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Strength and durability recovery of fire-damaged concrete after post-fire-curing

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Abstract

The effect of post-fire-curing on the strength and durability recovery of fire-damaged concrete was investigated. Twenty normal- (NSC) and high-strength concrete (HSC) mixes incorporating different pozzolans were prepared and exposed to elevated temperatures till 800°C. After natural cooling, the specimens were subjected to post-fire-curing in water and in a controlled environment for a total duration of 56 days. Unstressed compressive strength, rapid chloride diffusion, and mercury intrusion porosimetry (MIP) tests were conducted to examine the changes in the macro- and microstructure of the concrete. The test results indicated that the post-fire-curing results in substantial strength and durability recovery and its extent depend upon the types of concrete, exposure temperature, method, and duration of recuring. In one case, the recovered strength was 93% of the original unfired strength. Scanning electron microscopy (SEM) investigations indicated that the recovery was due to a number of rehydration processes that regenerate the calcium-silicate-hydrate (C-S-H). The new rehydration products were smaller in size than the original hydration products and filled the internal cracks, honey combs, and capillaries created during the fire. The surface crack widths were also reduced during the recuring process, and in most cases, they were found within the maximum limits specified by the American Concrete Institute (ACI) building code. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: High temperature; Compressive strength; Durability; Microstructure; Hydration products

1. Introduction

When exposed to high temperatures, such as in a fire, concrete undergoes a series of changes in its chemical composition and physical structure. These changes occur primarily in the hardened cement paste (HCP) starting from the dissociation of calcium hydroxide (CH) at 400°C, and continue until the complete destruction of the calcium-silicate-hydrate (C-S-H) gel at around 900°C. As a result of these changes, concrete gradually and sometimes sharply loses its mechanical strength and durability [1]. Recently, Poon et al. [2] found that the durability loss is usually higher than the mechanical strength losses especially in high-strength concrete (HSC). The effects of high temperature can be visually seen in the form of surface cracking, spalling, and disintegration that render the concrete structure unserviceable.

Resources could be conserved if the fire-damaged concrete structure is repairable. The common repairing processes essentially involve the removal of weakened layers of concrete and their replacement with fresh concrete [3]. However, a few past studies indicated that the fire-damaged concrete could regain its strength without repairing, if it is properly recured in water or in a moist environment [4–8]. This phenomenon is significant as it could reduce the expenses required for repair and rehabilitation of the concrete structure and worth more detailed investigations.

The phenomenon of strength regain after post-fire-recuring was first reported by Crook and Murray [4] in 1970 who studied the ceramic glazing of concrete and involved the firing of concrete blocks at 620°C. The strength of concrete was reduced by the exposure to high temperature, but when the blocks were soaked in water for a short time, the original strength was substantially regained. In one case, the postfire strength was more than the original strength and longer periods of soaking gave higher strength. It was concluded that the capillaries initially blocked by the C-S-H gel were opened during the fire and filled by smaller rehydration

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Table 1
Chemical composition and physical properties of cementitious materials

Cementitious materials	OPC	SF	FA	GGBS	MK
Chemical composition (%)					
Silicon dioxide (SiO_2)	19.61	90.26	56.79	38.14	53.20
Aluminum oxide (Al_2O_3)	7.33	0.63	28.21	6.53	43.90
Ferric oxide (Fe_2O_3)	3.32	0.33	5.31	0.40	0.38
Calcium oxide (CaO)	63.15	3.18	< 3.00	35.77	0.02
Magnesium oxide (MgO)	2.54	0.33	5.21	13.65	0.05
Sodium oxide (Na_2O)	–	–	–	0.36	0.17
Potassium oxide (K_2O)	–	–	–	0.40	0.10
Sulfur trioxide (SO_3)	2.13	0.4	0.68	–	–
Loss on ignition	2.97	4.84	3.90	0.76	0.50
Physical properties					
Specific gravity	3.16	2.22	2.31	2.52	2.62
Specific surface (cm^2/g)	3519	–	4120	4700	12,680

products produced by the carbonation process in the presence of moisture. The rehydration process reduced the porosity of concrete and resulted in strength regain.

These findings were confirmed by Harada et al. [5] during their investigations on concrete used for nuclear reactors. However, they observed that the process of strength regain was slow and followed by an initial drop during the first 1 month. For concrete subjected to 500°C, approximately 70% strength was recovered after 4 months and about 90% after 12 months. A recovery was also observed in elasticity with a linear trend, but it was not as significant as in the case of compressive strength. They further mentioned that large cracks were produced after 500°C that were not reclosed during the recuring process.

Khoury [6] suggested that the regain of strength was due to the rehydration of the gel, as well as the hydration of unhydrated cement grains. A loss of strength was also observed in some specimens after recuring due to the rehydration of lime, which is an expansive process. It was recommended that the blended concretes with less CH content could perform better during firing and recuring.

In a later study, Sarshar and Khoury [7] indicated that the initial reduction of strength during post-fire-curing might be due to the relative expansion of the moistened outer layers of concrete, and the subsequent recovery was a result of the regeneration of C-S-H bonds upon rehydration. They confirmed the importance of the method of recuring as the specimens soaked in water for 7 days registered lower compressive strengths than the specimens exposed to 100% relative humidity (RH). The best recovery was shown by a slag concrete with fire brick aggregates that regained 90–100% of its original strength after 90 days of recuring from 500°C exposure.

Lin et al. [8] investigated the microstructures of fire-damaged concrete using scanning electron microscopy (SEM). They found that the absorption of moisture from the surrounding medium provides a mechanism for the rehydration of calcium oxide and unhydrated cement grains that refilled the void spaces. They observed long irregular fibers of C-S-H gel mingled with ettringite and CH crystals formed as a result of rehydration. It was suggested that

Table 2
Concrete mix proportions

Mix	SF (%)	FA (%)	GGBS (%)	MK (%)	Water/binder	Batched quantities (kg/m^3)					28 days compressive strength (MPa)
						Water	Cement	Fine aggregate	Coarse aggregate	SP[a]	
HSC											
HS-CC[b]	–	–	–	–	0.30	150	500	758	927	0.5	85.9
HS-SF5	5	–	–	–	0.30	150	475	710	1066	0.6	96.5
HS-SF10	10	–	–	–	0.30	150	450	620	1151	0.8	108.3
HS-FA20	–	20	–	–	0.30	150	400	618	1147	0.8	82.7
HS-FA30	–	30	–	–	0.30	150	350	615	1143	0.7	80.2
HS-FA40	–	40	–	–	0.30	150	300	613	1139	0.7	76.7
HS-SF + FA	10	20	–	–	0.30	150	350	615	1142	0.8	105.3
HS-BS30	–	–	30	–	0.30	150	350	616	1145	0.7	83.9
HS-BS40	–	–	40	–	0.30	150	300	615	1142	0.7	80.9
HS-MK5	–	–	–	5	0.30	150	475	713	1065	0.6	107.3
HS-MK10	–	–	–	10	0.30	150	450	625	1149	0.8	123.1
HS-MK20	–	–	–	20	0.30	150	400	609	1142	1.1	131.3
NSC											
NS-CC[b]	–	–	–	–	0.50	195	390	768	917	–	35.8
NS-FA30	–	30	–	–	0.50	195	273	626	1133	–	39.3
NS-FA40	–	40	–	–	0.50	195	234	625	1129	–	36.9
NS-BS30	–	–	30	–	0.50	195	273	626	1135	–	46.4
NS-BS40	–	–	40	–	0.50	195	234	625	1132	–	39.8
NS-MK5	–	–	–	5	0.50	195	370	710	1067	–	40.7
NS-MK10	–	–	–	10	0.50	195	351	620	1154	0.2	47.6
NS-MK20	–	–	–	20	0.50	195	312	618	1149	0.5	58.4

[a] SP content in percentage by weight of binder.
[b] Control concrete.

