Pergamon

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Cement and Concrete Research 33 (2003) 2009–2016

CEMENT AND CONCRETE RESEARCH

Influence of PFA on cracking of concrete and cement paste after exposure to high temperatures

Y. Xu, Y.L. Wong*, C.S. Poon, M. Anson

Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong, China

Abstract

Cracking is a visible type of damage to concrete that has significant adverse effects on the mechanical and durability properties of concrete. An experimental study on the identification and quantification of cracking in postheated concrete was conducted to provide a better understanding of the mechanisms of damages to concrete after exposure to high temperatures. In addition to the quantification of the residual compressive and tensile strengths of concrete after high temperature exposure, both macroscale and microscopic cracks were observed and measured. The crack patterns in different concretes, including concrete made with different water to binder (w/b) ratios and PFA dosages, were classified. Also examined was the cracking in the corresponding hardened cement pastes (hcp's) prepared without adding aggregates. The relation of cracking with deterioration of the durability properties of concrete, with respect to the chloride diffusion test results, was discussed. Crack density, a quantitative term, which had been introduced to study the microcrack properties in concrete, was adopted for measuring the severity of cracking. Severe cracking of concrete was observed after exposure to 450 °C and higher temperatures. The presence of PFA reduced the extent of these thermal cracks.

Keywords: Compressive strength; Diffusion; Microstructure; Fly ash; High temperature

1. Introduction

Concrete is a nonhomogenous material consisting of hardened cement paste (hcp) and aggregates. With an increase in temperature, cracking is initiated due to thermal incompatibilities between the aggregates and the hcp [3]. Generally, at elevated temperatures, the cement paste would shrink due to the dehydration/decomposition of the hydrates while the aggregates usually expand before disintegration. It was reported that hcp's expanded on heating from room temperature to about 150 °C. The maximum experienced expansion was about 0.2% [4,5]. With a rise of temperature from 150 to 300 °C, cement pastes started to shrink. As the temperature was increased to 800 °C, the shrinkage of hcp could be as large as 2.2%. Thus, thermal stresses and cracks develop under conditions of high temperature exposure.

When concrete is heated at a rapid rate, a steep thermal gradient may develop between the outer and inner layers of concrete because concrete is a poor conductor, this gradient can also cause cracking. The thermal gradient largely depends on the heating regime and the concrete thermal properties, such as specific heat, thermal conductivity and thermal diffusivity [3]. However, It was reported that the rate of heating has little effects on the residual properties of concrete if the temperature gradients in the concrete are lower than 10 °C/cm [6–8].

Building up of vapor pressure might be another cause of cracking. During exposure to high temperatures, very high pore pressure may be built up as functions of temperature, heating rate and size of specimens [3]. The pore pressure might be as high as 8 MPa, which is much higher than the concrete's tensile strength of about 5 MPa [9]. Such a pressure could cause a dramatic type of cracking, generally known as thermal spalling of concrete, which has been reported by many researchers [10–14].

Thermal-induced microcracking might also be initiated inside an hcp since hcp is also a nonhomogenous material. The cracking started around the $Ca(OH)_2$ crystals and then progress to areas near the unhydrated cement grains, as supported by SEM observations [15]. This cracking is usually microscopic in scale and thus is identified as microcracking. Cracking increases significantly as the temperature is raised beyond 300 °C [15,16]. When the maximum exposure temperature is below 300 °C, concrete damage is

* Corresponding author. Tel.: +852-2766-6009; fax: +852-2334-6389.
E-mail address: ceylwong@polyu.edu.hk (Y.L. Wong).

0008-8846/$ – see front matter © 2003 Published by Elsevier Ltd.
doi:10.1016/S0008-8846(03)00216-3

Table 1
Chemical composition and physical properties of binders

Binder	Chemical composition (%)							Physical properties	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition	Specific gravity	Specific surface (m^2/kg)
OPC	19.61	7.33	3.32	63.15	2.54	2.13	2.97	3.16	3519.5
PFA	56.79	28.21	5.31	< 3.00	5.21	0.68	3.90	2.31	4120

dominated by only localized boundary cracking between aggregates and the cement paste.

