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The effect of a proprietary inorganic coating on compressive strength and carbonation depth of simulated fire-damaged concrete

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This paper describes the effect of an inorganic coating of concrete (ICC) on the residual compressive strength and carbonation depth of fire-damaged concrete. The concrete specimens were cooled by water-spraying, which is usually used for fire extinguishing in a real fire. The ICC was applied to enhance the residual compressive strength and to reduce the carbonation depth of fire-damaged concrete at different recurring periods. The results showed that the performance of concrete with ICC was better than that of uncoated concrete. After being exposed to 150, 300, 450, 600 and 750°C, compared to uncoated concrete, the compressive strength of concrete with ICC was enhanced by 3·8%, 3·7%, 11·0%, 17·3% and 6·1%, respectively. For concrete exposed to temperatures below 750°C, the carbonation depth of concrete with ICC was reduced significantly compared to the uncoated concrete. In the case of 750°C, the concrete was neutralised completely for both uncoated and coated concrete. The most obvious enhancement of the compressive strength and the most significant reduction of carbonation depth of concrete with ICC can be found after the concrete was exposed to 600°C. Similar results were confirmed with the other two types of concrete with different compressive strength.

Introduction

When concrete is subjected to a fire, transformations of physical structure and chemical compositions in concrete lead to deterioration of mechanical properties and durability. The deteriorations of mechanical properties and durability of concrete are mainly influenced by the exposure temperature. Georgali and Tsakiridis (2005) concluded that the effect of elevated temperature occurred between 100 and 200°C owing to the evaporation of the moisture in the concrete. The concrete exposed to up to 100°C was still safe. The first sizable degradation in compressive strength usually happens between 200 and 250°C. At 300°C, strength can be reduced in the range of 15–40%. Mendes *et al.* (2008) confirmed that 400°C was the critical temperature for the breakdown of cement pastes due to the dehydration of calcium hydroxide $Ca(OH)_2$, followed by the expansive rehydration of lime (CaO) after cooling. Othuman and Wang (2011) found that between 400 and 600°C, complete desiccation occured and crystals of calcium hydroxide decomposed into calcium oxide and water, resulting in weakened concrete. Peng *et al.* (2008) showed that the compressive strength of concrete significantly decreased between 400 and 600°C, and most of the compressive strength lost from 600 to 800°C. Bastami *et al.* (2011) found that the relative compressive strength of concrete exposed to elevated temperature increased with increasing water–cement ratio.

It has been reported (Poon *et al.*, 2001) that high-strength concrete exposed to elevated temperature had a more severe loss in permeability-related durability than in the compressive strength. Janotka and Bagel (2003) found that the permeability of concrete increased significantly with increasing temperature. The effect of heating temperature on the durability was more significant than on the mechanical properties of concrete. Poon *et al.* (2003) found that high-strength concrete had a very low permeability at 20°C. However, the permeability was clearly increased as the temperature increased to 600°C.

Several researchers have investigated (Alonso and Fernandez, 2004; Annerel and Taerwe, 2009; Lin *et al.*, 1996, 2011; Poon *et al*

2 *al.*, 2001; Souza, 2010; Yang *et al.*, 2009) the compressive strength recovery of concrete exposed to elevated temperature. It is realised that the fire-damaged concrete could regain part of its strength in the post-fire-curing period owing to the rehydration of the C-S-H gel. It has been mentioned (Lin *et al.*, 1996) that spraying water on the fire-damaged concrete could enhance the
3 rehydration of concrete. Poon *et al.* (2001) reported that the maximum relative compressive strength of concrete recovered to 49% for 600°C and 31% for 800°C after recurring for 56 days. Annerel and Taerwe (2009) concluded that, after recurring in water for 56 days, the compressive strength of concrete exposed to 350 and 550°C can be recovered to about 70% and 30% of the original value, respectively. The compressive strength of concrete exposed to 600°C can be recovered to 85% after recurring in water for 56 days (Souza, 2010). Lin *et al.* (2011) found that the compressive strength of the concrete exposed to 400°C can be fully recovered to the original strength after the concrete were cured in water for 180 days. Yang *et al.* (2009) found that the residual compressive strength of concrete decreased with increasing exposure temperature, and prolonging the recurring period did not help restore compressive strength significantly. It has been reported (Alonso and Fernandez, 2004) that the heated cement paste was not stable in the wet atmosphere and rehydration processes took place. In addition, a progressive damage was developed with coarse cracking because of rehydration.