Table 3
Unstressed residual compressive strength before and after recuring

Mix	Compressive strength (MPa)														
				Recuring after 600°C						Recuring after 800°C					
	After cooling			Air-recuring			Water-recuring			Air-recuring			Water-recuring		
	20°C	600°C	800°C	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
HSC															
HS-CC	91.3	53.0 (58%)	21.9 (24%)	59.2 (65%)	61.2 (67%)	61.8 (68%)	64.9 (71%)	71.6 (78%)	63.0 (69%)	30.2 (33%)	33.5 (37%)	34.2 (37%)	49.4 (54%)	56.1 (61%)	47.5 (52%)
HS-SF5	106.1	55.2 (52%)	22.3 (21%)	59.1 (56%)	61.5 (58%)	61.9 (58%)	83.9 (79%)	87.4 (82%)	88.5 (83%)	31.5 (30%)	36.8 (35%)	37.9 (36%)	46.8 (44%)	54.1 (51%)	57.3 (54%)
HS-SF10	119.9	52.8 (44%)	19.2 (16%)	57.2 (48%)	57.9 (48%)	58.3 (49%)	76.9 (64%)	78.2 (65%)	82.0 (68%)	21.2 (18%)	24.9 (21%)	26.1 (22%)	42.1 (35%)	46.0 (38%)	54.1 (45%)
HS-FA20	96.6	59.8 (62%)	27.0 (28%)	68.9 (71%)	72.0 (75%)	73.6 (76%)	76.3 (79%)	83.5 (86%)	84.1 (87%)	35.1 (36%)	40.5 (42%)	41.7 (43%)	54.3 (56%)	60.3 (62%)	62.8 (65%)
HS-FA30	102.8	68.9 (67%)	32.9 (32%)	73.9 (72%)	77.0 (75%)	79.2 (77%)	86.5 (84%)	91.7 (89%)	96.0 (93%)	42.5 (41%)	47.9 (47%)	50.0 (49%)	65.9 (64%)	71.1 (69%)	81.4 (79%)
HS-FA40	107.7	61.4 (57%)	32.3 (30%)	70.2 (65%)	74.2 (69%)	76.2 (71%)	74.4 (69%)	81.0 (75%)	84.3 (78%)	32.1 (30%)	35.2 (33%)	37.9 (35%)	58.6 (54%)	60.5 (56%)	64.6 (60%)
HS-SF + FA	123.9	63.2 (51%)	23.5 (19%)	69.2 (56%)	70.6 (57%)	71.8 (58%)	79.3 (64%)	80.8 (65%)	84.6 (68%)	30.6 (25%)	33.5 (27%)	34.2 (28%)	54.8 (44%)	58.7 (47%)	68.1 (55%)
HS-BS30	111.9	59.3 (53%)	30.2 (27%)	76.0 (68%)	78.5 (70%)	80.1 (72%)	79.4 (71%)	88.6 (79%)	92.2 (82%)	41.7 (37%)	46.4 (41%)	48.9 (44%)	57.5 (51%)	66.2 (59%)	73.2 (65%)
HS-BS40	115.5	70.5 (61%)	33.6 (29%)	75.9 (66%)	77.5 (67%)	79.5 (69%)	83.0 (74%)	86.3 (77%)	95.3 (85%)	41.0 (35%)	41.6 (36%)	44.9 (39%)	55.3 (49%)	61.8 (55%)	67.1 (60%)
HS-MK5	116.3	53.5 (46%)	19.8 (17%)	61.8 (53%)	65.2 (56%)	67.7 (58%)	86.2 (74%)	92.1 (79%)	97.7 (84%)	26.9 (23%)	31.7 (27%)	35.1 (30%)	46.8 (40%)	58.6 (50%)	63.3 (54%)
HS-MK10	126.7	46.9 (37%)	17.7 (14%)	53.5 (42%)	54.6 (43%)	56.0 (44%)	83.9 (66%)	86.7 (68%)	91.7 (72%)	20.5 (16%)	24.1 (19%)	24.6 (19%)	43.6 (34%)	53.2 (52%)	55.9 (44%)
HS-MK20	135.3	43.3 (32%)	12.2 (9%)	46.3 (34%)	47.5 (35%)	47.9 (35%)	74.4 (55%)	80.1 (59%)	89.4 (66%)	15.2 (11%)	18.0 (13%)	19.5 (14%)	33.0 (24%)	43.6 (32%)	46.5 (34%)
NSC															
NS-CC	38.2	11.5 (30%)	3.8 (10%)	16.8 (44%)	17.8 (47%)	18.8 (49%)	23.8 (59%)	25.0 (62%)	26.7 (66%)	10.4 (27%)	11.9 (31%)	12.0 (31%)	16.6 (41%)	19.0 (47%)	20.9 (52%)
NS-FA30	49.1	18.2 (37%)	7.9 (16%)	24.2 (49%)	26.2 (53%)	27.1 (55%)	33.4 (68%)	36.9 (75%)	38.9 (79%)	14.8 (30%)	15.9 (32%)	16.7 (34%)	19.8 (40%)	21.8 (44%)	25.1 (51%)
NS-FA40	55.6	25.0 (45%)	10.0 (18%)	32.3 (58%)	34.8 (63%)	35.7 (64%)	39.5 (71%)	45.7 (82%)	47.5 (85%)	17.2 (31%)	20.2 (36%)	21.9 (39%)	23.0 (41%)	27.3 (49%)	31.4 (56%)
NS-BS30	61.7	31.5 (51%)	12.9 (21%)	39.0 (63%)	40.4 (65%)	41.5 (67%)	40.1 (65%)	44.1 (71%)	47.8 (77%)	19.3 (31%)	21.1 (34%)	21.7 (35%)	23.0 (37%)	27.1 (44%)	30.5 (50%)
NS-BS40	66.8	36.1 (54%)	13.4 (20%)	37.5 (56%)	39.6 (59%)	41.5 (62%)	42.2 (63%)	45.7 (68%)	50.2 (75%)	20.9 (31%)	23.6 (35%)	25.5 (38%)	24.8 (37%)	27.5 (41%)	30.3 (45%)
NS-MK5	43.9	14.1 (32%)	6.2 (14%)	17.2 (39%)	19.4 (44%)	20.4 (46%)	23.3 (53%)	25.5 (58%)	27.0 (61%)	7.1 (16%)	8.0 (18%)	8.9 (20%)	11.0 (25%)	12.8 (29%)	13.7 (31%)
NS-MK10	51.2	12.8 (25%)	5.6 (11%)	21.0 (41%)	22.2 (43%)	22.7 (44%)	28.3 (55%)	30.4 (59%)	32.8 (64%)	6.2 (12%)	8.4 (17%)	10.9 (21%)	13.5 (26%)	17.2 (34%)	18.1 (35%)
NS-MK20	64.9	13.6 (21%)	4.5 (7%)	28.0 (43%)	30.6 (47%)	31.9 (49%)	37.7 (56%)	41.0 (63%)	44.2 (66%)	9.2 (14%)	12.6 (19%)	15.1 (23%)	19.1 (29%)	22.4 (35%)	23.6 (36%)