Cracks of the heated concrete could be further extended/developed during postcooling [17–19]. Such phenomena can be ascribed to the rehydration of dissociated CaO, which could result in significant volume increase [19]. Therefore, a reduction of calcium hydroxide content in the cement paste containing PFA due to the pozzolanic reaction could help to reduce cracking due to postcooling. Dias et al. [20] conducted tests on cement pastes containing 10%, 25% and 40% of PFA replacement (by weight) and found that even a 10% fly ash replacement could eliminate all visible surface cracking in specimens during postcooling after exposure to 600 °C. They also pointed out that 400 °C was a critical temperature for Portland cement concretes. Concretes exposed to higher temperatures could not maintain their integrity and would disintegrate on subsequent cooling to ambient conditions.

Although the residual properties of concrete after exposure to high temperatures have been studied for over a decade, the influence of PFA on the cracking of concrete has scarcely been systematically studied, especially for concretes made with high PFA contents. The research described in this paper aimed to gain a better understanding of the cracking characteristics of PFA concrete after exposure to high temperatures. It will be shown that the observed cracking results correlate well with the deterioration of the mechanical properties and the durability properties of the concrete.

2. Experimental details

The crack patterns of concretes made with different water to binder (w/b) ratios and PFA contents were studied using a visual imaging technique and quantified in terms of crack density after they had been exposed to a series of the high temperatures of 250, 450, 650 and 800 °C. The residual compressive and tensile strengths of the concrete specimens were also determined. Companion paste specimens were also prepared and studied for thermal crack patterns using photographic means.

2.1. Sample preparation

For residual compressive strength tests and macrocracking observation, 100-mm cubes were prepared, and for determining residual tensile splitting strength, 100 mm diameter × 200 mm height cylinders were cast. The mix proportions are given in Table 1. The details of the raw materials are presented in Table 2. The coarse and fine aggregates are crushed granite and river sand, respectively. The coefficients of expansion of the crushed granite were found to be $6 \times 10^{-6}/°C$, $9 \times 10^{-6}/°C$ and $14 \times 10^{-6}/°C$ at the temperatures of 250, 450 and 600 °C, respectively. For the examination of internal crack patterns of the concretes, the conventional method of cutting the specimens into slices would not be appropriate as this would create more cracks in these fired damaged weaken concrete during the cutting process. To overcome this problem, each concrete cube specimen was precut into three slices, and the slices were assembled back to the original cubical form when they were subjected to heating.

The companion cement paste specimens of w/b ratios shown in Table 2 were prepared for the study of crack formation under high temperatures.

2.2. Curing regime

The specimens were demolded 24 h after casting and then cured in water for 7 days. Thereafter, the specimens

Table 2
Mix proportions (per cubic meter)

Mix	w/c	Replacement ratio (%)	OPC (kg)	PFA (kg)	Sand (kg)	Coarse aggregate (kg)	Water (kg)	Superplasticizer (l)
C-0.5-00	0.5	0	410	0	609	1132	205	0
C-0.5-25	0.5	25	307.5	102.5	576	1132	205	0
C-0.5-55	0.5	55	184.5	225.5	536	1132	205	0
C-0.3-00	0.3	0	500	0	724	1086	150	10.5
C-0.3-25	0.3	25	375	125	683	1086	150	10.5
C-0.3-55	0.3	55	225	275	634	1086	150	10.5

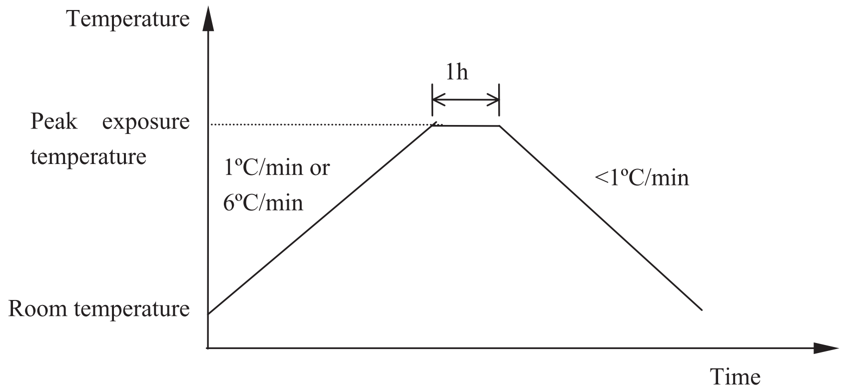


Fig. 1. Temperature versus time.

were moved to a curing chamber, which was kept at 75% relative humidity and 23 °C until the age of 90 days.