Carbonation resistance is one of the most important issues of concrete durability. Few investigations on the durability recovery of the concrete exposed to elevated temperature have been carried
4 out. Poon *et al.* (2001) concluded that most of the concrete still had very high permeability, although there was a significant recovery after post-fire-curing for 56 days in water. There was a significant decrease in the average pore diameter after recurring in water.

The surface coating had been used to protect concrete structures which were located in a corrosive environment (Almusallam *et al.*, 2003; Moon *et al.*, 2007; Moradllo *et al.*, 2012; Seneviratne *et al.*, 2000). Seneviratne *et al.* (2000) applied three elastomeric surface coatings to the naturally carbonated concrete components obtained from buildings and successfully extended the service life of reinforced concrete structures. The concrete surface coatings were applied (Moradllo *et al.*, 2012) and caused a reduction in the chloride penetration and enhanced the service life of concrete structures. Moon *et al.* (2007) adopted an inorganic coating to improve the penetration of chloride, freezing–thawing and carbonation resistance of concrete. The results showed that the durability of concrete was improved with a calcium–silicate compound. The effectiveness of five types of surface coating in improving concrete durability has been presented (Almusallam *et al.*, 2003) and the results indicated that the epoxy and polyurethane
5 coating could improve the durability of concrete than the others.

In spite of the importance of regaining properties of fire-damaged concrete in terms of repair, the results are still lacking for enhancing the mechanical property and durability of fire-damaged concrete with inorganic coating of concrete (ICC). This study was conducted to evaluate the effect of inorganic coating on the compressive strength and the carbonation depth of concrete. The concrete specimens were heated to different temperatures and cooled by spraying water. The compressive strength and carbonation depth of concrete with and without ICC were measured at different post-fire-curing periods.

Research significance

Although there are many investigations on the mechanical properties and durability of concrete exposed to elevated temperature, there is a lack of information about the enhancement of compressive strength and durability of fire-damaged concrete with surface
coating material. Compared to recurring in water, improving the 6
property recovery of fire-damaged concrete with ICC is more feasible and effective. The lack of enhancing properties of fire-damaged concrete with inorganic coating makes it necessary to investigate the effectiveness of ICC in improving the compressive strength and carbonation depth of fire-damaged concrete.

Experimental programme

In this paper, the variables of exposure temperature, inorganic coating of concrete and recurring period were taken into account. Three types of concrete – M1, M2 and M3 – were prepared. Concrete specimens of M1 were exposed to temperatures up to 750°C. Concrete specimens of M2 and M3 were exposed to 600°C. After heating, concrete specimens were divided into two groups: specimens with and without ICC. Then the compressive strength and the carbonation depth of fire-damaged concrete after recurring for 0, 30, 60 and 90 days were tested.

Materials

Ordinary Portland cement of 42·5 grade was used to prepare the concrete. The specific gravity of cement is 3·16. The chemical and physical properties of cement are presented in Table 1. Crushed siliceous stone with a maximum size of 25 mm was used

Characteristics	Value
SiO_2	20·88
Al_2O_3	5·54
Fe_2O_3	2·75
CaO	64·34
Na_2O	0·25
MgO	1·72
K_2O	0·42
SO_3	1·94
Ignition loss: %	0·92
Specific gravity	3·16
Specific surface: cm^2/g	3280

Table 1. Chemical and physical properties of cement

as a coarse aggregate. Sea sand was used as a fine aggregate. The physical properties of the coarse aggregate and fine aggregate are summarised in Table 2. The water used in this study was potable water which is free from a harmful amount of deleterious materials. The superplasticiser was used to obtain workable concrete mixtures. Polypropylene fibre with a length of 12 mm was used at 0·1% per cubic meter to improve the spalling resistance of concrete during heating.

In order to increase the compressive strength and reduce the carbonation depth of concrete, the ICC was applied on the surface of concrete exposed to an elevated temperature. The ICC is a viscous liquid, which is a patented product with a silicate system material produced in Japan. It is usually used on the surface of concrete to strengthen concrete or repair cracks in order to lower the water permeability. The ICC reacts with $Ca(OH)_2$ in concrete to form C-S-H when the water exists. The reaction product fills into the pores and cracks in concrete. The main component and physical properties of the ICC are listed in Table 3.