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

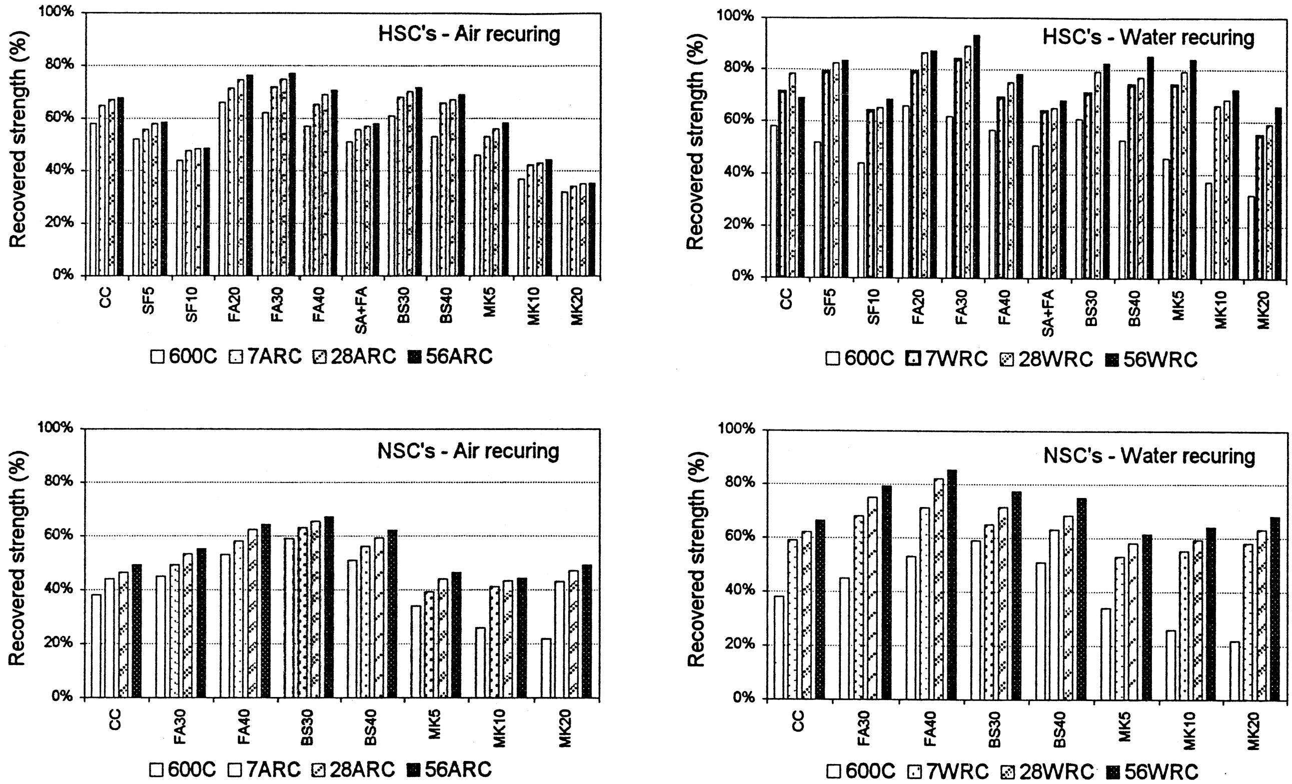

Fig. 1. Compressive strength recovery of NSCs and HSCs subjected to heating at 600°C.

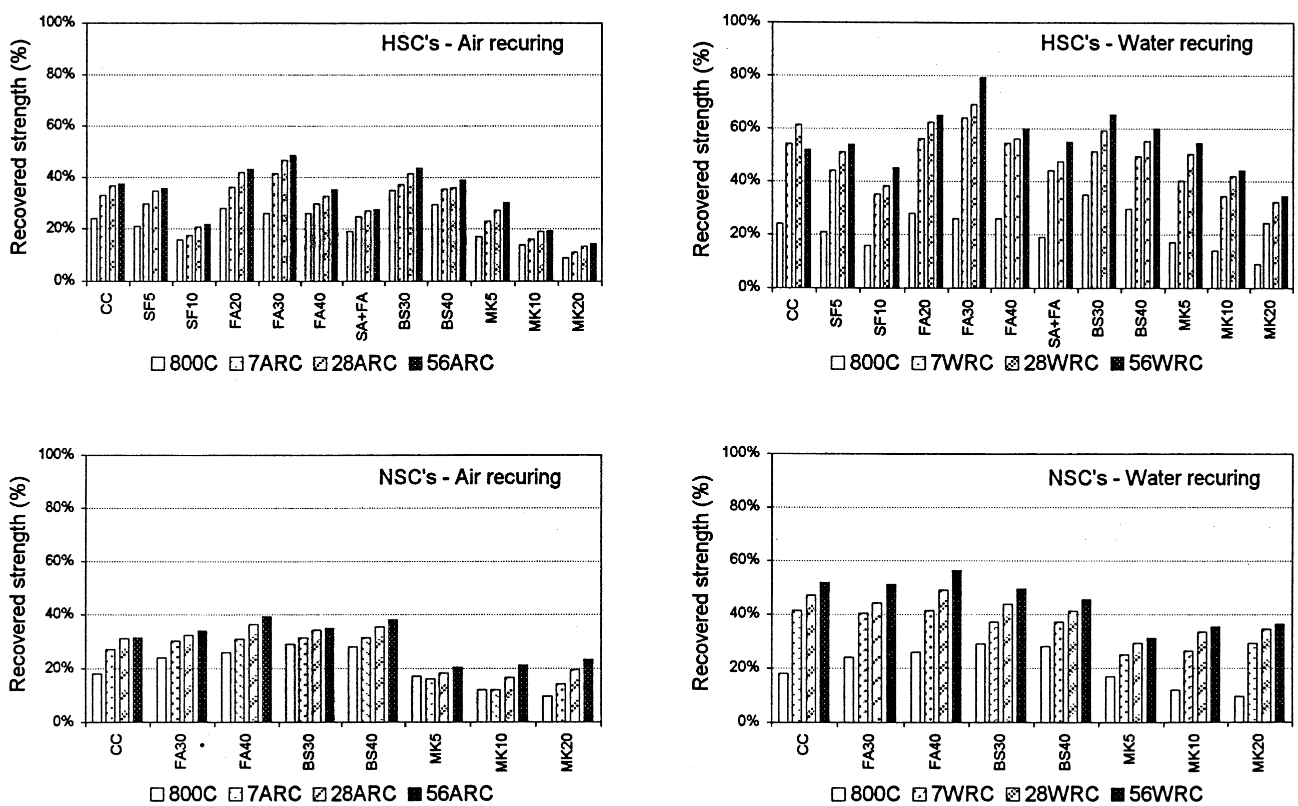

Fig. 2. Compressive strength recovery of NSCs and HSCs subjected to heating at 800°C.