2.3. Heating regime

The specimens were heated at a rate of 1 °C/min and then kept for 1 h at the peak exposure temperature to establish a stable temperature profile in the samples (as shown in Fig. 1). This heating regime was identical to that previously reported for investigating the residual mechanical and durability properties of PFA concretes [1].

2.4. Definition of crack density

A crack density approach proposed by Mobasher et al. [2] was adopted to quantify the severity of cracking. The

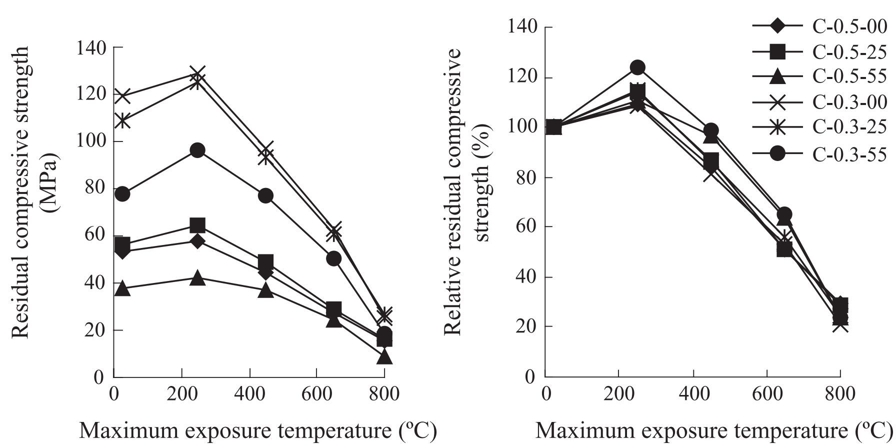


Fig. 2. Residual compressive strength and percentage of original value.

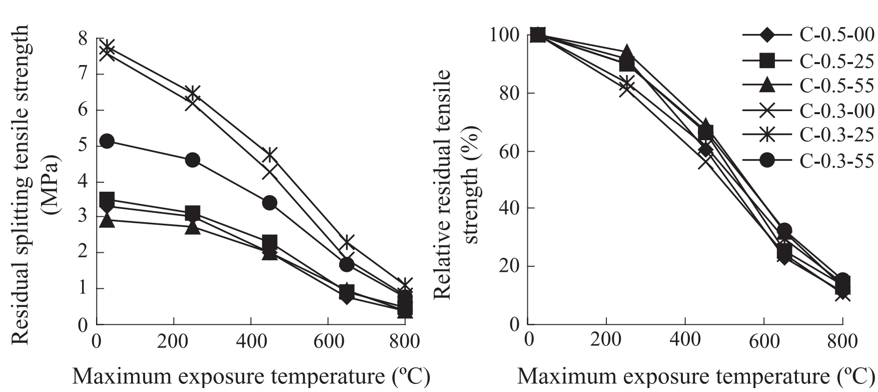


Fig. 3. Residual splitting tensile strength and percentage to original value.

crack density L_A is defined as the ratio of the cumulative crack length to the crack area under examination.

$$L_A = 2L/S$$

where L is the average cumulative crack length; S is the area of the test section.