Mixture proportions and specimens

The concrete mix proportions are shown in Table 4. Three types of concrete were prepared using water–cement ratios of 0·50, 0·55 and 0·35, respectively. Cylindrical specimens with diameter of 100 mm and length of 200 mm were produced for the compressive strength test. The dimensions of concrete specimens used for carbonation test were 100 × 100 × 400 mm. After a period of 28 days curing in water at 20 ± 2°C, the specimens were placed in a curing room maintained at 20 ± 2°C and 60 ± 5% relative humidity for 90 days until they were heated.

Heating and cooling regimes

Before heating, the compressive strength of concrete M1, M2 and M3 were 46·0, 41·2 and 65·1 MPa, respectively. At the age of 90 days, the specimens of concrete M1 were heated in an electric furnace up to 150, 300, 450, 600 and 750°C. The concrete specimens M2 and M3 were heated up to 600°C. The average heating rate of the electric furnace used in this study was 5°C/min. The concrete specimens were exposed to the chosen peak temperatures for 150 min, and then they were taken out from the electric furnace and cooled down to room temperature by spraying water. No explosive spalling was observed during the heating test.

Content	Property
Main components	Sodium silicate
Appearance	Colourless, transparent
Odours	Odourless
Specific gravity	1·24
pH	11·3
Kinematic viscosity	< 5·70 cSt

Table 3. Properties of inorganic coating of concrete (ICC)

Mix	w/c ratio	Mixture proportion: kg/m^3				
		Water	Cement	FA	CA	SP
M1	0·50	175	350	757	1035	1·24
M2	0·55	175	318	812	982	1·10
M3	0·35	175	500	719	940	2·98

FA: fine aggregate, CA: coarse aggregate, SP: superplasticiser.

Table 4. Mix proportions of concrete

Coating process of ICC

The surface of the concrete specimen was moistened with water before applying the ICC. The total dosage of ICC used on the concrete surface was approximately 0·4 kg/m^2. The quantity of ICC coated on the surface of concrete specimen for the first time was about 0·2 kg/m^2. Then the surfaces were sprinkled with water (approximately 1 lit/m^2) after the ICC on the surface became dry naturally. The quantity of ICC applied on the surface of concrete for the second time was also about 0·2 kg/m^2. The concrete specimens with ICC were cured with sprinkling water about 1 lit/m^2 twice every day for 7 days.

Post-fire-curing method

After cooling down to the room temperature, the concrete specimens were divided into two groups: cured with ICC and cured without ICC. In order to expedite rehydration of concrete without ICC the same as for concrete with ICC, the concrete specimens

Aggregates type	D_{max}: mm	Solid volume percentage: %	FM	Specific gravity	W_b: %
Coarse aggregate	25	58·6	6·67	2·73	0·40
Fine aggregate	5	65·1	2·57	2·59	1·65

D_{max}: maximum aggregate size; FM: fineness modulus; W_b: water absorption

Table 2. Physical properties of coarse aggregate and fine aggregate

without ICC were also sprinkled with water about 1 lit/m^2 twice every day for 7 days. Afterwards, all of the concrete specimens were stored in air (20 ± 2°C and 60 ± 5%) in the laboratory for 30, 60 and 90 days.

Accelerated carbonation testing

In order to measure the carbonation depth of concrete, the accelerated carbonation test was carried out at 0, 30, 60 and 90 days after the specimens were cooled down to room temperature. At the age of the scheduled recurring period, the specimens were put into the accelerated carbonation apparatus – the Asahi neutralisation test chamber – at a temperature of 20 ± 2°C and a relative humidity of 60 ± 5%. After being exposed to carbon dioxide at a concentration of 10% for 7 days, the concrete specimens were taken out and the carbonation depth was determined by the phenolphthalein method according to the Japanese standard (JIS A1152-2011 (JIS, 2011)). The concrete specimens were split in an indirect tensile test and the freshly split surfaces, which had been cleaned of dust and loose particles, were sprayed with a pH indicator. The indicator was a phenolphthalein 1% ethanol solution with 1 g phenolphthalein and 90 ml (95·0% V/V) ethanol diluted in water to 100 ml.

Results and discussion

Compressive strength

The residual compressive strength and relative compressive strength ratios of concrete after post-fire-curing for 0, 30, 60 and 90 days are reported in Table 5 and Figure 1.