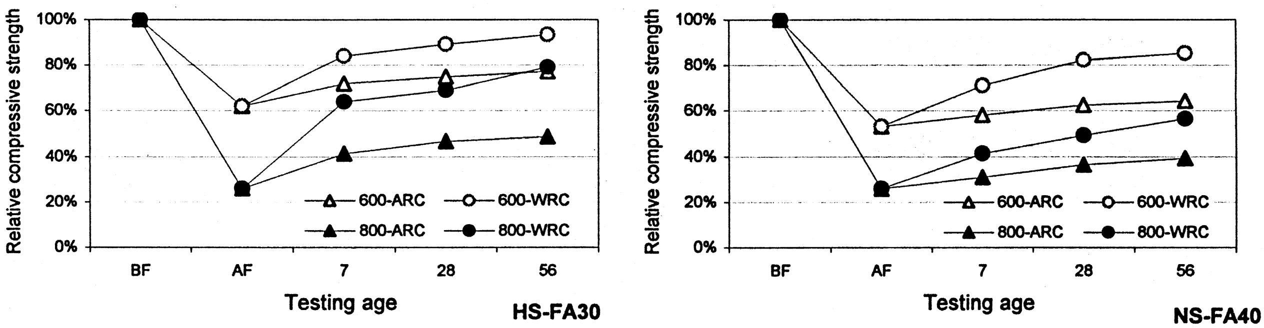

Fig. 3. Rate of compressive strength recovery in selected FA concretes.

spraying water on fire-damaged concrete is a proper procedure to enhance its rehydration.

In spite of the importance of strength regain of fire-damaged concrete in terms of repair and rehabilitation, very few studies had been conducted. Most of the available data are in qualitative form and restricted to strength recovery only. Moreover, these studies were mostly conducted on normal-strength concrete (NSC) and cannot be generalized for HSC due to its different composition and properties. There is a need to conduct a comprehensive investigation to understand the nature of the rehydration process and its effect on the strength and durability recovery of fire-damaged concretes. For this purpose, this experimental study was organized to quantitatively investigate the rehydration process using different types of concrete, exposure temperatures, and recuring conditions. A number of tests were conducted to analyze the changes in the macro- and microstructure of the concrete, which result in strength and durability recovery.

2. Methodology and experimental details

The type of concrete, exposure temperature, and recuring conditions are taken as the main variables in this study. Twenty NSC and HSC mixes incorporating siliceous aggregates and various pozzolans were prepared and subjected to elevated temperatures till 800°C. After firing, recuring was done both in water and in a controlled environment. The strength and durability recovery were investigated by means of various macro- and microlevel tests.

2.1. Materials and concrete mix proportions

The cementitious materials used were ordinary Portland cement (OPC) complying with ASTM Type I, low-calcium fly ash (FA) equivalent to ASTM class F, condensed silica fume (SF), ground granulated blast furnace slag (GGBS), and metakaolin (MK). All the pozzolans are commercially available in Hong Kong. The chemical compositions and physical properties of these materials are shown in Table 1.

The fine aggregate was a natural river sand while crushed granite with maximum nominal sizes of 10 and 20 mm, which were later mixed in a ratio of 1:2, was used as coarse aggregate. A liquid sulfonated naphthalene–formaldehyde condensate containing 38.6% solids was used as the superplasticizer.

The concrete mix proportions are shown in Table 2. All the mixtures were produced at a slump of over 200 mm and no air entraining admixture was used.

2.2. Curing and heating regimes

The specimens were demolded 24 h after the casting and placed in a water tank at 20°C. After 28 days of water-curing, they were transferred to an environmental chamber maintained at 20°C and 75% RH, which are the average climatic conditions in Hong Kong.

At an age of 60 days, the specimens were heated in an electric furnace up to 600°C and 800°C. These temperatures were selected after considering many real cases of electric and hydrocarbon fires [9]. Each temperature was

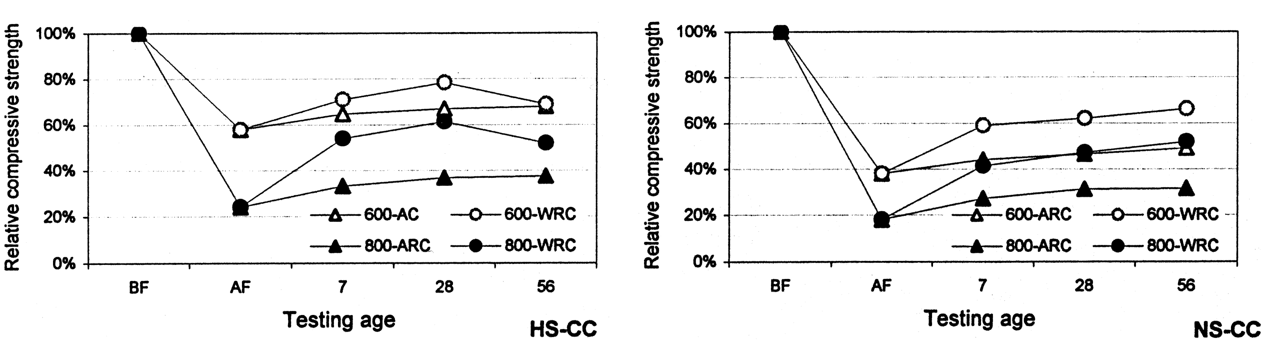

Fig. 4. Rate of compressive strength recovery in pure OPC concretes.

Table 4
Resistance against chloride-ions penetration before and after recuring

	Total charge passed (C)														
				Recuring after 600°C						Recuring after 800°C					
	After cooling			Air-recuring			Water-recuring			Air-recuring			Water-recuring		
Mix	20°C	600°C	800°C	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
HSC															
HS-CC	941	12,534	23,396	8672	6847	6271	4934	4357	4864	18,001	14,992	14,123	12,737	10,592	12,082
HS-SF5	610	8619	18,390	6500	5309	4895	3662	3213	2914	13,049	12,195	11,204	10,189	9165	7818
HS-SF10	285	10,080	25,170	7346	6337	5785	4318	4092	3729	17,476	16,439	15,689	12,770	11,997	10,965
HS-FA30	449	5373	9049	3605	2798	2130	1833	1383	1171	7130	6104	5410	4480	3971	3656
HS-BS30	334	6772	10,673	4541	3774	3002	2725	2304	1831	7064	6673	6022	5446	4934	4266
HS-MK5	561	9643	20,230	7433	6853	6618	4835	4326	3647	13,606	12,778	12,045	11,131	10,365	8875
HS-MK20	112	14,091	32,501	9079	7796	7344	6289	5715	5280	25,169	23,261	19,309	15,345	13,434	11,493
NSC															
NS-CC	2941	21,792	35,724	14,800	11,530	10,620	8647	7200	6441	29,230	22,742	20,646	17,604	15,575	13,943
NS-FA40	1454	8550	20,666	5605	3847	3533	2964	2591	2375	15,525	11,600	9640	8892	7596	6752
NS-BS40	1181	6306	15,368	5867	4620	4170	3313	3021	2792	13,136	11,060	10,320	7701	7321	6476
NS-MK5	1960	17,523	32,513	16,346	13,071	11,060	8432	7374	6209	23,735	19,298	17,499	15,003	13,468	11,775
NS-MK20	718	24,024	45,556	20,075	16,866	15,082	12,816	11,731	9318	34,488	28,484	27,244	17,593	16,123	14,184

maintained for 1 h to achieve the thermal steady state [10]. The heating rate was set at 2.5°C/min. The specimens were allowed to cool naturally to room temperature after the heating cycle.

2.3. Post-fire-curing regimes

After natural cooling, the specimens were placed in two recuring regimes termed as the *water-recuring* and *air-recuring*. In water-recuring, the specimens were placed in a water tank at 20°C till the time of testing. In air-recuring, the specimens were first soaked in water for 2 h and then placed in an environmental chamber at 20°C and 75% RH. The initial water soaking was done to supply the necessary moisture to the inner layers of the concrete to expedite rehydration. The 2-h duration was selected after many trials to find the minimum soaking time for optimized results. Testing was done after 7, 28, and 56 days of recuring.

