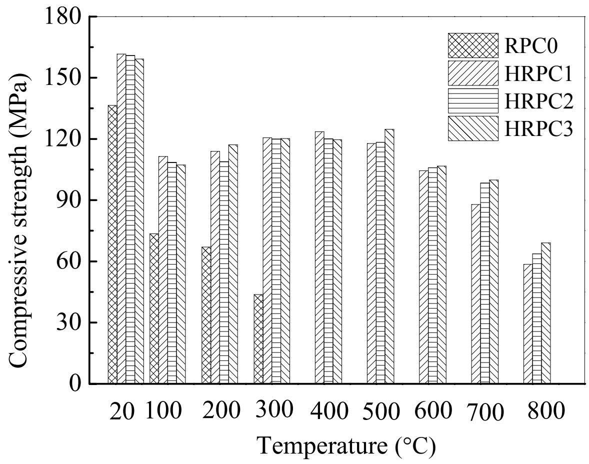


Fig. 4- Compressive strength of cube RPC with hybrid fibres.

Figure 5 displays fitting curves and comparisons of relative compressive data with Codes. Eurocode Siliceous [28] and ACI 216R [29] are designated for normal strength concrete and

Table 2

Color changes, surface characteristics variation and porosity at different temperatures

Temperature (°C)	Color	Cracks	Surface flaking	Corner flaking	Porosity
20~200	Gray	N.O.	No	No	No
300~400	Brown	H	No	No	No
500	Reddish gray	m	Slight	No	No
600	Dark brown	M	Few	Few	Slight
700	Gray	S	Many	Few	Few
800	Yellow white	S	Serious	Many	Many

Symbols for cracking: N.O.=No obvious cracks observed, H=Hair cracks observed, m=Micro cracks observed, M=Macro cracks observed, S=Serious cracks observed

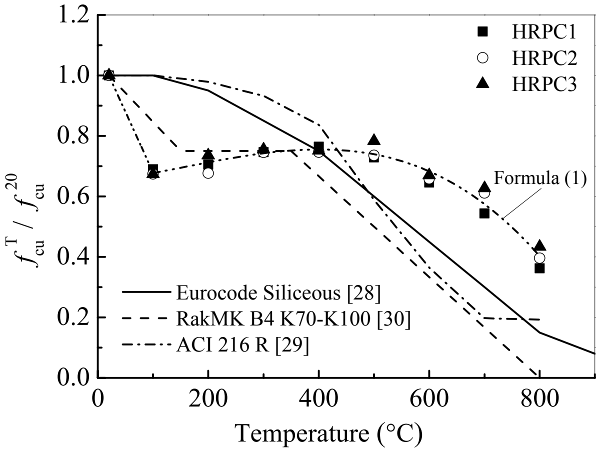


Fig. 5- Relative compressive strength of cube RPC with hybrid fibres.

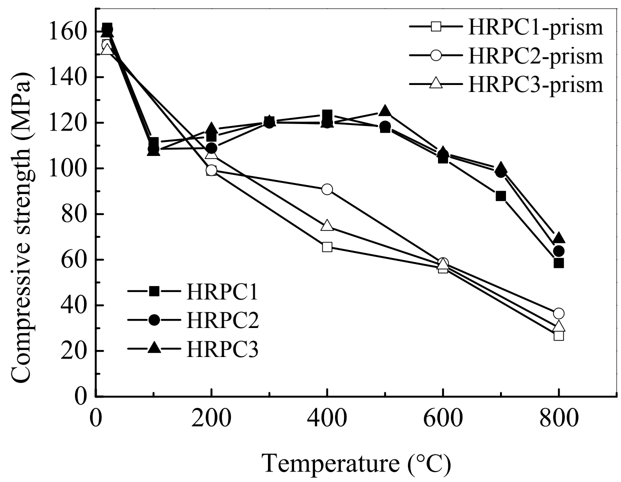


Fig. 6- Compressive strength of prism RPC with hybrid fibres.

high strength concrete, but RakMK B4 K70-K100 [30] is suitable for normal strength concrete. Relative compressive strength of RPC with hybrid fibres is seriously lower than Eurocode Siliceous, RakMK B4 and ACI 216R below 400 °C. Eurocode Siliceous, ACI 216R and RakMK B4 are unsafe when used for estimating compressive strength of RPC below 400 °C. From 500 to 800 °C, it was conservative to estimate compressive strength of RPC with hybrid fibres by Eurocode Siliceous, ACI 216R and RakMK B4. Particularly, compressive strength of RakMK B4 K10-K70 is zero at 800 °C but relative compressive strength of RPC with hybrid fibres is about 39.7%. Therefore, RPC with hybrid fibres maintains high compressive strength and has a sufficient safety reserves assessing by Codes at elevated temperatures.

