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SELF-HEALING CONCRETE USING FLY ASH

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In recent studies, it has been recognized that concrete deterioration is accelerated by growth of the fine cracks of a few micron meter wide which was induced by dry shrinkage and/or freezing damage. Research of the concrete which carries out self-healing of these fine cracks has been abundantly expected. To confirm the ability of fly ash on self-healing, we conducted fundamental test of mortar using fly ash (replacement ratio: 20%) which was deteriorated by accelerated freeze-thaw cycle until the relative dynamic modulus of elasticity reduced to 80% and 60%. The mortar specimens were then cured in water at 40°C and 20°C. We have evaluated the self-healing degree of the cured mortar specimens by strength test, some durability tests, and concrete structure observations. From the test results, it was confirmed that fly ash functioned effectively as a self-healing material of concrete.

Keywords: Dynamic modulus of elasticity, Compression strength, Pore size distribution, Pozzolanic reaction, Reaction rate of fly ash.

1 INTRODUCTION

There are two main types of techniques for adding self-healing properties to concrete (Joseph and Jefferson 2006). The first technique is to fill cracks with resin filler, for example. Once resin filler is supplied, cracked open areas are healed by the unreacted filler (Katsuhata *et al.* 2000). The second technique is to fill cracks using the hydration reaction of the remaining unreacted components of cement or similar materials. The fact that the pozzolanic reaction of fly ash does not initially occur may possibly give a theoretical advantage to the healing of cracks (Taniguchi *et al.* 2011). The envisioned self-healing effects take place over a long period of time. In order to apply self-healing concrete to practical usage, however, it is necessary to evaluate its self-healing capabilities in a short period of time before putting in service by conducting various tests such as acceleration tests.

2 MATERIALS AND METHODS

2.1 Overall Flow of Testing

Two different methods were used to prepare deteriorated test specimens. One was a freeze-thaw method, the other was a compression load method. Under the compression load method, the degree of deterioration did not advance after repeating a maximum of 10 compressions. This is why we used the freeze-thaw method.

The following tests and measurements were conducted to confirm the self-healing effects of specimens mixed with fly ash. Measurement of the relative dynamic modulus of elasticity, strength test, pore size distribution measurement, accelerated carbonation test, chloride permeability test, and confirmation of healed crack images through radiographic visualization and back scattered electron image.

2.2 Materials Used

Mortar specimens (4cm x 4cm x 16cm) were prepared. Table 1 shows the materials used in testing. The fly ash used is a typical type commercially available in Japan as a concrete admixture (Density: 2.23 g/cm^3, Blaine specific surface area: 3,670cm^2/g).

Table 1. Materials used.

Type	Specifications	Remarks
Cement (C)	Ordinary portland cement	Density: 3.16 g/cm^3
Admixture (FA)	Japanese Industrial Standard, type II fly ash	Density: 2.23 g/cm^3
Fine aggregate (S)	Natural river sand	Density: 2.57 g/cm^3
Water (W)	Public water supply	-

2.3 Mixing Conditions

Table 2 shows mortar mixing conditions.

Table 2. Mortar mixing conditions.

W/C (%)	FA/(S+FA) Volume (%)	Unit quantity (kg/m^3)				Flow (mm)
		W	C	S	FA	
55.0	10	334	608	1094	105	244

2.4 Specimen Preparation and Curing Conditions

After applying standard curing to specimens at 20°C for 4 weeks, we conducted a few cycles of freeze-thaw testing and created deteriorated specimens, whose relative dynamic modulus elasticity fell to 80% and 60%. After creating deteriorated specimens, we performed curing at the curing temperatures of 20°C and 40°C for curing periods of 1 week, 2 weeks, and 4 weeks. We conducted tests to confirm the properties of the specimens before and after deterioration and after healing.

3 TEST RESULTS

3.1 Relative Dynamic Modulus of Elasticity and Strength

For either deterioration degree, the relative dynamic modulus of elasticity and strength tends to recover after post-deterioration curing. The tendency of such recovery is greater at a higher curing temperature and for a lower deterioration degree (60%) (Figure 1).