2.4. Specimen dimensions and testing details

1. Unstressed residual compressive strength test was performed on 100-mm concrete cubes according to BS 1881: Part 120:1983. Three specimens were tested at each stage and the average values are reported.

2. Rapid chloride diffusion test in accordance with ASTM C1202-94 was conducted on 100 × 50 mm concrete slices to determine the permeability and resistance to chloride-ions penetration of the concrete. This test provides a quick indication of the resistance of concrete to the penetration of chloride ions and gives an indirect measure of its permeability and internal pore structure, as more charges pass through a more permeable concrete. These results may be used to assess the durability of concrete.

3. Mortar cubes of 70-mm size were prepared for mercury intrusion porosimetry (MIP) and SEM investigations. The mix proportions, curing, heating, and recuring conditions were exactly similar to the concrete specimens. This was done to avoid small particles of aggregates in the HCP, which can affect the test results substantially. Pellets of about 5 × 5 × 5 mm in size of HCP were collected from the crushed cubes and immediately soaked in acetone to stop the further hydration. The samples were dried in an oven at 60°C for 48 h before testing.

4. Crack widths of heated and recured concrete cubes were measured using a Nikon digital microscope that can measure the surface crack width up to an accuracy of 1 μm.

3. Test results and discussion

3.1. Compressive strength recovery

The unstressed compressive strengths of concrete cubes before heating, immediately after cooling, and after 7, 28, and 56 days of recuring are reported in Table 3 and shown in Figs. 1 and 2.

All the specimens showed a substantial compressive strength recovery after recuring. The test results clearly indicate that the compressive strength recovery depends on

Table 5
Chloride-ions penetrability based on charge passed (C)

Charge passed (C)	Chloride-ions penetrability
> 4000	high
2000–4000	moderate
1000–2000	low
100–1000	very low
< 100	negligible

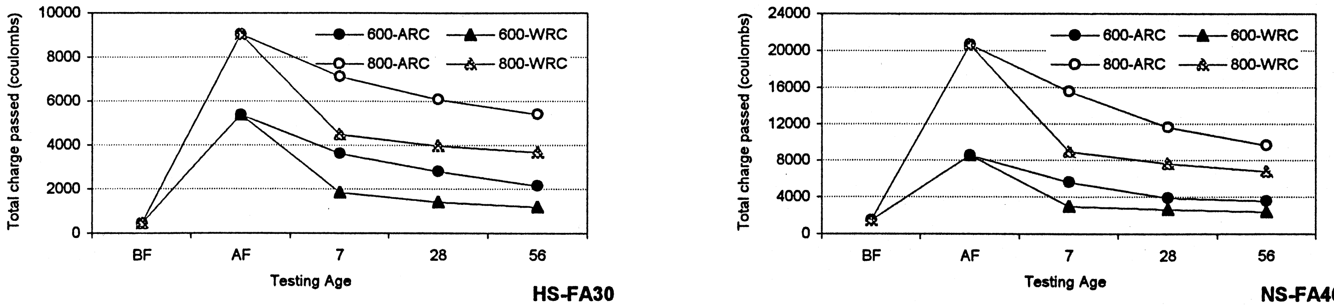

Fig. 5. Rate of impermeability loss recovery in selected FA concretes.

the type of concrete, method of recuring, and exposure temperature. Despite high losses during heating, the HSCs showed better strength recovery as compared to the NSCs. For 600°C, the HSCs regained 66–93% of their original strength after 56 days, while it was 61–85% for NSCs. Similarly for 800°C, these values were 34–79% for HSCs and 31–56% for NSCs. The blended concretes performed better than the pure OPC concrete. The best performance was shown by FA concrete followed by GGBS, SF, and MK concretes. The compressive strength recovery was faster and more enhanced after water-recuring as compared to the air-recuring. On the average, the water-recured specimens regained 15–20% more strength than the air-recured specimens. The compressive strength recovery was better after 600°C than 800°C. At 800°C, the C-S-H gel was mostly destroyed and large surface and internal cracks appeared that were difficult to refill, hence less strength was recovered.

Among the HSCs, the maximum compressive strength recovery was shown by HS-FA30, which was 93% for 600°C and 79% for 800°C after 56 days of water-recuring, while for air-recuring these values were 77% and 49%, respectively. For NSCs, the best results were shown by NS-FA40, which were 85% and 56% for water-recuring and 64% and 39% for air-recuring, respectively. The good performance of these concretes was probably due to the rehydration reaction between the unhydrated FA particles and the newly formed CH. In blended concretes containing FA or GGBS, a portion of pozzolans remained unhydrated due to the blocking of capillaries [11]. During the fire, these capillaries were opened and they were refilled by the new hydration products that resulted in more strength recovery.

An exception was the high-strength pure OPC concrete (HS-CC), which showed a strength decrease after 28 days of recuring. A possible explanation was the volume expansion caused by the rehydration of lime [12]. Initially, the rehydrated lime filled up the capillaries and internal cracks and resulted in strength increase. But once the capillaries were refilled, the continued rehydration process started to induce cracking and disintegration that reduced the compressive strength.

The rehydration rate and hence the possible expansion depends on the amount of unhydrated lime present, but the reaction can be controlled by the presence of unhydrated pozzolans that would react with lime to produce additional C-S-H that does not expand. The relative proportions of unhydrated lime and unreacted pozzolans would determine the level of expansion. More research is needed to study the balance of the above two reactions so that the rehydration process can be conducted in a controlled manner.

For water-recuring, the rate of strength recovery was found to be rapid during the first 7 days and then continued at a slower rate. This pattern was followed by almost all concretes, which gained 60–70% of their total recovered strength during that period. The rates of compressive strength recovery in FA and pure OPC concretes are shown in Figs. 3 and 4. It is believed that the continuous filling of capillaries during that period was responsible for the strength increase. However, for air-recuring, the rate of strength recovery was slower and more gradual. This

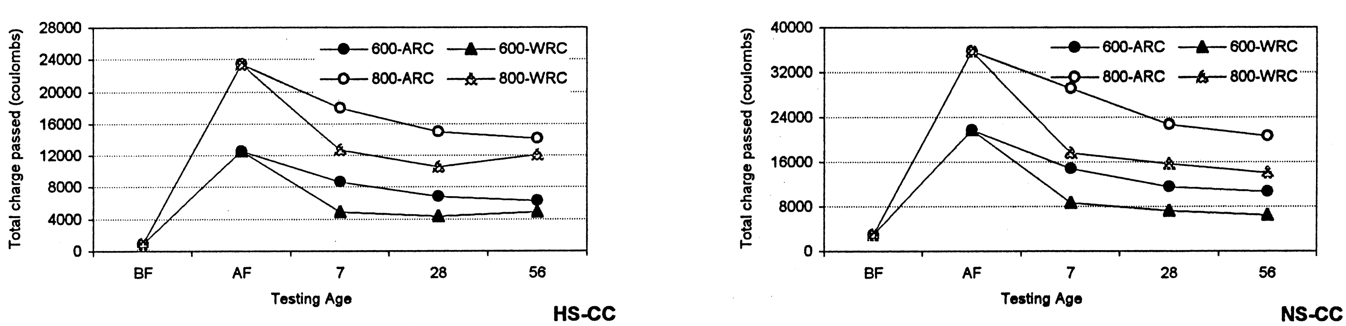

Fig. 6. Rate of impermeability loss recovery in pure OPC concretes.