Through the regression analysis, the relationship of the normalised compressive strength f_{cu}^{T} / f_{cu}^{20} with temperature T can be expressed as Eq. (1).

Where f_{cu}^{T} is compressive strength of cube RPC at elevated temperature; f_{cu}^{20} is compressive strength of cube RPC at 20 °C; T is temperature.

3.3. Prism compressive strength of RPC with hybrid fibres

Figure 6 shows prism compressive strength of RPC with hybrid fibres. HRPC1-prism, HRPC2-prism and HRPC3-prism are prism specimens of SRPC1, SRPC2 and SRPC3, respectively. Prism compressive strength of RPC with hybrid fibres decrease linearly from 20 to 800 °C with temperature, which is different from compressive strength of cube RPC with hybrid fibres.

Prism compressive strength of specimens is lower than cube compressive strength of specimens. For example, the compressive strengths of HRPC2-prism at 20, 200, 400, 600, 800 °C are 154.1, 99.2, 90.84, 58.53, 36.45 MPa, respectively, which is lesser than the compressive strengths of the cube specimens (HRPC2) at different temperatures. Prism compressive strength of RPC decreases as PP fibre content increases below 200 °C, but increases as PP fibre content increases beyond 200 °C. Prism compressive strength of HRPC2 is higher than that of HRPC3.

3.4. Prism compressive strength of RPC with different hold time

Figure 7 indicates the compressive strength for HRPC2 at different hold times. Hold times for HRPC2, HRPC2-h1 and HRPC2-h3 are 0 h, 1 h and 3 h, respectively. The compressive strengths with a hold time of 3 h (HRPC2-h3) are greater than the compressive strengths without any hold time and a hold time of 1 h (HRPC2 and HRPC2-h1) below 400 °C. Compressive strength of RPC decreases from 400 to 600 °C as hold time increases. However, the compressive strengths for HRPC2, HRPC2-h1 and HRPC2-h3 are 28.34, 38.67 and 52.95 MPa, respectively, at 800 °C. Compressive strengths of RPC increase at 800 °C as hold time increases. Figure 8 shows compressive strengths of HRPC1, HRPC2 and HRPC3 for different hold times at 600 °C. Compressive strength of HRPC2 is higher than that of HRPC1 at 600 °C. Compressive strength of HRPC3 is higher than that of HRPC2 at 600 °C. It is due to thermal expansion between the steel fibres and cement resulting in decreased strength

$$f_{cu}^{T} / f_{cu}^{20} = \begin{cases} 1.08 - 4.01(\frac{T}{1000}), & 20\,°\text{C} \le T \le 100\,°\text{C}; \\ 0.648 + 0.224(\frac{T}{1000}) + 0.884(\frac{T}{1000})^2 - 1.94(\frac{T}{1000})^3, & 100\,°\text{C} < T \le 800\,°\text{C}. \end{cases} \quad (1)$$

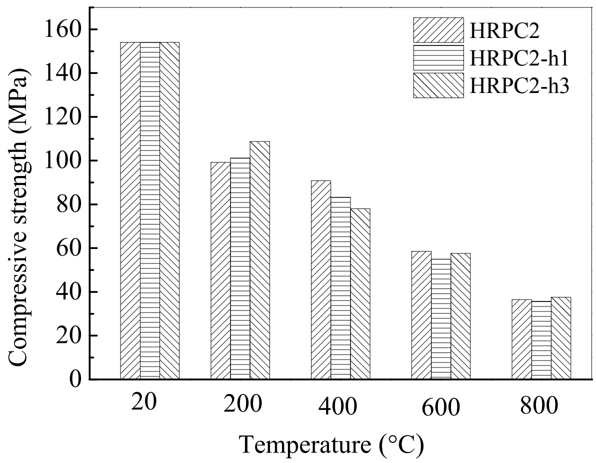


Fig. 7- The effect of hold time on compressive strength of HRPC2.

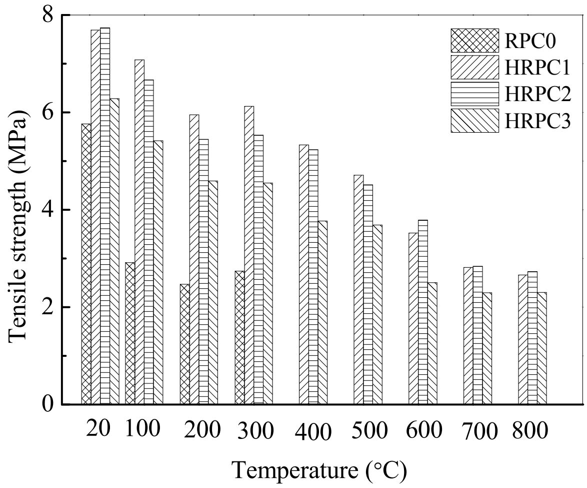


Fig. 9- Tensile strength of RPC with hybrid fibres.