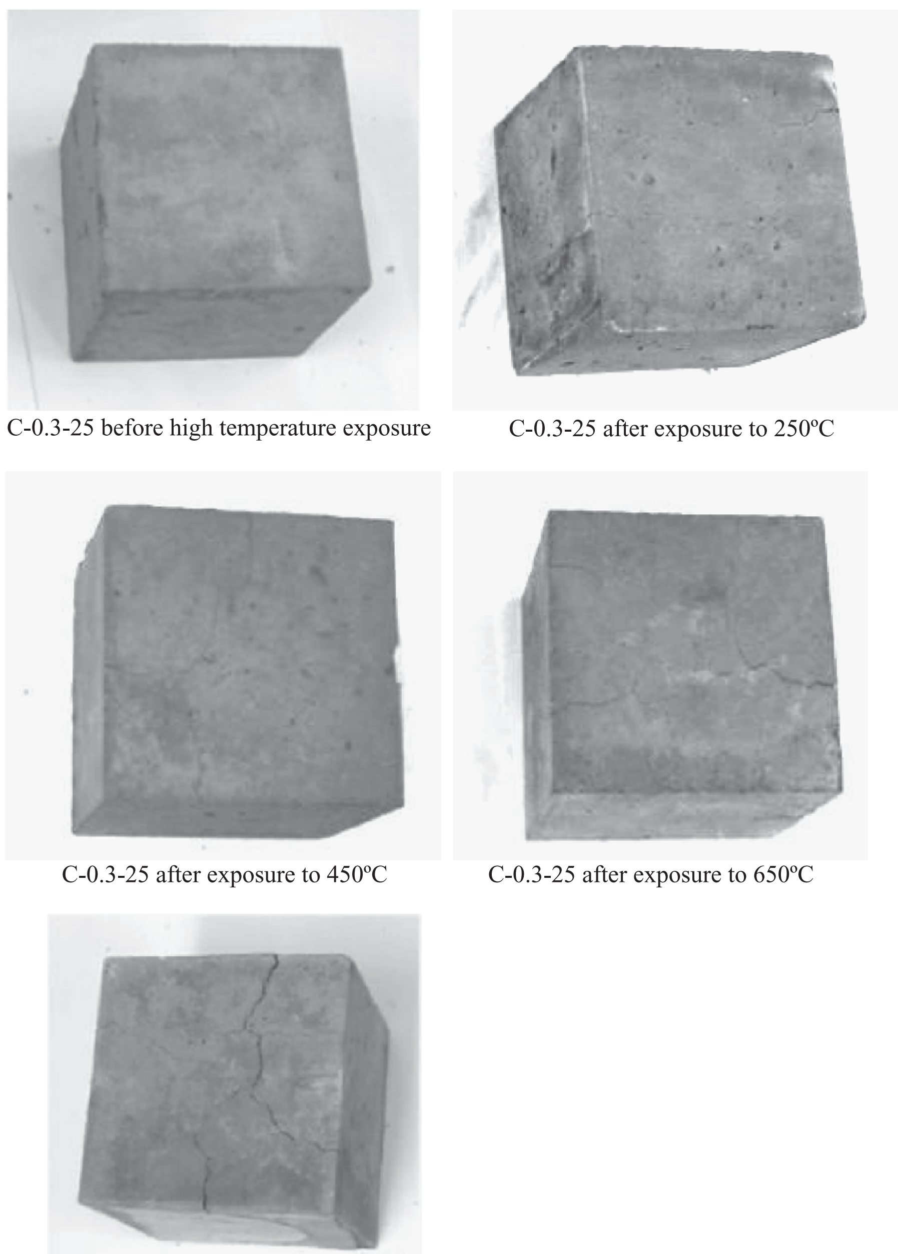
Since the cracks extend across the observed surfaces, the factor 2 accounts for the cracks as internal surface of finite thickness.

Quantitative measurements of cracks were performed using a Nikon digital microscope that can measure the surface crack widths up to 1 μm. Three 80 × 380 mm internal areas were studied on slices made from each cube, and the average value was reported.

3. Results and discussions

3.1. Residual mechanical properties

As concrete strengths vary with PFA content and w/b ratios, the term "relative strength" was adopted to normalize and analyze the experimental results. A relative residual strength is the postheated (residual) strength value expressed



C-0.3-25 before high temperature exposure

C-0.3-25 after exposure to 250ºC

C-0.3-25 after exposure to 450ºC

C-0.3-25 after exposure to 650ºC

C-0.3-25 after exposure to 800ºC

Fig. 4. Cracking of C-0.3-25 after exposure to high temperatures.

as a percentage of the respective preheated (original) strength value. That is:

$$\text{relative residual strength} = (\text{residual strength}/\text{original strength})100\%$$

Thus, we have "relative residual compressive strength" and "relative residual tensile strength." In this paper, conclusions are based on normalized values unless otherwise specified.