Table 6
Porosity and average pore diameters before and after recuring

				Recuring after 600°C						Recuring after 800°C					
	After cooling			Air-recuring			Water-recuring			Air-recuring			Water-recuring		
Mix	20°C	600°C	800°C	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
Porosity (%, v/v)															
HS-CC	9.52	18.32	29.13	17.71	16.56	15.80	16.37	15.23	16.96	27.80	26.66	25.61	26.08	24.56	23.04
HS-FA30	6.69	11.28	21.96	10.44	10.10	9.63	9.75	8.83	7.96	20.61	19.60	18.46	18.20	15.79	11.91
Average pore diameter (μm)															
HS-CC	0.0329	0.0632	0.1102	0.0579	0.0533	0.0467	0.0434	0.0336	0.0368	0.0961	0.0888	0.0819	0.0829	0.0665	0.0540
HS-FA30	0.0309	0.0522	0.0921	0.0476	0.0405	0.0383	0.0383	0.0297	0.0260	0.0890	0.0844	0.0760	0.0624	0.0531	0.0368

indicates the need for constant moisture supply to continue and expedite the rehydration reactions.

3.2. Recovery of impermeability loss

Impermeability losses were observed in all the specimens after heating due to the internal cracking and coarsening of the pore structure. However, the rehydration process resulted in substantial recovery due to the filling of capillaries and internal cracks. In order to measure the impermeability loss and recovery quantitatively, the rapid chloride diffusion test was performed on selected concrete mixes, which showed either good or poor performance in terms of compressive strength recovery. The results are reported in Table 4. To assess the permeability of concrete, ASTM C1202-94 provides the limiting values as shown in Table 5.

The test results indicate that all concrete mixes suffered a high loss of impermeability after exposure to high temperatures. Although there was a significant recovery after post-fire-curing, most of the specimens still had very high permeability even after 56 days of recuring. This demonstrates the need to carefully investigate the durability properties of concrete after a fire even if the concrete has recovered a substantial portion of its compressive strength. It is particularly important for offshore and industrial structures, which are often subjected to various chemical attacks. The impermeability recovery pattern was found to be similar to those observed in the compressive strength recovery.

Fig. 5 shows the rate of impermeability recovery in HS-FA30 and NS-FA40, which showed the best performance. In both mixes, the water-recuring resulted in rapid impermeability recovery and the rate of recovery was higher during

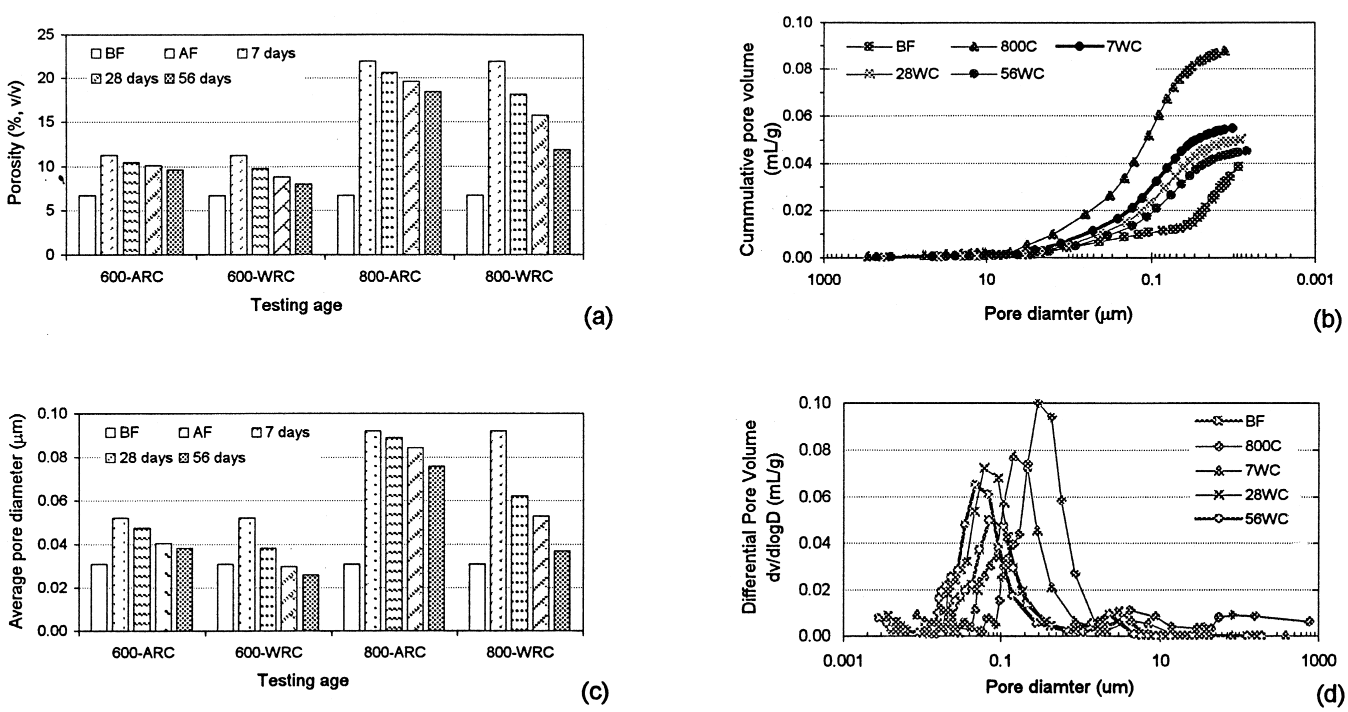

Fig. 7. Porosity and pore size distribution in HS-FA30 under different recuring conditions.

the first 7 days. The air-recuring resulted in slow and gradual recovery similar to those observed earlier for the compressive strength recovery. The HS-FA30 showed ‘low’ and ‘moderate’ permeabilities after 56 days of water-recuring for the 600°C and 800°C specimens, respectively, while in NS-FA40 they were ‘moderate’ and ‘high.’ These values are satisfactory according to the American Concrete Institute (ACI) code and the concrete can be considered as durable in most situations except in offshore structures that require a very low permeable concrete.

The impermeability recovery in NS and HS pure OPC concretes is shown in Fig. 6. Both concretes showed ‘very high’ permeabilities when compared to the blended concretes at all stages of recuring. Moreover, another additional loss of impermeability was observed in the HS-OPC concrete after 28 days of recuring due probably to the expansion of lime upon rehydration as discussed earlier.

3.3. Porosity and pore size distribution

Porosity and pore size distribution are the primary factors governing the strength and permeability of concrete [13]. To investigate the changes in the pore structure of concrete due to firing and recuring, MIP test was performed on selected specimens and the results are reported in Table 6 and Figs. 7 and 8.

Fig. 7(a) shows the porosity changes in HS-FA30 which showed maximum strength and impermeability recovery after recuring. As reported earlier [14], the high temperature resulted in an increase in porosity and coarsening of the pore structure of the concrete. When compared with the original values, the porosity after firing was 192% at 600°C and 306% at 800°C. However, the recuring decreased the porosity significantly. After 56 days of water-recuring, the total porosity was 119% for 600°C and 178% for 800°C, while these values were 144% and 276% for the air-recured specimens.

The pore size distributions of the same specimens are plotted in Fig. 7(b). The cumulative volume of pores larger than 0.1 μm, which influenced the strength of concrete [15], was greatly increased after firing, but recuring brought it close to the original value. Similarly, the cumulative pore volume larger than 1.3 μm, which should be responsible for the permeability of concrete [16], was also very close to the original value after recuring. This helped the concrete to recover its strength and durability.