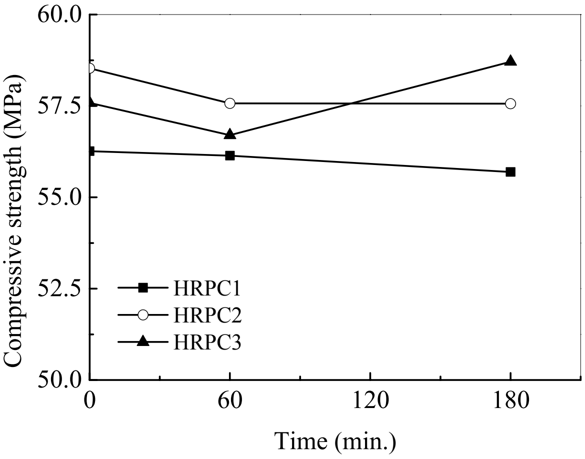


Fig. 8- Compressive strength of prism RPC for different hold time at 600 °C.

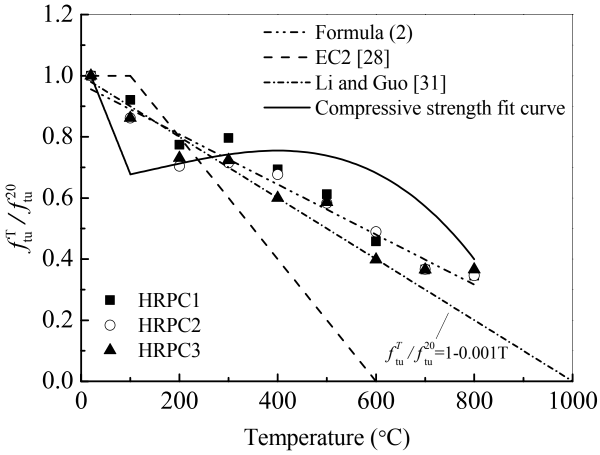


Fig. 10- Relative tensile strength of RPC with hybrid fibres.

[19]. Thus, RPC with higher steel fibre content has lower compressive strength and PP fibres improve compressive strength of RPC.

3.5. Tensile strength of RPC with hybrid fibres

Figure 9 shows the tensile strength of RPC with hybrid fibres versus temperature. Tensile strength of RPC0 decreases sharply between 20 and 100 °C, yet increases slightly from 100 to 300 °C. Tensile strengths of HRPC1, HRPC2 and HRPC3 decrease linearly from 20 to 200 °C. The tensile strengths of HRPC1, HRPC2 and HRPC3 are 5.95, 5.45 and 4.59 MPa at 200 °C, what represent 77.39%, 70.4%, 73.08% of the original strength at 20 °C, respectively. The tensile strength loss of RPC with hybrid fibres at 100 °C is due to the evaporation of free water resulting in cracks and pores. Tensile strengths of RPC with hybrid fibres increase slightly at 300 °C versus tensile strengths at 200 °C. Tensile strength of HRPC1 at 300 °C is higher than that of at 200 °C, about 2.3%. Tensile strengths of HRPC1, HRPC2 and HRPC3 decrease and the performance has extremely deteriorated at 300~800 °C. Tensile strengths of HRPC1, HRPC2 and HRPC3 at 800°C are 2.66, 2.73, 2.33 MPa, what represent 34.5%, 34.6% and 36.6% of the original strength at 20 °C. It is attributed to decomposition of C–S–H gel resulting in strength loss at 800 °C [27]. Figure 9 depicts also the relation between tensile strength and hybrid fibre content. Tensile strength of HRPC1 is higher than that of HRPC2 between 20 and 600 °C, but lower than that of HRPC2 for 600 to 800 °C. Relative tensile strength of HRPC2 is higher than HRPC3 between 20 to 700 °C, but lower than that of HRPC3 at 800 °C. It is due to different thermal expansion between the steel fibres and cement producing cracks [19].