Figure 1(a) illustrates the variation of relative compressive strength of concrete M1. The test results clearly indicate that the compressive strength of concrete depends on the heating temperature and ICC. For the concrete specimens exposed to temperatures of 150, 300 450 and 600°C, the compressive strength increased obviously with the recurring period without ICC. The compressive strength of concrete with ICC increased more than that of concrete without ICC. After being exposed to 750°C, the compressive strength of concrete without ICC cannot be recov-
7 ered further after recurred for longer than 30 days. The compressive strength of concrete with ICC was higher than that of concrete without ICC. Figures 1 (b) and (c) show the compressive strength of concrete M2 and M3 exposed to 600°C, respectively. The test results indicate that the compressive strength recovery of concrete with ICC was substantially higher than those without ICC.

As shown in Figure 1(a), for concrete specimens without ICC, the residual compressive strength increased with the recurring period only when the concrete specimens were subjected to temperatures below 750°C and cooled by spraying water. The residual compressive strength ratios reduced with the increasing temperature. The relative compressive strength ratios of concrete exposed to 150°C increased from 96·1% to 99·2%, 100·5% and 102·7% after recurring for 30, 60 and 90 days, respectively. For concrete specimens with ICC, the residual compressive strength ratio increased obviously with recurring period and was higher than that of the concrete without ICC. The relative compressive strength ratios of concrete exposed to 150°C increased from 96·1% to 101·1%, 103·7% and 106·5% after recurred for 30, 60 and 90 days, respectively. For concrete exposure to 300°C, the residual strength ratios of concrete without ICC increased from 80·5% to 96·7% after recurring for 90 days, and they increased from 80·5% to 100·4% for concrete with ICC. After recurring for 90 days, the residual strength ratios of concrete exposed to 450°C increased to 80·2% and 91·3% for concrete without ICC and with ICC, respectively. The effect of ICC on the compressive strength recovery of concrete exposed to 600°C was more obvious. Without ICC, the relative compressive strength of concrete exposed to 600°C increased from 33·6% to 46·9% after recurring for 90days. However, the relative compressive strength of concrete with ICC increased from 33·6% to 64·2%. For the case of 750°C, the

Temperature: °C		Days after heating	Without ICC: MPa	With ICC: MPa
M1	150	0	44·2 (96·1%)	
		30	45·7 (99·2%)	46·5 (101·1%)
		60	46·2 (100·5%)	47·7 (103·7%)
		90	47·3 (102·7%)	49·0 (106·5%)
	300	0	37·0 (80·5%)	
		30	41·1 (89·4%)	42·1 (91·5%)
		60	42·3 (91·9%)	44·7 (97·2%)
		90	44·5 (96·7%)	46·2 (100·4%)
	450	0	31·0 (67·3%)	
		30	33·8 (73·4%)	37·0 (80·3%)
		60	35·7 (77·5%)	39·8 (86·5%)
		90	36·9 (80·2%)	42·0 (91·3%)
	600	0	15·5 (33·6%)	
		30	18·8 (41·0%)	23·4 (50·9%)
		60	21·9 (47·5%)	28·8 (62·7%)
		90	21·6 (46·9%)	29·5 (64·2%)
	750	0	8·5 (18·4%)	
		30	12·9 (28·0%)	15·5 (33·7%)
		60	13·4 (29·0%)	16·1 (35·0%)
		90	13·2 (28·7%)	16·0 (34·8%)
M2	600	0	13·3 (32·3%)	
		30	17·5 (42·8%)	21·3 (51·9%)
		60	19·5 (47·6%)	23·5 (57·3%)
		90	20·2 (49·1%)	25·8 (62·9%)
M3	600	0	18·2 (28·1%)	
		30	21·8 (33·6%)	28·6 (44·0%)
		60	23·4 (36·0%)	32·1 (49·3%)
		90	25·6 (39·4%)	37·7 (58·0%)

The values in brackets indicate the relative compressive strength as compared to the original strength before heating.