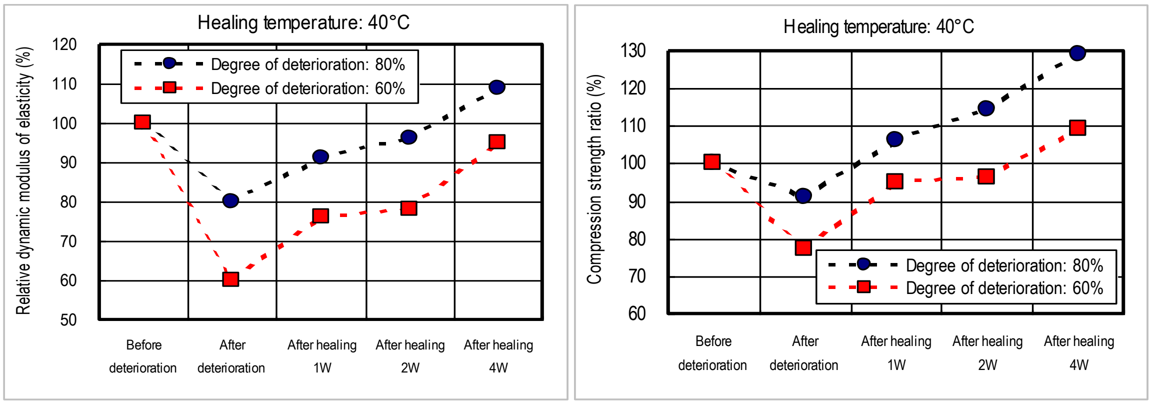


Figure 1. Healing effects in terms of the relative dynamic modulus of elasticity and strength (in case of healing temperature 40°C).

3.2 Confirmation of Healing Effects by Pore Size Distribution

The peak for the pore diameter of 0.1mm or less shifts toward smaller pore diameters according to the age of the healing material. It was also confirmed that those with a pore diameter of 0.1mm or more were close to pre-deterioration conditions after healing, indicating structural densification (Figure 2).

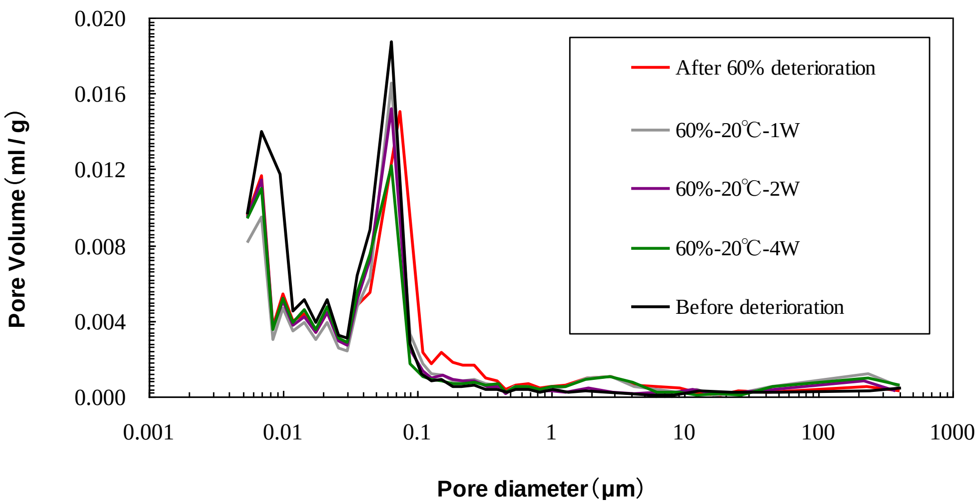


Figure 2. Changes of pore size distribution before and after healing (60% deterioration degree, healing temperature of 20°C).

3.3 Confirmation of Healing Effects by Accelerated Carbonation Test

The greater the deterioration degree, the faster the carbonation progresses. For either deterioration degree, the carbonation rate coefficient tends to recover after post-deterioration curing. The tendency of such recovery is greater with a higher curing temperature and smaller deterioration degree (Figure 3).

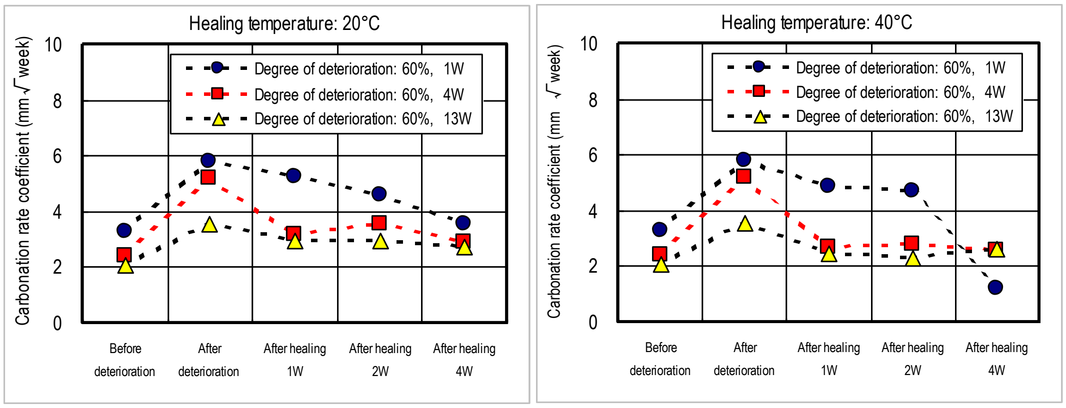


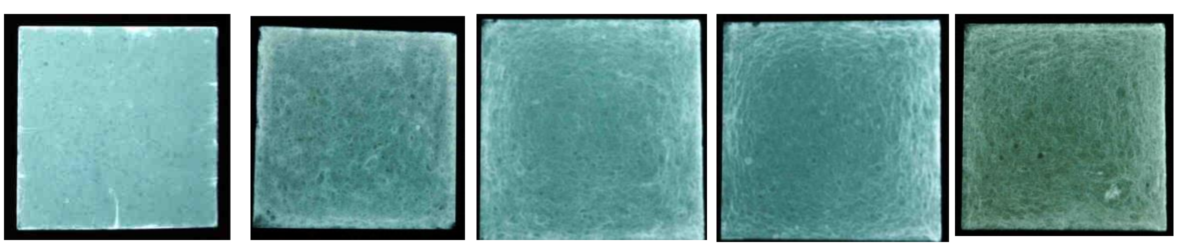
Figure 3. Changes in carbonation rate coefficient (60% deterioration degree).