Figure 10 shows fitting curves and comparisons of relative tensile data with Codes. The results show that tensile strength of RPC with hybrid fibres decreases linearly as temperature increases. Compared with Eurocode 2 [28] and Li and Guo [31], it is conservative when used for estimating tensile strength of RPC at elevated temperatures. However, the tensile strength loss comparing to compressive strength loss increases with temperature. Because growth of new cracks reduced the available load-carrying area causing an increased in stresses at critical crack tips, while the cracks tended to close up under compressive loads.

Through the regression analysis, the relationship of the normalised compressive strength f_{tu}^{T} / f_{tu}^{20} with temperature T can be expressed as Eq. (2).

$$f_{tu}^{T} / f_{tu}^{20} = 0.972 - 0.82(\frac{T}{1000}) \qquad 20\ °C \leq T \leq 800\ °C \quad (2)$$

where f_{tu}^{T} is tensile strength of RPC at elevated temperature; f_{tu}^{20} is tensile strength of RPC at 20 °C; T is temperature.

3.6. RPC compared to NSC and HSC on mechanical properties and spalling

Relative compressive strengths of NSC, HSC and RPC are shown in Figure 11. Compressive strength of NSC has slightly changed, even exhibits higher degree of increase between 100 and 400 °C [32,33]. However, Compressive strength of HSC decreased from 100 to 400 °C [33,34]. Compressive strength of RPC with hybrid fibres also decreases from 100 to 400 °C. Furthermore, relative compressive strength of RPC with hybrid fibres is lower than that of NSC and HSC in the temperature range from 100 to 400 °C. As the temperature increases, the cement paste attempts to shrink as absorption, capillary and hydration water is driven out, while the aggregate expands resulting in a smaller 1oss of bond in leaner mixes (low cement/aggregate ratio) [35], therefore, the strength reduction of NSC is 1ower than that of HSC and RPC. Furthermore, the adsorbed water first fills the capillary pores, and the remaining amount is adsorbed between the paste particles as the temperature increases Therefore, more adsorbed water present in HSC and RPC than NSC due to less capillary voids of HSC, which results in a higher loss of compressive strength of HSC and RPC [35]. Relative compressive strength of RPC with hybrid fibres is higher than that of NSC and HSC for 500 to 800 °C. Descending trend of compressive strength of RPC with hybrid fibres is slower than that of NSC and HSC. It is due to more pores and increase in pores diameter in NSC than in HSC with temperature, which is responsible for strength loss [36]. As compared to Anderberg & Thelandersson [37], Bazan & Chern [38] and Terro [39], relative tensile strength of RPC with hybrid fibres is also lower between 100 and 500 °C (Figure 12). From 500 to 800 °C, RPC with hybrid fibres maintains a higher percentage value of tensile strength than Anderberg & Thelandersson [37], W. Bazan & Chern [38] and Terro [39]. Therefore, RPC with hybrid fibres maintains higher compressive and tensile strength than NSC and HSC.

Diederichs et al. [33] reported explosive spalling of their HSC specimens. Furumura [34] and Hammer [40] also reported that explosive spalling occurred at 700 and 600 °C. However, no obvious explosive spalling occurred in all specimens of RPC, with the exception for RPC0 (without fibres). First, steel fibres in the RPC are randomly distributed in matrix, which can delay crack formation limit crack propagation by reducing the crack tip opening displacement. Second, steel fibres have good thermal conductivity reducing temperature gradient of RPC. Finally, melting PP fibres create many pores and mico-channels resulted in water vapour escaping, which can prevent explosive spalling of RPC.

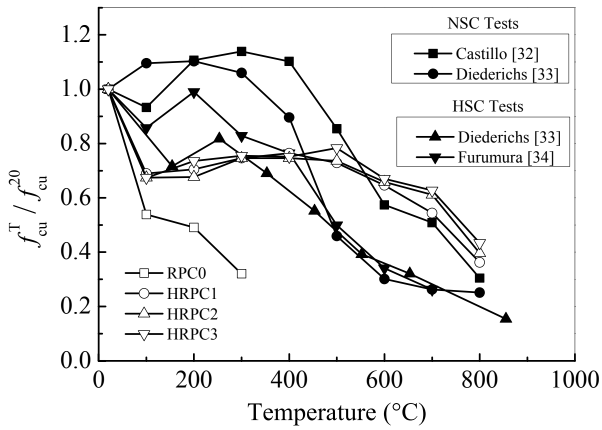


Fig. 11- Comparison of relative compressive strengths for RPC, NSC and HSC.