Table 5. Compressive strength of post-fire-curing concrete

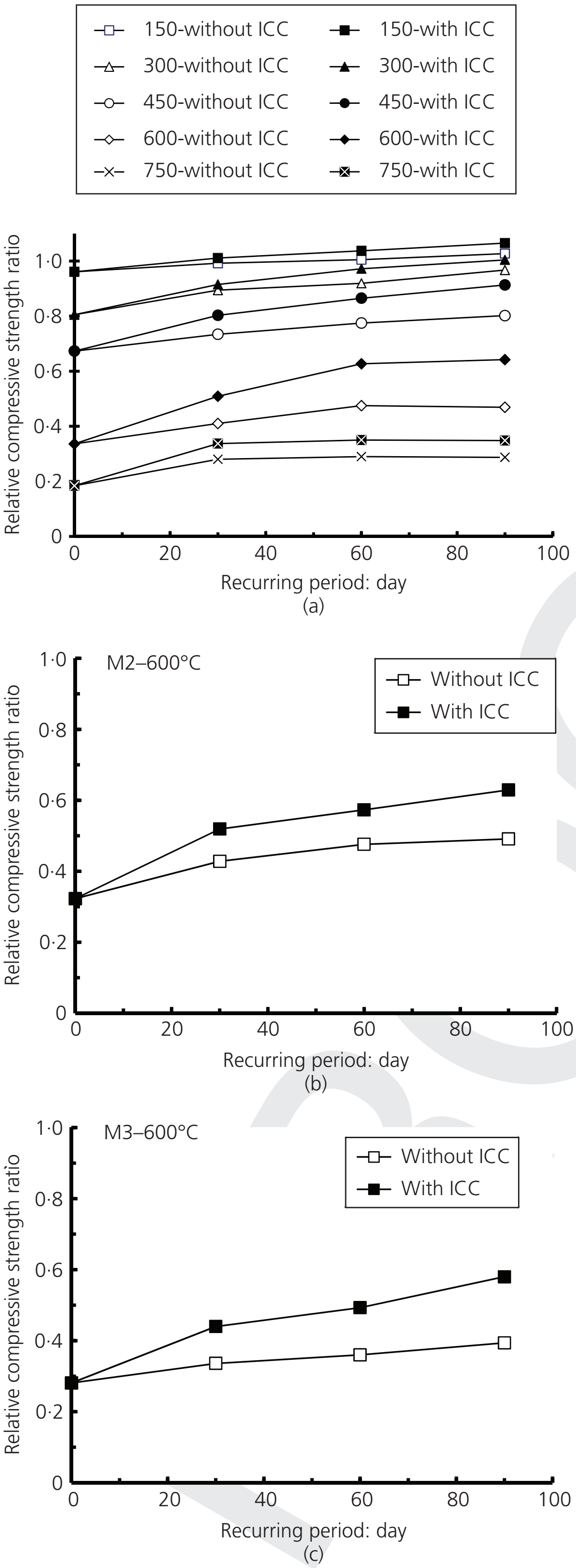

Figure 1. Residual compressive strength of post-fire-curing concrete: (a) M1, (b) M2 and (c) M3

relative strength ratio of concrete without ICC increased gradually from 18·4% to 28·7% after recurring for 90 days, whereas the relative strength ratio of concrete with ICC increased from 18·4% to 34·8%. This means that, after exposure to temperatures of 600 and 750°C, the compressive strength of water-cooling concrete without ICC can only increase by 13·3% and 10·3%, respectively. However, with ICC the relative compressive strength of concrete exposed to 600 and 750°C can increase by 30·6% and 16·4%, respectively.

According to Georgali and Tsakiridis (2005), cracking and softening, following by decrepitation of the concrete surface is caused first by expansion and then by shrinking of the cement paste due to the transformation of $Ca(OH)_2$ to CaO in the temperature between 450 and 500°C. Alonso and Fernandez (2004) stated that rehydration process of fire-damaged concrete took place in the wet atmosphere. According to the conclusions of the study (Lin *et al.*, 2011), the residual compressive strength of air-cooling concrete exposed to 600°C only recovered to 28% after recurring in the air for 180 days. The advantage of ICC on the recovery of compressive strength of concrete was probably attributed to the permeation of ICC and rehydration reaction. ICC permeated into the concrete through the cracks and coarsened pore structure due to elevated temperature. The reaction product between ICC and $Ca(OH)_2$, C-S-H, fills into the pores and cracks in the concrete.

In Figure 1(b), for concrete M2 exposed to 600°C, the relative compressive strength of concrete without ICC increased from 32·3% to 49·1% after recurring for 90 days. However, for the concrete with ICC, the relative compressive strength increased to 62·9% after recurring for 90 days. The relative compressive strength of concrete with ICC was 13·8% higher than that of concrete without ICC.