Fig. 7(c) shows the changes in average pore diameter and indicates an increase with the rise in temperature. However, there was a significant decrease in the average pore diameter after recuring and this effect was more pronounced for water-recuring. For specimens subjected to 600°C, after 56 days of water-recuring, the average pore diameter was 84% of the original value, which indicates that the rehydration resulted in a finer pore structure. This fact was further confirmed by considering the differential pore volume as shown in Fig. 7(d). Before firing, the largest pore fraction existed between 0.06 and 0.2 μm, but after 56 days of water-recuring, it moved to between 0.02 and 0.09 μm. This proved that the rehydration products were smaller than the original hydration products and produced a finer pore structure which was responsible for strength and durability recovery.

Fig. 8 shows the pore-structure changes in pure OPC concrete that followed the same pattern as the HS-FA 30 concrete. However, after 28 days of water-recuring of the 600°C sample, there was again an increase in porosity and average pore diameter due to the expansion of lime that resulted in strength and impermeability reduction.

3.4. SEM investigations

To confirm the formation of rehydration products and observe their morphologies, the microstructure of a few selected specimens was studied by SEM and the results are shown in Fig. 9.

Fig. 9(a) shows severe shrinkage, cracks, and honeycombs after the concrete was exposed to 800°C. These cracks and honeycombs were responsible for strength and durability reduction. The effects of rehydration can be seen in Fig. 10(b) and (c), which shows that the rehydration products eventually filled the cracks and honeycombs. The noticeable microstructures observed were ettringite, C-S-H, and some unhydrated cement particles.

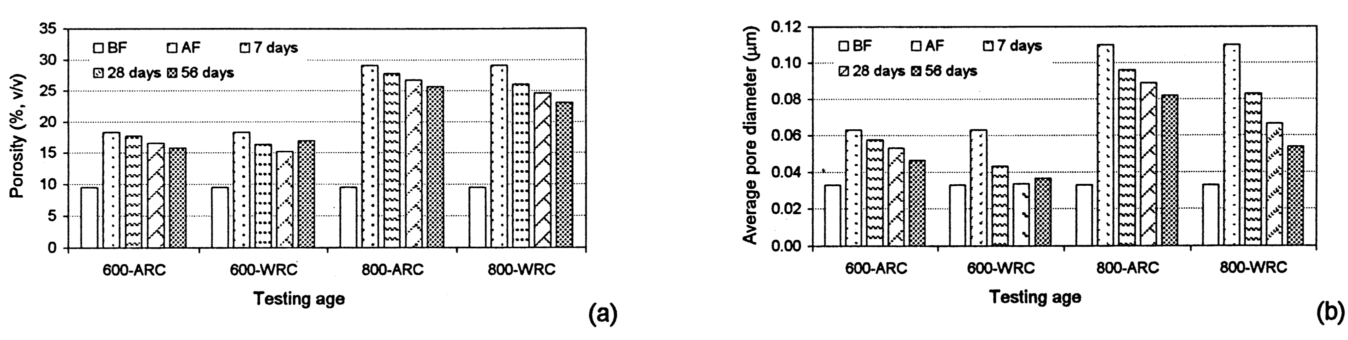

Fig. 8. Porosity and pore size distribution in HS-CC under different recuring conditions.

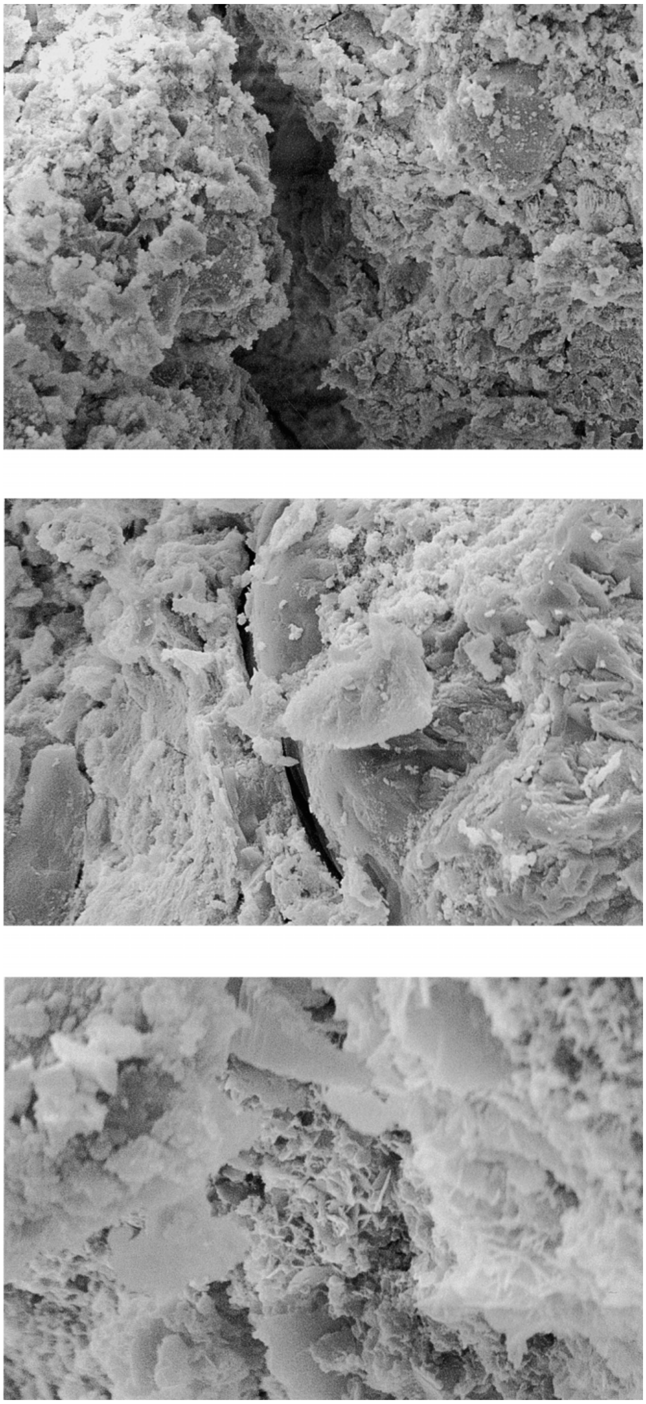

Fig. 9. Morphologies of samples after 800°C exposure and water-recuring. (a) 800°C; (b) 7 days water-recuring; (c) 28 days water-recuring.

3.5. Crack width analysis

A significant reduction in surface crack widths was also observed during post-fire-curing. The surface crack widths were measured immediately after cooling and after recuring. Since a better recovery was observed in the water-recured specimens, only these specimens were studied during this stage. The results are summarized in Table 7.