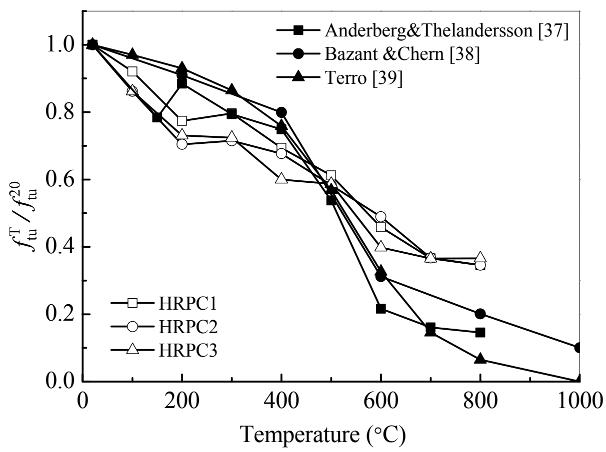
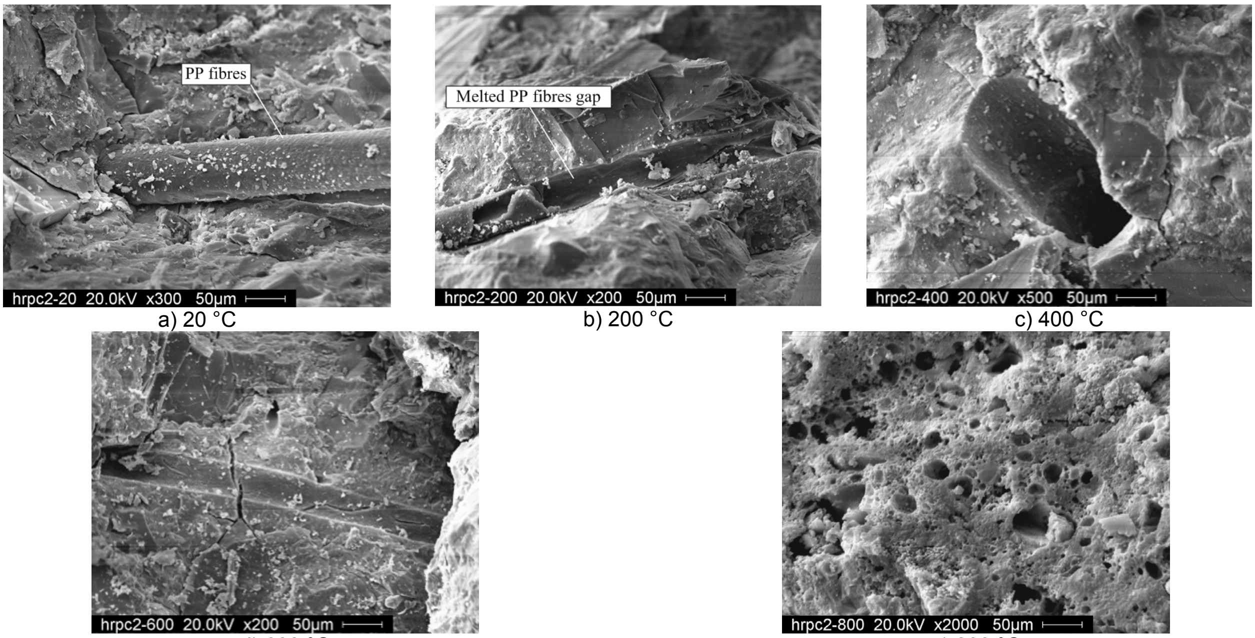


Fig. 12- Relative tensile strength of RPC compared to that of NSC and HSC.