Figure 1 (c) shows the effect of ICC on the compressive strength of high-strength concrete M3 exposed to 600°C. Without ICC, the relative compressive strength increased from 28·1% to 39·4% of the initial value after recurring for 90 days. For concrete with ICC, the relative compressive strength of concrete was 58·0%, which was higher than that of the concrete without ICC. The relative compressive strength of high-strength concrete M3 was lower than that of normal-strength concrete M1 and M2. This result is similar to the conclusions obtained by the researchers (Ichise *et al.*, 2003; Matsudo *et al.*, 2006). Ichise *et al.* (2003) observed that the residual compressive strength of high-strength concrete exposed to 600°C was 38% of the initial value after recurred for 56 days. Matsudo *et al.* (2006) found that the residual compressive strength ratio of ultra-high strength concrete exposed to 600°C was only 0·2 after recurred for 2 years. The loss in compressive strength of concrete exposed to high temperatures may be related to the loss in bound water, the increased porosity and consequently the increased permeability, which makes the concrete progressively more susceptible to the further destruction.

Carbonation depth

In order to measure the carbonation depth of concrete, the accelerated carbonation test was performed. The carbonation depth of concrete, which was placed in the accelerated carbonation apparatus for 7 days, was measured. The results are presented in Table 6 and Figure 2.

Figure 2(a) shows the carbonation depth of the post-fire-curing concrete M1 exposed to 150, 300, 450, 600 and 750°C. It is clear that the carbonation depth of concrete increased with increasing heating temperatures. The carbonation depth was also influenced significantly by ICC.

As shown in Figure 2(a), for the concrete M1 without ICC, the carbonation depth of the concrete exposed to 150 and 300°C decreased gradually with recurring period. The carbonation depth of concrete reduced from 2·1 to 1·1 mm for the exposure of 150°C. The carbonation depth of concrete reduced from 4·2 to 3·8 mm for the exposure of 300°C. This means that, the carbonation resistance of concrete recovered obviously for the concrete

Temperature: °C		Days after heating	Without ICC: mm	With ICC: mm
M1	150	0	2·1	
		30	1·5	1·0
		60	1·3	0·7
		90	1·1	0·6
	300	0	4·2	
		30	4·0	2·2
		60	3·9	2·0
		90	3·8	1·4
	450	0	12·5	
		30	15·5	5·1
		60	15·0	8·3
		90	16·5	8·5
	600	0	21·5	
		30	26·5	9·8
		60	27·5	17·3
		90	28·0	18·2
	750	0	50·0	
		30	50·0	50·0
		60	50·0	50·0
		90	50·0	50·0
M2	600	0	21·2	
		30	25·6	9·4
		60	26·5	16·3
		90	27·8	17·8
M3	600	0	13·2	
		30	14·4	6·5
		60	17·9	11·4
		90	21·6	13·0