As shown in Figs. 2 and 3, a peak residual strength of each concrete specimen after exposure to 250 °C was higher than that under the ambient condition by 3–25%. However, all concrete showed some losses of tensile strength after exposure to 250 °C. When the maximum exposure temperature was raised to 450 °C or higher, concretes suffered losses in both compressive and tensile strengths. For the maximum exposure temperatures of 250, 450, 650 and 800 °C, the relative residual compressive strengths were 103% ~ 125%, 81% ~ 99%, 50% ~ 66% and 21% ~ 29%, respectively, and the relative residual tensile strengths were 81% ~ 92%, 56% ~ 71%, 24% ~ 31% and 11% ~ 15%. The addition of PFA was found to contribute positively to the residual compressive strength and the residual tensile strength. When the maximum exposure temperatures were not higher than 650 °C, the improvements of relative residual strengths (either compressive or tensile) were roughly 5% and 10% when replacing 25% and 55% OPC by PFA, respectively. When the maximum exposure temperature was 800 °C, the improvement turned out to be negligible.

3.2. Determining cracking severity

3.2.1. Graphic observations

3.2.1.1. Cracking of concrete. From Fig. 4, it can be seen that the cracking of concrete became significant when the exposure temperatures were higher than 450 °C, which is in good agreement with some previous reported observations [15,16]. The crack patterns in the inner layers of concrete were quite similar to but less severe than that observed on the surface of the specimens. There were evidences that cracks propagated from the surface to the inner core of the concrete specimen. Thus, most cracks are believed to have emerged initially on the surface and then extended inwards. However, there were few isolated cracks formed inside the concrete and these might be caused by shrinkage effects.

3.2.1.2. Cracking of hcp. The cracking of the hcp was more severe than that of the corresponding concrete due to the absence of aggregates that would act as crack arresters (see Fig. 5). Cracks were more apparent when no PFA was added in the mixes.

3.2.1.3. Influence of PFA content. The crack patterns of concretes made with different PFA contents were quite distinguishable from each other. Seven days after exposure to 650 °C, pure OPC concrete exhibited several major cracks. With the addition of 25% PFA by weight of the total binders, the heated concretes showed a network of minor cracks. The crack widths and lengths became further smaller when the PFA content was 55% by weight. Similar observations were also found in the pastes, where the influence of PFA could be easily identified (Fig. 6).

3.2.1.4. Influence of aggregates. It appears that the presence of aggregates generates barriers that restrain the propagation of cracking. The most severe cracking was observed in pure hcp, which did not have any aggregate. Without the aggregates, the influence of PFA content and w/b ratio became increasingly significant, which infers that the aggregate plays a major role in relieving cracking. Thus, an appropriate grading of aggregates in concrete is an effective

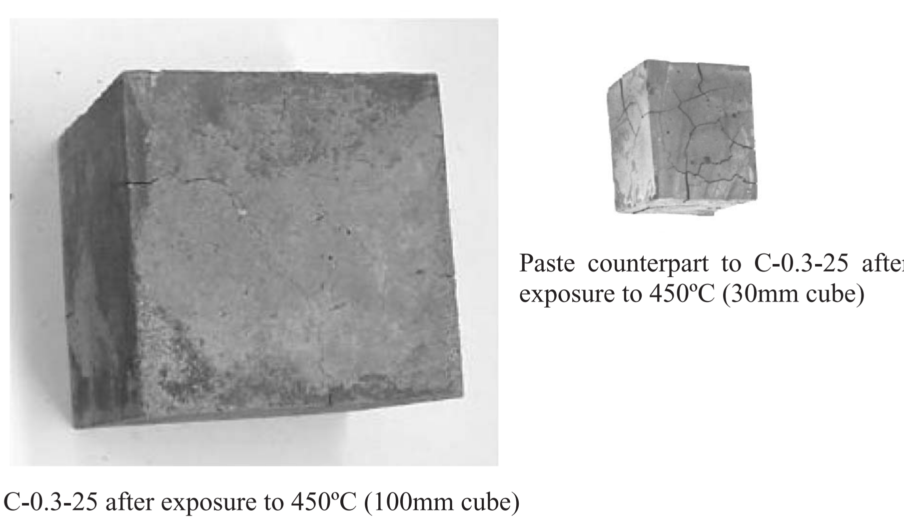


Fig. 5. Comparison of cracking in concrete and pure cement paste.