3.7. Microstructure of RPC

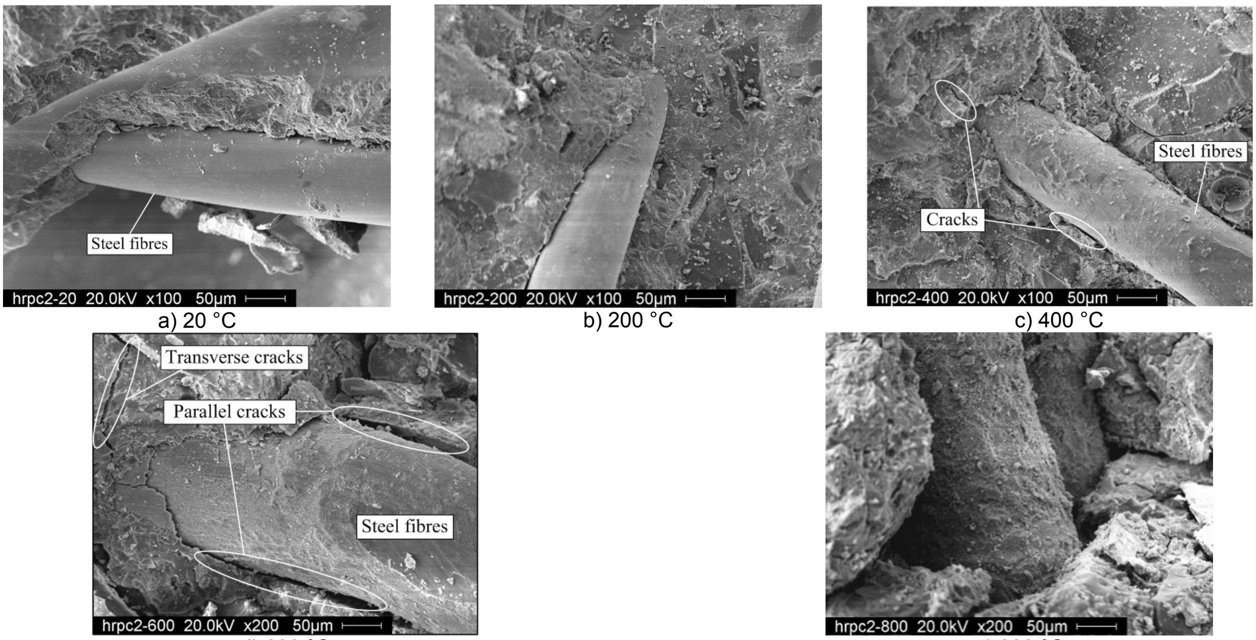
The microstructure of RPC specimen after different high temperatures using SEM is showed in Figures 13 and 14. It can be concluded that the research has identified a correlation that exists between pores and cracks changes and the mechanical properties from a macro perspective. RPC with hybrid fibres has dense microstructure at 20 °C (Figures 13a and 14a). Figures 13b and 14b display that microstructure of RPC with hybrid fibres is complete at 200 °C. Silica fume containing SiO_2 can react with cement hydrates [19], what



a) 20 °C b) 200 °C c) 400 °C

d) 600 °C e) 800 °C

Fig. 13- SEM micrographs of PP fibres and matrix in RPC with hybrid fibres at different temperatures.



a) 20 °C b) 200 °C c) 400 °C

d) 600 °C e) 800 °C

Fig. 14- SEM micrographs of steel fibres and matrix in RPC with hybrid fibres at different temperatures.

has as results strength increasing from 100 to 300 °C. PP fibres in RPC melted at the high temperature (at about 170 °C). As mentioned above, melting of PP fibres offers a channel for moisture to diffuse and reduce thermal inside damage. Meanwhile, steel fibres are closely with cement paste and not materially different from that of at room temperature, in addition, matrix has no obvious cracks. Figures 13c and 14c illustrate the microstructure of RPC with hybrid fibres at 400 °C. Hairline cracks and pores form are resulting from pressure by water vapor increasing with temperature. Moreover, width of cracks increases and a few cracks produce in interface between steel fibres and cement paste due to their different thermal expansion. Figures 13d and 14d reveal the microstructure of RPC with hybrid fibres at 600 °C. The thermal cracks may form transverse or parallel to the steel fibre axis and PP fibres gap is also present. Diameter and number of pores continuously increase and steel fibres have partly oxidized, what result in mechanical properties diminishing significantly. Figures 13e and 14e show the microstructure of RPC with hybrid fibres at 800 °C. Width as well as the number of cracks increase at 800 °C. The gap created by the melting of PP fibres in the RPC with hybrid fibres matrix can be observed clearly for 200 to 800 °C, what can provide the micro-channels to release the water vapour pressure in the matrix pores for mitigating the explosive spalling. Steel fibres are completely oxidized and lose little basic mechanical properties. Furthermore, the bond breakdowns between steel fibres and cement paste. Decomposition of C–S–H gel produces cracks and pores, which are responsible for strength and impermeability loss of RPC.

4. Conclusions

The following conclusions can be drawn from the experimental results:

1. Failure modes of RPC improve as the steel fibre content increases, but width of cracks increases as steel fibre content increases. Failure modes of RPC also improve as PP fibre content increase.

2. The use of color changes, width and numbers of cracks, surface flaking, unfilled corner flaking and porosity were determined what maximum temperature had been exposed and estimated mechanical properties. The addition of 2% steel fibres and 0.2% PP fibres prevents explosive spalling and significantly improves the compressive and tensile strength of RPC.

3. Cube compressive strengths of RPC with hybrid fibres decrease at 100 °C, increase between 200 and 500 °C, and decrease beyond 600 °C. Cube compressive strengths of RPC decrease as the PP fibre content increases below 300 °C, but increase as the PP fibre content increases beyond 300°C when steel fibres are the same content. Cube compressive strengths of RPC increase as the steel fibre content increases below 100 °C, but decrease as the steel fibre content increases beyond 200 °C when PP fibres are the same content.