Table 6. Carbonation depth of post-fire-curing concrete

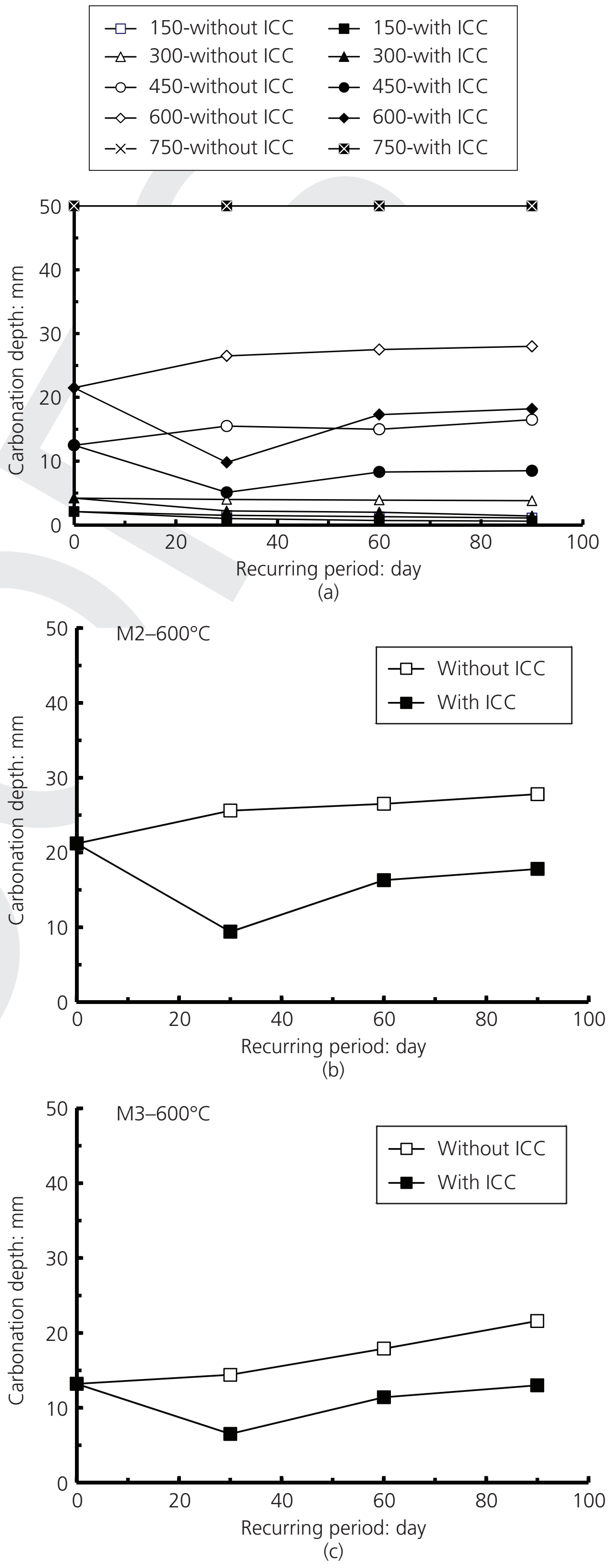

Figure 2. Carbonation depth of post-fire-curing concrete: (a) M1, (b) M2 and (c) M3

exposed to temperatures of 150 and 300°C. After recurring for 90 days, the carbonation depths of concrete exposed to 150 and 300°C with ICC were 0·6 and 1·4 mm, respectively. The carbonation depths of the concrete with ICC were much smaller than those of concrete without ICC.

From Figure 2(a) it can be seen that, without ICC, the carbonation depth of the concrete specimens exposed to 450 and 600°C increased gradually with recurring period. For 450°C, the carbonation depth increased from 12·5 to 15·5, 15·0, 16·5 mm after recurring for 30, 60, 90 days, respectively. The carbonation depth of concrete exposed to 600°C increased from 21·5 to 26·5, 27·5 and 28·0 mm after recurring for 30, 60, 90 days, respectively. The reduction in carbonation resistance is mainly attributed to the decline in the permeability with increasing temperature. The higher the temperature heated, the greater the carbonation depth became. This can be explained by the evaporation of free water, which leads to many gas channels in the concrete. It has been reported that the increase in permeability was directly related to the maximum temperature (Noumowe *et al.*, 2009). A similar result was concluded in another research (Janotka and Bagel, 2003): the permeability of concretes increased drastically with increasing heating temperature. This means that when the heating temperature rose up to 450 and 600°C, the carbonation resistance could not recover in the same
8 way as those heated at 150 and 300°C. This is because heating at 450 and 600°C caused more severe damage than at 150 and 300°C. For 450°C, the carbonation depth of concrete without ICC increased from 12·5 to 16·5 mm, whereas the carbonation depth of concrete with ICC reduced gradually from 12·5 to 8·5 mm. For concrete exposed to 600°C, the carbonation depths were 28·0 mm and 18·2 mm for concrete without ICC and with ICC, respectively. For specimens subjected to 750°C, the carbonation depth of the concrete came up to 50 mm, and could not reduce after recurred for 90 days even if the ICC was used. This means that, if the concrete were heated up to 750°C, the carbonation resistance could not be recovered due to the damage of elevated temperature. The application of ICC significantly reduced the carbonation depth of the concrete specimens subjected to elevated temperature. It was attributed to the reaction products of ICC, which obstructed the diffusion of carbon dioxide into the concretes. However, it is invalid for the concrete exposed to temperatures of 750°C and above.

According to Georgali (2005), the existence of cracking owing to the internal shrinkage of concrete is caused by heating followed by rapid cooling (due to fire-extinguishing). Therefore, sudden cooling by water produces many micro-cracks in concrete exposed to 600 and 750°C. The dehydrated cement paste would rehydrate, and the CaO would participate in rehydration process with water to form new portlandite. This would expand to aggravate the damage of the pore structure in concrete. It becomes easy to react with carbon dioxide after CaO transforms to $Ca(OH)_2$. In addition, the porous structure was filled with water in case of the water cooling, which accelerates carbon dioxide to penetrate into concrete. The carbonation depth of the concrete specimens was still very high even re-cured for 90 days.