3.4 Confirmation of Healing Effects by Chloride Permeability Test

Comparing the chloride ion concentration before and after deterioration, in the place where the depth from the surface is shallow, deterioration does not have significant effects. When the depth exceeds 1cm, chloride ion concentration increases depending on the degree of deterioration. When the depth exceeds 3cm, post-deterioration chloride ion concentration tends to increase. However, the difference between before and after deterioration is not remarkable since the chloride ion concentration value itself is small. The chloride ion concentration after healing decreases as the healing period gets longer. The healing period has considerable effects on chloride ion concentration when the depth from the surface is up to 2cm.

3.5 Confirmation of Healing Effects through Radiographic Visualization Test

The observation results of radiographic visualization show clear healing as the healing period gets longer. The 1-week curing case in Figure 4 shows that cracks develop outwardly and in a circle from the center of a specimen and that they are healed as the curing period progresses. Through this experiment, as a result of calculating and digitizing X-ray transmission factors, we confirmed that there is a roughly linear relationship between the X-ray transmission factor and the relative dynamic modulus of elasticity.



Before deterioration | Deterioration 80% | 1 week curing | 2 week curing | 4 week curing

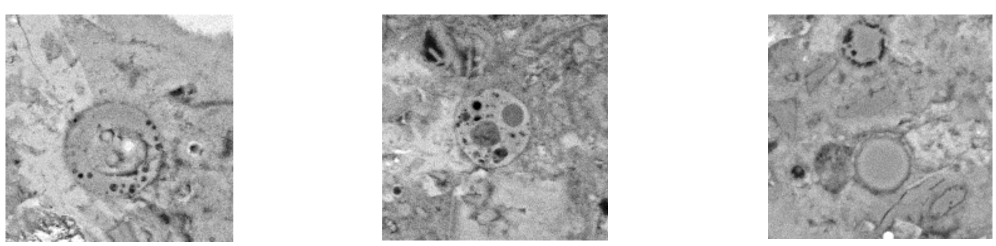
Figure 4. Observation results of radiographic visualization (60% deterioration degree, healing temperature 20°C).

3.6 Confirmation of Healing Effects through Microscope Observation

Figure 5 (SEM image) shows an example of the fly ash particles observed in 80% restoration degree and 100% restoration degree. We estimated the reaction rate of the fly ash from the average thickness of the reaction layer of fly ash particles（Sagawa *et al.* 2009). Table 3 shows average thickness of the reaction layer of fly ash particles and reaction rate of the fly ash. At 80% restoration degree (Healing temperature 40℃), there is hardly any difference in comparison with before deterioration in the average thickness of fly ash particles. At this point, most of the fly ash particles didn't hydrate and the hydration of the cement contributed to restoration than the pozzolanic reaction of the fly ash. At 100% restoration degree (Healing temperature 40℃), the reaction layer of the fly ash particles was recognized definitely and the average thickness of those was about 1 μ m, the reaction rate of fly ash was 35%. The observation results show that the pozzolanic reaction of fly ash progresses conspicuously between 80% and 100% restoration degree.

Table 3. Average thickness of the reaction layer of fly ash particles and reaction rate of the fly ash.

	Average thickness of the reaction layer of fly ash particles (μ m)	Reaction rate of fly ash (%)
Before deterioration	0.4	15
After deterioration（Degree of deterioration：60%）	0.5	18
80% restoration degree (Healing temperature 40℃)	0.5	19
100% restoration degree (Healing temperature 40℃)	1.0	35



Before deterioration　　80% restoration degree (Healing temperature 40℃)　　100% restoration degree (Healing temperature 40℃)

Figure 5. Back scattered electron image of fly ash particles.

4 CONCLUSION

(1) We confirmed the self-healing tendency in terms of the relative dynamic modulus of elasticity and strength as a result of post-deterioration healing/curing.

(2) In the pore size distribution after healing, the peak in segments of pore diameter of 0.1mm or less shifts toward the smaller pore diameter as the healing materials age.

(3) It was confirmed that the carbonation rate coefficient tends to recover after post-deterioration curing.

(4) It was confirmed that the chloride ion concentration decreases after post-deterioration curing as the healing period gets longer.

(5) Based on the observation results of radiographic visualization, we confirmed how cracks are repaired as the healing period gets longer.

(6) The observation results of SEM show that the pozzolanic reaction of fly ash progresses conspicuously between 80% and 100% restoration degree.

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