4. Compressive strengths of RPC with hybrid fibres increase as hold time inreases below 400 °C, decrease as hold time increases between 400 °C and 600 °C, and increase as hold time increases at 800 °C.

5. Tensile strengths RPC with hybrid fibres decrease at 200 °C, increase from 200 to 300 °C, and decrease between 300 and 800 °C. Tensile strengths of RPC decrease as the PP fibre content increases below 600 °C, and increases as the PP fibre content increases between 600 and 800 °C when steel fibres is the same content. Tensile strengths of RPC increase as the steel fibre content increases below 700 °C, and decrease as the steel fibre content increases at 800 °C when PP fibres are the same content.

6. Prism compressive strengths decrease linearly as the temperature increases, and are lower than cube compressive strengths at the same temperature. The tensile strength of RPC with hybrid fibres suffers more loss than the compressive strength. Furthermore, RPC with hybrid fibres maintains higher compressive and tensile strength than NSC and HSC at elevated temperatures.

7. Pores and cracks changes in microstructure for 20 to 800 °C reveal mechanical properties in a macro perspective. The gap created by the melting PP fibres in the RPC matrix can be observed clearly from 200 to 800 °C, which can provide the micro-channels to release the water vapour pressure in the matrix pores for mitigating the explosive spalling. Steel fibres are completely oxidized and the bond breakdowns between steel fibres and cement paste at 800 °C.

Acknowledgements

Financial support from Changjiang Scholar Program of China (2009-37), PhD Programs Foundation of Ministry of Education of China (20092302110046), and the Fundamental Research Funds for the Central University (HIT.NSRIF. 201197). The authors thank Fei Xu and Hai-tao Qu for their assistance in preparing and testing the specimens for the research reported in this paper, and Dr. Ji-ping Jiang for him valuable guidance and advice.

REFERENCES

1. P. Richard, and M.Cheyrezy, Composition of Reactive Powder Concretes. Cement and Concrete Research, 1995, **25**(7), 1501.
2. P. Richard, and M.Cheyrezy, Reactive Powder Concrete with High Ductility and 200-800MPa Compressive Strength. ACI SP144, 1994, 507.
3. O. Bonneau, and M. Lachemi, Mechanical properties and durability of two industrial reactive powder concretes. ACI Mater J, 1997, **94**(4), 286.
4. M. Cheyrezy, Structural Application of RPC. Concrete, 1999, **33**(1), 359.
5. U. Schneider, Fire Resistance of High Performance Concrete. Proceedings of the RILEM International Workshop. Vienna, Austria, February 1994, 237.
6. P. Kalifa, G. Chene, and C. Galle, High-temperature behavior of HPC with polypropylene fibres from spalling to microstructure. Cem. Concr. Res., 2003, **31**(10), 1487.
7. A. Noumowe, Mechanical properties and microstructure of high strength concrete containing polypropylene fibres exposed to temperatures up to 200°C. Cement and Concrete Research, 2005, (35), 2192.
8. Bertil Persson, Mitigation of fire spalling of concrete with fibers. Presentation in technical committee “Durability of Self-Compacting Concrete”, Ghent (Belgium), April 2005.
9. Mucteba Uysal, Kemalettin Yilmaz, Metin Ipek. Properties and behavior of self-compacting concrete produced with GBFS and FA additives subjected to high temperatures. Construction and Building Materials, 2012, **28**(1), 321.
10. Serdar Aydın, Halit Yazıcı, and Bülent Baradan, High temperature resistance of normal strength and autoclaved high strength mortars incorporated polypropylene and steel fibers. Construction and Building Materials, 2008, **22**(4), 504.
11. Albert N. Noumowe, Rafat Siddique, and G. Debicki. Permeability of high-performance concrete subjected to elevated temperature (600 °C). Construction and Building Materials, 2009, **23**(5), 1855.
12. Jianzhuang Xiao and H. Falkner. On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures. Fire Safety Journal, 2006, **41**(2), 115.
13. Ali Behnood, and Masoud Ghandehari, Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibres heated to high temperatures. Fire Safety Journal, 2009, **44**(8),1015.
14. B. Chen, and J. Liu Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures, Cem. Concr. Res., 2004, **34**(6), 1065.

15. G. Hoff, A. Bilodeau, and V.M. Malhotra, Elevated temperature effects on HSC residual strength. Concr. Int., 2000, **22** (4), 41.