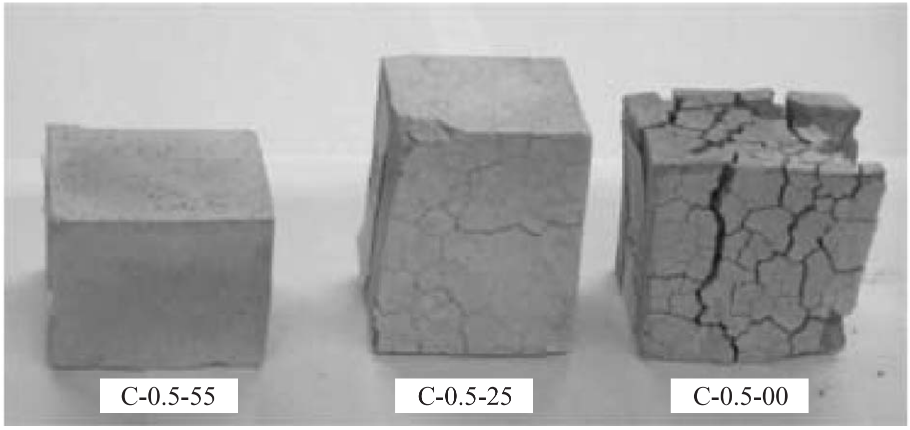


Fig. 6. Cracking of hcp made with a w/b of 0.5 and different PFA contents after exposure to 650 °C.

method for improving its resistance to cracking after exposure to high temperatures.

3.2.1.5. Influence of w/b ratio. In general, a lower w/b ratio leads to higher strength concretes than can resist cracking. Compared with concretes made with a w/b ratio of 0.5, concretes with a w/b of 0.3 showed fewer cracks, but the crack widths and lengths were larger. However, w/b ratios had less influence on the crack pattern than the PFA content. Disintegration occurred in specimens made with a w/b ratio of 0.5, possibly because the specimens had a lower strength that offered less resistance to crack propagation.

3.2.2. Quantitative determination

The results of quantitative determination of crack severity are given in Fig. 7. The crack density almost linearly increased with the maximum exposure temperature starting from room temperature to 650 °C. When the maximum exposure temperature increased from 650 to 800 °C, the development of cracking was significantly increased. These results supported the observations on the influence of PFA contents and w/b ratios discussed previously and confirmed that PFA contents had a more dominant influence than w/b ratios, as the difference between the curves for the concretes made with the same PFA content but different w/b ratios was smaller than those made with different PFA contents but with the same w/b ratio.

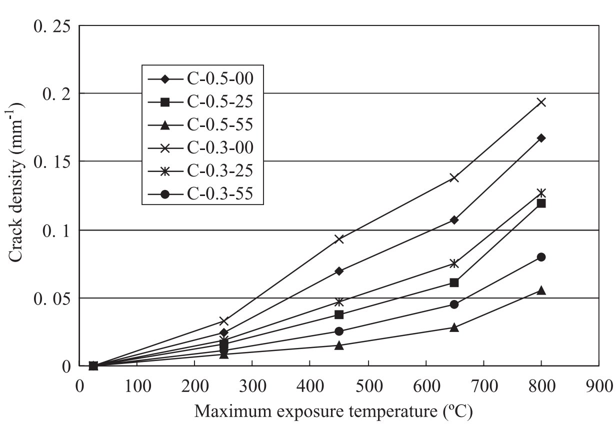


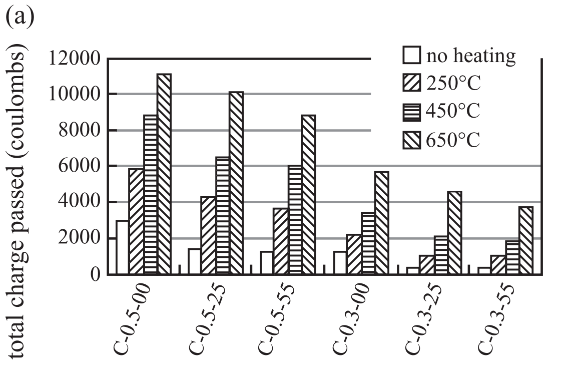
Fig. 7. Crack density of concretes after high temperature exposure.