The results indicate that the surface crack widths of the samples immediately after cooling were well above the maximum limits specified by ACI building code (0.10 mm for wet conditions and 0.44 mm for dry conditions). The rehydration resulted in a decrease in the surface crack widths and in many specimens, the crack widths were again within the desired range. For HS-FA30, which showed the best recovery, the maximum crack width after 56 days of recuring was 0.31 mm for 600°C and 0.51 mm for 800°C. It is anticipated that rehydration beyond 56 days should result in a further

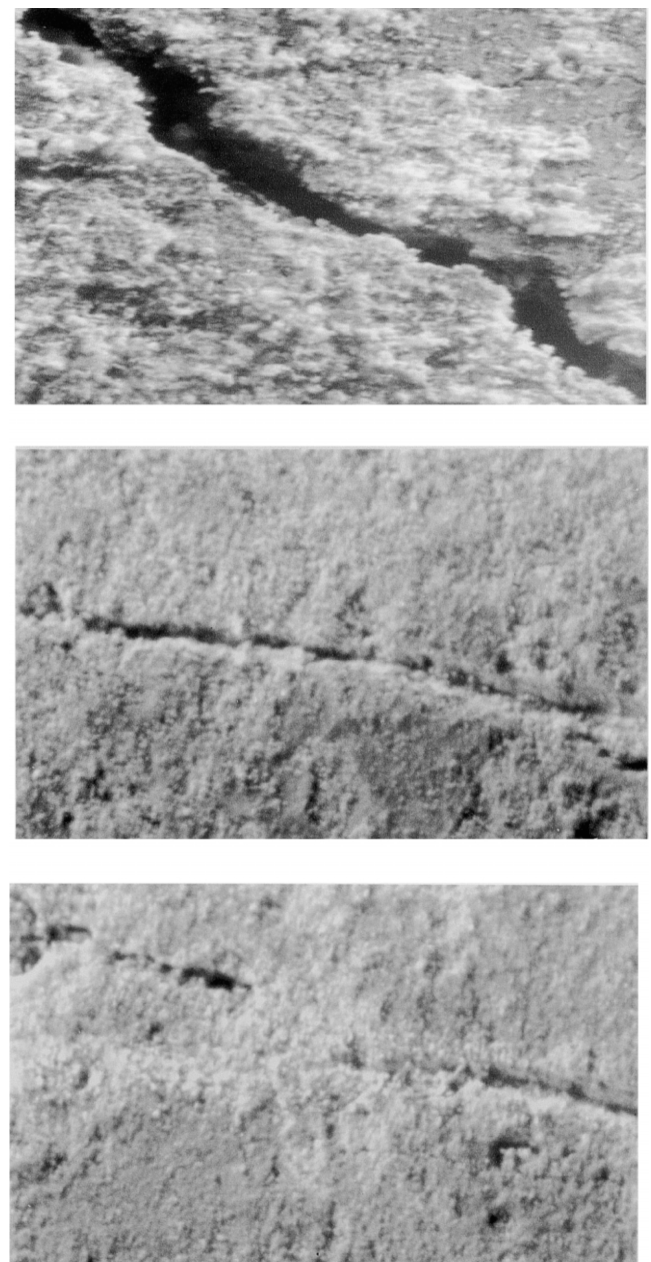

Fig. 10. Refilling of surface cracks at different stages of recuring. (a) 800°C; (b) 28 days water-recuring; (c) 56 days water-recuring.

Table 7
Surface crack widths of selected concrete specimens

Mix	Crack widths (mm)							
	600°C				800°C			
	After cooling		56 days recuring		After cooling		56 days recuring	
	Min	Max	Min	Max	Min	Max	Min	Max
HSC								
HS-CC	0.32	1.26	0.19	0.56	0.75	1.84	0.29	0.82
HS-SF10	0.71	1.74	0.32	0.91	1.30	2.89	0.51	1.64
HS-FA20	0.15	0.98	0.12	0.34	0.48	1.32	0.35	0.65
HS-FA30	0.19	1.09	0.09	0.31	0.52	1.44	0.23	0.51
HS-FA40	0.21	1.16	0.13	0.27	0.52	1.49	0.29	0.57
HS-BS30	0.21	1.19	0.14	0.29	0.56	1.46	0.31	0.71
HS-BS40	0.23	1.24	0.14	0.32	0.59	1.52	0.33	0.69
HS-MK5	0.32	1.54	0.19	0.86	1.10	2.05	0.47	1.34
NSC								
NS-CC	0.28	0.94	0.19	0.35	0.59	1.44	0.34	0.82
NS-FA30	0.16	0.95	0.14	0.23	0.48	0.98	0.26	0.74
NS-FA40	0.17	1.06	0.11	0.22	0.52	1.10	0.23	0.70
NS-BS30	0.16	0.75	0.11	0.24	0.38	0.82	0.32	0.65
NS-BS40	0.15	0.90	0.08	0.20	0.44	0.88	0.30	0.62
NS-MK5	0.24	0.74	0.19	0.59	0.55	1.32	0.39	0.83

decrease in the surface crack widths and the concrete structure can be considered as serviceable.

Fig. 10 shows the refilling of surface cracks at different stages of recuring. The rehydration products were visible between the aggregate boundary layers and in voids and eventually filled the surface cracks.

3.6. Integrative analysis

Combining all the test results, it can be seen that when concrete was exposed to high temperature, coarsening of the pore structure and internal cracking would occur. These reduced the strength and durability of concrete. When such concretes were subjected to recuring either in water or in a controlled environment, rehydration took place due to some or all of the following reactions: (i) partial rehydration of the newly formed calcium silicates, (ii) hydration of unhydrated cement grains, (iii) rehydration of lime, (iv) pozzolanic reaction between unhydrated pozzolans and the newly produced CH, and (v) carbonation of lime.

The high temperature opened the capillaries that were initially blocked by the hydration products. During the recuring, these capillaries were refilled by the rehydration products. The size of those rehydration products was smaller than the original hydration products. This generated a finer pore structure that helped the concrete to regain its strength and durability.

The water-recuring resulted in a quick and better recovery as compared to the air-recuring. This shows the need of constant moisture supply to continue the rehydration reactions.

The fire-damaged concrete in a structure can be rehydrated by spraying water over it once it is cooled. Since most of the rehydration took place during the first 7 days, it would be beneficial to constantly sprinkle water over the fire-damaged structure during that period to expedite rehydration. However, there are a number of factors that affect the effectiveness of the rehydration process including: means of spraying water, depth of penetration of water and how to ensure that water has reached the proper depth, and period of spraying water, that need further investigation. This technique is also only applicable to moderately damaged concrete structures as the effectiveness of the rehydration depends on the width of the cracks generated by the high-temperature exposure. If the cracks are too large, they may not be refilled properly and separate rehabilitation programs may be needed.

4. Conclusion

1. Post-fire-curing resulted in a substantial strength and durability recovery and the effect was more pronounced in blended concretes as compared to the pure OPC concrete. Among HSCs, the mix with 30% FA replacement showed the maximum recovery, while among NSCs the mix with 40% FA replacement produced the best results. The reason for the best performance of FA concretes was the rehydration reaction between the newly formed CH and the unhydrated FA particles that filled the capillaries and decreased the total porosity of concrete.
2. The effect of recuring was more pronounced in the case of water-recuring. This indicates the need for constant moisture supply to continue the rehydration reactions. In water-recuring, the rate of rehydration was rapid during the first 7 days and then slowed down. For air-recuring, the rehydration rate was slow and gradual.
3. The HSCs showed better recovery than the NSCs due to their dense microstructure which helped the refilling of the cavities quickly during the rehydration. The reduced amount of CH (and lime after firing) that would have otherwise caused expansion was another reason for the better recovery of HSCs.
4. The exposure of concrete to 600°C resulted in a better strength and durability recovery than for those concrete exposed to 800°C. The reason was that the decomposition of structure of the C-S-H gel started at about 550°C. This indicates that during a fire, if the temperature of the concrete can be kept below 600°C, the concrete can recover its original strength and durability properties with proper recuring alone without the need of special repairs.
5. High temperatures produced large surface cracks, which were refilled by the new rehydration products. In several tested specimens, the surface crack widths were within the maximum specified limits after 56 days of recuring.

Acknowledgments

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