16. C.S. Poon, Z.H. Shui, and L. Lam. Compressive behavior of fibre reinforced high performance concrete subjected to elevated temperatures. Cem. Concr. Res., 2004, **34**(12): 2215.

17. A. Lau, and M. Anson, Effect of high temperatures on high performance steel fibre reinforced concrete. Cement and Concrete Research, 2006, **36**(9), 1698.

18. T.T. Lie, and V.K.R Kodur, Mechanical properties of fibre-reinforced concrete at elevated temperatures. Institute for Research in Construction, National Research Council of Canada, Ottawa, ant., 1995, Internal Report No. 687.

19. Yuh-Shiou Tai, Huang-Hsing Pan, and Ying-Nien Kung, Mechanical properties of steel fibre reinforced reactive powder concrete following exposure to high temperature reaching 800 °C. Nuclear Engineering and Design, 2011, **241**(7), 2416.

20. V.R. Kodur, Spalling in high strength concrete exposed to fire–concerns, causes, critical parameters, and cures, Proceedings of the ASCE Structures Congress, 2000, 1.

21. F. Ali, and A. Nadjai, Fire Resistance of Concrete Columns Containing Polypropylene and Steel Fibers, ACI Special Publication, 2008, 255, 199.

22. L.T. Phan, Fire performance of high strength concrete. A Report of the State-of the-art, Building and Fire Research Laboratory, National Institute of Standards and Technology, Maryland, 1996.

23. G.A. Khoury, Compressive strength of concrete at high temperature: a reassessment. Mag Concr Res 1992, **44**(161), 291.

24. W.P.S. Dias, G.A. Khoury, and P.J.E. Sullivan, Mechanical properties of hardened cement paste exposed to temperatures up to 700 °C. ACI Mater J, 1990, **87**(2), 160.

25. Y. Xu, Y.L. Wong, C.S. Poon, and M. Anson, Influence of PFA on cracking of concrete and cement paste after exposure to high temperatures. Cem Concr Res 2003, **33**(12), 2009.

26. M.S. Abrams, Compressive strength of concrete at temperatures to 1600F. ACI SP 25, Temperature and Concrete (American Concrete Institute, Detroit, Michigan, 1971)

27. B. Demirel, and O. Kelestemur, Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. Fire Saf J, 2010, 45, 385.

28. British Standard Institute. Eurocode 2: Design of Concrete Structures-Part1.2: General Rules-Structural Fire Design. BS EN. 1992-1-2:2004.

29. American Concrete Institute. Guide for Determining the Fire Endurance of Concrete Elements. ACI 216R-89 (1989).

30. Concrete Association of Finland. High Strength Concrete Supplementary Rules and Fire Design. RakMK B4 (1991).

31. Li W, and Guo ZhH, Experimental investigation on strength and deformation of concrete under high temperature. Chin J Build Struct 1993, **4** (1),8.

32. C. Castillo, and A.J. Durrani, Effect of transient high temperature on high-strength concrete. ACI Materials Journal, 1990, **87**(1), 47.

33. U. Diederichs, U.M. Jumppanen, V. Penttala. Material properties of high strength concrete at elevated temperatures. IABSE 13th Congress, Helsinki (June 1988).

34. F. Furumura, T. Abe, and Y. Shinohara, Mechanical properties of high strength concrete at high temperatures. Proceedings of the Fourth Weimar Workshop on High Performance Concrete: Material Properties and Design, Hochschule für Architektur und Bauwesen (HAB) (Weimar,Germany, 1995, October 4–5) 237.

35. M.S. Castillo, Carlos, Effect of transient high temperature on high-strength concrete. Master of Science thesis, 1987.

36. S.Y.N. Chan, G. F. Peng, and M. Anson, Residual strength and pore structure of high-strength concrete and normal-strength concrete after exposure to high temperatures. Cement and Concrete Composites. 1999, (21), 23.

37. Y. Anderberg, and S. Thelandersson, Stress and deformation characteristics of concrete at high temperatures: 2. experimental investigation and material behaviour model. Bulletin 54. Sweden (Lund): Lund Institute of Technology, 1976.

38. P. Bazant, J.C. Chern, Stress-induced thermal and shrinkage strains in concrete. Journal of Engineering Mechanics, 1987, **113**(10),1493.

39. M.J. Terro, Numerical modeling of the behavior of concrete structures in fire. ACI Struct J, 1998, **5**(2),183.

40 T.A. Hammer, High-strength concrete phase 3, Compressive strength and E-modulus at elevated temperatures. SP6 Fire Resistance, Report 6.1, SINTEF Structures and Concrete (February, 1995).

****