3.3. Influence of cracking on residual mechanical properties

The degree of concrete cracking seems to have more influence on the tensile strength than on the compressive strength. When the maximum exposure temperature was 250 °C, an increase in compressive strength was observed and yet there was a drop in the tensile strength of concrete. This might be due to the insensitivity of compressive strength to minor cracks. Heating to only 250 °C generated a relatively small amount of cracking, which did not cause any immediate loss of carrying capacity in compression because the slightly cracked concrete could work as a highly redundant structure [21]. However, the orientation of cracking affected the tensile strength of concrete. After exposing to 450 °C and higher temperatures, the residual compressive strength also dropped below the original values with the further crack development. The tensile strength further deteriorated to about 60% of its original value.

3.4. Influence of cracking on deterioration of durability

ASTM-C1202 rapid chloride diffusion tests were conducted on the heated and unheated concrete slices to determine the total charges passed through them. It was found that the total charges passed increased as the maximum exposure temperature rose from 250 to 650 °C (Fig. 8a). The relative total charge passed, expressed as the percentage of total charges passed through the heated specimen to those through the unheated companion specimens, increased almost linearly with the increase in the maximum exposure temperature for concretes with a w/b ratio of 0.5 (Fig. 8b). This observation was consistent with the experimental results on crack density (Fig. 7). It can be explained that cracks shortened the paths of chloride ions



Chloride ion penetrability based on charge passed	
Charge Passed (coulombs)	Chloride Ion Penetrability
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
< 100	Negligible

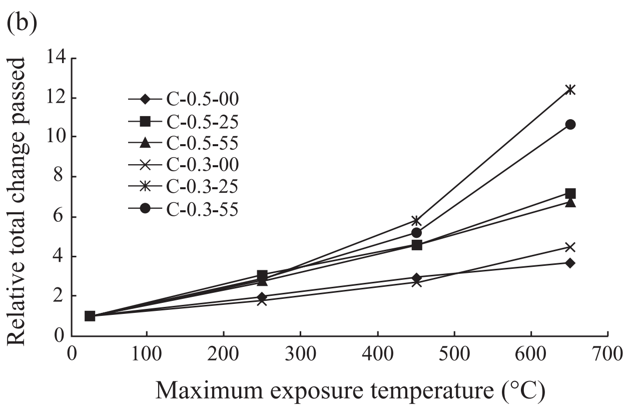


Fig. 8. Chloride diffusion test results. (a) Total charge passed in chloride diffusion tests. (b) Relative total charge passed versus exposure temperature.

to pass through the concrete slices. The presence of cracks seemed to have induced more damage, in terms of chloride ion penetrability, to the concretes with a w/b ratio of 0.3, especially when the maximum exposure temperature was 650 °C. For instance, the C-0.3-25 concrete series showed a rapid nonlinear increasing rate of relative total charge passed but a constant linear increasing rate of crack density. The greatest deterioration in durability, indicated by the relative total charge passed, was observed in the C-0.3-00 concrete series. This might be due to the concretes with a low w/b ratio tended to develop fewer but wider cracks, especially for those without PFA, when exposed to high temperatures.

4. Conclusions

Small cracks were observed after concrete specimens had been exposed to 250 °C. After exposure to 450 °C or higher temperatures, the cracking of concrete was more significant. The crack density increased almost linearly with the exposure temperature up to 650 °C. But significant increase in cracking was observed between 650 and 800 °C.

Cracking patterns varied when different PFA dosages were used in PFA concretes. Pure OPC concrete exhibited several major cracks. With the addition of PFA, a fine network of cracks was observed. Higher PFA contents led to more evenly distributed cracks.

Lower w/b ratios resulted in fewer cracks. However, the cracks were wider and longer in comparison with the cracks in specimens made with higher w/b ratios.

Loss of tensile strength after exposure to 250 °C could be largely ascribed to the emergence of minor cracks in concrete. Concretes suffered losses in compressive strength only when severe cracking occurred after exposure to 450 °C or higher. High temperature exposures induced more damage to the tensile strength of concrete than to the compressive strength.

