



Self-healing ability of fly ash–cement systems

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ABSTRACT

Concrete is susceptible to cracking due to both autogenous and drying shrinkage. Nevertheless, most of these types of cracks occur before 28 days. Because fly ash continues to hydrate after 28 days, it is likely that hydrated products from fly ash may modify microstructure, seal these cracks, and prolong the service life. This research investigates the self-healing ability of fly ash–cement paste. Compressive strength, porosity, chloride diffusion coefficients, hydration reactions and hydrated products were studied. The research focuses on behavior after 28 days. According to the experimental results, the fly ash–cement system has the self-healing ability for cracks that occur from shrinkage. The self-healing ability increased when the fraction of fly ash increased.

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1. Introduction

The self-healing ability of concrete has been researched for over a decade. Jacobsen and Sellevold [1,2] reported the self-healing of concrete after deterioration: concretes that lost as much as 50% of initial relative dynamic modulus during freeze/thaw cycling could recover almost completely during subsequent storage in water. Edvardsen [3] has reported autogenous healing of cracks in concrete during water flow: the experimental studies showed the formation of calcite in the crack to be the main reason for the autogenous healing. Reinhardt and Jooss [4] have reported permeability and self-healing of cracked concrete as a function of temperature and crack width. The mechanism involved water flow from an external supply. Neville [5] has reported that there are two major hypotheses regarding the reactions in self-healing mechanisms: the hydration of anhydrous cement available in the microstructure of hardened concrete and the precipitation of calcium carbonate CaCO_3 . Granger et al. [6] have reported that the self-healing of cracks in an ultra high-performance cementitious material by mechanical tests and acoustic emission analysis.

From the literature review, in all cases, additional water is essential for the self-healing mechanism. This is not a problem for underground structures where water saturation generally exists. However, for aboveground structures, the availability of water is limited.

Meanwhile, fly ash is a pozzolanic material that reacts with $\text{Ca}(\text{OH})_2$ from cement hydration and produces C–S–H gel. In fact, this reaction is less influenced by the availability of free water than the hydration reaction of cement [7].

Fly ash is also effective for improving various properties of concrete such as long term compressive strength, permeability and resistance to chloride diffusion. The C–S–H gel produced by the pozzolanic reaction of fly ash may seal micro cracks, and accordingly it is expected that the concrete made with cement and fly ash may show self-healing ability.

The objective of this research is to investigate the self-healing possibility of fly ash–cement systems. The factors in this study are compressive strength, chloride diffusion, the cracks and/or the porosity formation, the hydration of cement and fly ash and hydrated products such as C–S–H gel and $\text{Ca}(\text{OH})_2$.

As for the hydration analysis, the individual hydrations of fly ash and cement were estimated by combination of selective dissolution and XRD-Rietveld analysis [7]. As for the cracks and/or the porosity formation, it is difficult to precisely measure the position and width of cracks in concrete because a multitude of factors influence the crack formation. In particular, in the case of a very small crack, the crack widths measured externally are not constant over the complete specimen height [4]. On the other hand, pore-structure modification can be detected by the mercury intrusion porosimetry. Jacobsen and Sellevold [1] have investigated the self-healing effects of conventional concrete by mercury intrusion porosimetry. Therefore, in this study, the pore modification measured by mercury intrusion porosimetry was used to analyze the cracks and the pore formation.

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2. Experiment

Ordinary Portland Cement (OPC) and fly ash type II following to JIS R5210 and JIS A6201 are used in this study. The physical and chemical properties of the fly ash and OPC are shown in Table 1. Paste samples were prepared with the water–binder ratio of 1.45 by volume. The cement was replaced with fly ash. The replacement ratios were 0%, 15%, 25% and 50% by volume, therefore, the water–binder ratio by weight are 0.48, 0.49 and 0.53, respectively. Samples were cured with a sealed curing condition so that there is no water exchange with the environment.