As shown in Figures 2(b) and (c), for concrete M2 and M3 exposed to 600°C, the carbonation depth of specimens with ICC was much smaller than that of concrete without ICC. Similar to concrete M1, after recurring for 90 days, the carbonation depth of concrete M2 and M3 with ICC was much smaller than half of the carbonation depth of concrete without ICC. After recurring for 90 days, the carbonation depths of concrete M2 and M3 with ICC were 10·4 and 6·7 mm, respectively. The carbonation depths of concrete M2 and M3 without ICC were 21·1 and 10·4 mm, respectively. Peng and Huang (2008) reported that the decomposition of concrete became significant and the decomposition rate of C-S-H increased dramatically at 600°C. Handoo *et al.* (2002) pointed out that concrete exposed to 600°C revealed massive changes in the morphology of concrete owing to the predominance of micro cracks, voids increasing the porosity of concrete deformed $Ca(OH)_2$ crystals, and disrupted C-S-H phase boundaries.

The carbonation depth is related to the permeability of concrete exposed to elevated temperature. The reduction in carbonation resistance is mainly attributed to a decline in the permeability with increasing temperature. That is the impermeability loss of fire-damaged concrete resulting in the increase of the carbonation
depth of concrete. Poon *et al.* (2001) pointed out that the 9
impermeability recovery pattern was similar to the compressive strength recovery of concrete re-cured in water. The reduction in carbonation resistance is mainly attributed to the decline in the permeability with increasing temperature. It has been concluded that total porosity increased in a non-linear way with an increase in temperature because of the decomposition of hydration products (Chan *et al.*, 2000). Piasta (1984) found that the increase in total porosity of cement paste in the temperature ranged from 300 to 500°C, mainly owing to the increase of porosity, which
may be caused by the formation of micro cracks. Poon *et al.* 10
(2001) concluded that it was necessary carefully to investigate 11
the durability properties of concrete after a fire even if the concrete has recovered a substantial portion of its compressive strength. Othuman and Wang (2011) explained that the carbon dioxide was released from calcium carbonation between 750 and 850°C.

Conclusions

In this study, the compressive strength and carbonation depth of fire-damaged concrete applied with ICC were investigated. The experimental results indicate that the elevated temperature and ICC have a noticeable effect on the compressive strength and carbonation depth of the concrete. The following conclusions can be drawn from this study

- The residual compressive strength of water-cooling concrete exposed to elevated temperature depends on the elevated temperature. For concrete subjected to temperatures below

750°C, the compressive strength obviously recovered along with the recurring period. Recurring for 90 days without ICC, the relative compressive strengths of concrete exposed to 150, 300, 450, 600 and 750°C were 102·7%, 96·7%, 80·2%, 46·9% and 28·7%, respectively.

- The ICC could effectively increase the residual compressive strength of concrete exposed to temperature up to 750°C. Recurring for 90 days with ICC, the relative compressive strengths of concrete exposed to 150, 300, 450, 600 and 750°C were 106·5%, 100·4%, 91·3%, 64·2% and 34·8%, respectively.
- The carbonation depth of concrete increased with increasing the heating temperature. The carbonation depth gradually reduced for concrete exposed to temperatures below 450°C. However, the carbonation depth of concrete exposed to temperatures of 450 and 600°C increased gradually without ICC. The concrete exposed to 750°C was neutralised completely.
- The ICC significantly decreased the carbonation depth of concrete exposed to elevated temperature, which means that the ICC could effectively enhance the carbonation resistance of concrete exposed to elevated temperatures below 600°C. The carbonation depth of concrete exposed to 750°C could not decrease, although they were coated with ICC.
- The ICC is a very attractive solution to improve the recovery of compressive strength and carbonation resistance of concrete exposed to elevated temperature. The most effective exposure temperature for ICC is 600°C.

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1: Is this Pool et al. 2001a or 2001b?
2: Poon et al. 2001a or 2001b
3: Poon 2001a or 2001b?
4: Poon 2001a or 2001b?
5: 'The effectiveness of...; At the end of this sentence, 'durability of concrete than the others'. Should this be 'more than the others' or 'less than the others'?
6: 'Compared to recurring in water'. Sense OK?
7: 'after recurred for longer'. Please check sense. Should this be 'after recurring for longer'?
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