The deterioration of concrete durability, indicated by the total charges passed in the rapid chloride diffusion test according to ASTM C1202, was related to the increase in crack density with the increase of maximum exposure temperatures. The rate of deterioration of durability was higher in concretes with low w/b ratios than those with higher ratios.

Acknowledgements

This study is part of the RGC Project HKP49/95E. Financial support from the Research Grants Council of the Government of the Hong Kong Special Administrative Region is acknowledged.

References

[1] Y.G. Xu, Y.L. Wong, C.S. Poon, M. Anson, Impact of high temperature on PFA concrete, Cem. Concr. Res. 31 (2001) 1065–1073.

[2] B. Mobasher, H. Stang, S.P. Shah, Microcracking in fiber reinforced concrete, Cem. Concr. Res. 20 (4) (1990) 665–676.

[3] Z.P. Bazant, M.F. Kaplan, Concrete at High Temperatures: Material Properties and Mathematical Models, Longman Group Limited, London, 1996.

[4] R. Philleo, Some physical properties of concrete at high temperatures, ACI J. 29/54 (10) (1958) 857–864.

[5] C.R. Cruz, M. Gilen, Thermal expansion of Portland cement paste, mortar and concrete at high temperatures, Fire Mater. 4 (2) (1980) 66–70.

[6] U. Schneider, Concrete at high temperatures—a general review, Fire Saf. J. 13 (1) (1988) 55–68.

[7] G.A. Khoury, Compressive strength of concrete at high temperatures: a reassessment, Mag. Concr. Res. 44 (161) (1992) 291–309.

[8] G.F. Peng, Evaluation of Fire Damage to High Performance Concrete, PhD thesis, Hong Kong Polytechnic University, 1999.

[9] V.K.R. Kodur, Studies on the fire resistance of high-strength concrete at the national research council of Canada, Proceedings of International Workshop on Fire Performance of High-Strength Concrete, NIST SP 919, NIST, Gaithersburg, MD, USA, 1997 February 13–14.

[10] G.N. Ahmed, Modeling of Coupled Heat and Mass Transfer in Concrete Structures Exposed to Elevated Temperatures, PhD thesis, Kansas State University, Manhattan, Kansas, USA, 1990.

[11] G. Sanjayan, L.J. Stocks, Spalling of high-strength silica fume concrete in fire, ACI Mater. J. 90 (2) (1993) 170–173.
[12] H.L. Malhotra, Design of Fire-Resisting Structures, Surrey Univ. Press, Glasgow, UK, 1982.
[13] K.D. Hertz, Heat Induced Explosion of Dense Concrete, Report No. 166, Institute of Building Design, Denmark, 1984, pp. 1–24.
[14] C. Castillo, A.J. Durrani, Effect of transient high temperature on high strength concrete, ACI Mater. J. 87 (1) (1990) 47–53.
[15] J. Piasta, Heat deformations of cement phases and the microstructure of cement paste, Mat. Struct. 17 (102) (1984) 415–420.
[16] M.A. Riley, Possible new method for assessment of fire-damaged concrete, Mag. Concr. Res. 43 (155) (1991) 87–92.
[17] F.C. Lea, R.A. Stradling, Resistance to fire of concrete and reinforced concrete, Engineering 114 (2959) (1922) 341–344; Engineering 114 (2960) (1922) 380–382.
[18] T. Harada, J. Takeda, S. Yamane, F. Furamura, Strength, elasticity and thermal properties of concrete subjected to elevated temperatures, International Seminar on Concrete for Nuclear Reactors, Detroit, ACI 1 (34) (1972) 377–406 (special publication).
[19] A. Petzold, M. Rohr, Concrete for High Temperatures, Maclaren and Sons, London, 1970.
[20] W.P.S. Dias, G.A. Khoury, P.J.E. Sullivan, Mechanical properties of hardened cement paste exposed to temperatures up to 700C (1292F), ACI Mater. J. 87 (2) (1990) 160–166.
[21] T.T.C. Hsu, F.O. Slate, G.M. Sturman, G. Winter, Microcracking of plain concrete and the shape of the stress–strain curve, ACI J. 60 (2) (1963) 209–224.