The compressive strength of the hardened pastes was measured until 182 days. The hydration degree and porosity were measured until 365 days. The compressive strength was the average value from three measurements and the porosity was based on one measurement. The standard method for compressive strength measurement in this study is JIS R5201. The effective chloride diffusion coefficient was measured at 28 and 91 days by acceleration method according to Japanese standard JSCE-G571-2003. This standard applies to concrete materials, but was adapted to paste specimens in this study. The paste was prepared in a cylinder mold with height and diameter of 200 and 100 mm, respectively. At each required age, the middle part of the specimens was cut. The thickness of specimen was 50 mm. The specimen was pre saturated with water for 24 h. The accelerated method was conducted under an applied electric potential of 15 V across samples. NaCl solution and NaOH solutions were prepared at cathode and anode with concentration 0.5 and 0.3 mol/L, respectively. The concentration of Cl

ion in the solution at cathode and anode were measured by an ion chromatography. In this experiment, only FA 0% and FA 25% were tested.

At the required age, the samples were broken into 2.5–5.0 mm pieces by hammer, soaked in acetone to stop the hydration reaction, and further dried at 105 °C. A part of each of the samples was kept in a desiccator for mercury intrusion testing. The remaining material was ground in a disc mill until particles smaller than 75 µm were created. The determination of the amount of unhydrated fly ash was based on the selective dissolution method using HCl and Na₂CO₃ solutions [8]. It should be noted that the different cracking and drying methods can give the different results of the porosity and the hydration degree; however, these matters are outside the scope of this study.

As for the XRD-Rietveld analysis, Cu Kα X-ray diffraction equipment was used. The experiments were carried out in the range of 5–70° in 2θ with 0.02 step scan and 1.00 s/step speed. The divergence slit, scattering slit and receiving slit were 1/2°, 1/2° and 0.3 mm, respectively. 10% of corundum was used as an internal reference. The sample and the internal reference were carefully mixed until a homogeneous color and texture were obtained. The Rietveld analysis program used in this study was the SIROQUANT version 3 software [9]. The hydration degree of cement and fly ash were measured until 365 days. The amount of C–S–H gel was calculated by combined method between the selective dissolution and XRD-Rietveld analysis [7,10,11].

An ignition loss was measured. The ignition loss of the sample is expressed as the weight loss of the sample between 105 °C and

Table 1
Physical and chemical properties of fly ash and OPC.

	Ignition loss (%)	Chemical composition from XRF analysis (mass)									Mineral composition from XRD-Rietveld analysis (mass)				Blaine surface area (m ² /kg)	Density (kg/m ³)
		SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)	Na ₂ O (%)	K ₂ O (%)	TiO ₂ (%)	MnO (%)	C ₃ S (%)	C ₂ S (%)	C ₃ A (%)	C ₄ AF (%)		
OPC	0.77	20.84	5.95	2.62	63.63	1.79	0.18	0.33	0.34	0.10	63.09	12.99	11.78	9.23	347	3150
Fly ash	0.90	59.90	29.60	4.80	1.30	0.60	0.00	0.70	0.00	0.00	–	–	–	–	376	2290

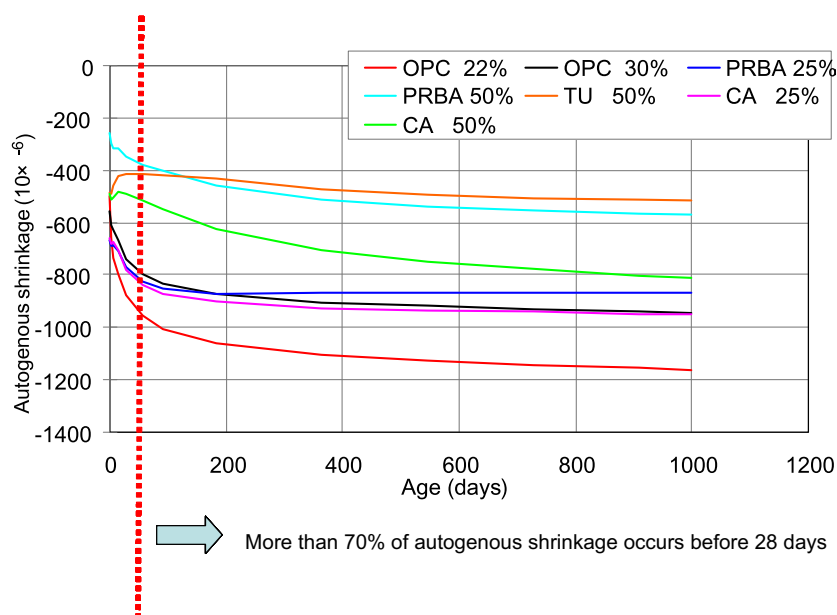


Fig. 1. Autogenous shrinkage of concretes.

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