



Hydration kinetics of high-strength concrete with untreated coal bottom ash for internal curing

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ARTICLE INFO

Keywords:

Coal bottom ash
Internal curing
Degree of hydration
Microstructure
Artificial lightweight aggregates
Thermogravimetric analysis
Mechanical properties

ABSTRACT

The present paper reported the hydration kinetics of high-strength concrete with untreated coal bottom ash to further understand the mechanism of internal curing with bottom ash. As a reference material, a type of commercialized artificial lightweight aggregate was used. Prior to investigating the hydration of concrete, the microstructure of the concrete was observed by using a backscattered electron (BSE) type scanning electron microscope. To systematically investigate the hydration kinetics of the concrete, the degree of hydration was measured and a thermogravimetric analysis (DTA/TGA) for cement mortar was conducted. In addition, the relationship between the hydration kinetics and mechanical properties of concrete containing both types of aggregates were analyzed. It was found that the tendency of hydration enhancement by bottom ash was affected by 1) the escape of water from bottom ash into the cement paste before setting of the fresh mixture, and 2) the high pozzolanic reactivity of bottom ash.

1. Introduction

The introduction of pre-wetted lightweight aggregates, i.e. ‘internal curing’, is a well-known technique for reducing or eliminating autogenous shrinkage of high-strength concrete with a low water-to-binding ratio [1,2]. The effect of self-desiccation in high-strength concrete, which is responsible for autogenous shrinkage, may be counteracted by compensating water from pre-wetted lightweight aggregates [3–5]. In addition to mitigating autogenous shrinkage, internal curing can enhance the degree of hydration of the cement matrix, which may improve the mechanical properties and durability of high-strength concrete. Many researchers have documented that the compressive strength and chloride resistance of concrete at later age may be attributed to hydration enhancement induced by internal curing water from lightweight aggregates [6–8].

In the present series of studies, coal bottom ash, a byproduct from coal combustion power plants, was evaluated as an alternative material for internal curing [9]. Bottom ash provides many advantages as an internal curing agent, including higher availability compared to conventional internal curing agents such as artificial lightweight aggregates or natural porous soils [9,10]. Moreover, the high pozzolanic reactivity of bottom ash aggregates may lead to enhanced durability of the concrete, especially the chloride resistance [11–15]. In addition, the use of bottom ash in concrete is one of the most effective ways to

circumvent the direct disposal of bottom ash, which may cause environmental contamination [12,15].

In our previous study, the shrinkage characteristics of high-strength concrete with bottom ash have been evaluated [9]. The experimental data in the study showed that autogenous shrinkage of high-strength concrete could be decreased or eliminated by the use of untreated bottom ash aggregates for internal curing. However, the effect of bottom ash on shrinkage reduction was different from that of artificial lightweight aggregates. According to theory, the degree of shrinkage reduction of concrete should be similar regardless of the type of aggregate when the amount of water in the aggregate is the same [1]. However, it was found that, although the amount of water in the aggregate was the same, high-strength concrete with untreated bottom ash tended to shrink more than concrete with artificial lightweight aggregates.

This phenomenon was supposed to be attributed to the unique pore structures of bottom ash and its effect on water transfer from aggregates into cement paste; however, limited experimental evidence supporting this supposition was presented. Therefore, to further understand the mechanism of internal curing by untreated bottom ash, which may differ from that of artificial lightweight aggregates, the hydration reaction according to time, i.e., hydration kinetics, in concrete with bottom ash should be studied.

The present paper investigates the hydration kinetics of high-

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strength concrete with bottom ash for internal curing. As a reference material to compare the effect of bottom ash on hydration kinetics of concrete, a type of commercialized artificial lightweight aggregate, expanded shale, was used. Prior to investigating, the microstructure of the concrete was then observed by using a backscattered electron (BSE) type scanning electron microscope (SEM). To systematically investigate the hydration kinetics of concrete, which may be influenced by both the water transfer characteristics and the pozzolanic properties of aggregates, the measurement of the degree of hydration and a thermogravimetric analysis (DTA/TGA) for cement mortar were carried out. In addition, the relationship between the hydration kinetics and mechanical properties of concrete containing both types of aggregates was analyzed.

2. Materials and mix proportion

All materials and mix proportion used in the present study are identical with those in our previous study on internal curing with bottom ash for high-strength concrete [9]. Two different sizes of raw bottom ash, finer and coarser particles in the range of 0–2 mm (BA1) and of 2–5 mm (BA2), respectively, were prepared. As a binder, Type I Portland cement that satisfied the standard specifications of ASTM C150 was used. River sand (specific gravities: 2.46) and crushed gravel (specific gravities: 2.67) were used as natural fine and coarse aggregates, respectively. As a reference internal curing material, a type of commercialized artificial lightweight aggregate, expanded shale with particle size of 0–2 mm (ES), was used. The water absorptions of BA1, BA2, and ES were 8.7%, 10.9%, and 16.7%, respectively. As a high-range water reducer, a polycarboxylic acid-based superplasticizer was added 1.4% of the weight of cement for all mixtures. Detail information on chemical composition and physical properties of materials were reported in Kim and Lee [9]. Table 1 presents the mix proportion of all mixtures. The sand was replaced with the internal curing materials, including BA1, BA2, and ES, by 25% and 50% of volumes. The slump flow of fresh concrete mixtures was also measured in accordance with ASTM C1611 and listed in Table 1.

3. Experimental details

It should be noted that all types of aggregates were immersed in water for 7 days and controlled at a saturated surface dry (S.S.D.) prior to mixing the concrete mixture. The mixtures to analyze hydration kinetics were mixed as mortar-level in a 3 L-capacity hand mixer, while the mixtures to measure mechanical properties, including compressive and splitting tensile strength and elastic modulus, were mixed as concrete-level in a 60 L-capacity fan mixer. The mixture to observe the microstructure was also mixed as concrete-level in the same mixer. Cement and aggregates were mixed for 1 min, and water with superplasticizer was then added, followed by mixing for 3 min more.

Table 1
Mix proportion of mixture [9].

Specimen	Unit weight, kg/m ³							
	Water	Cement	Fine aggregate				Coarse aggregates	Water in aggregates
			Sand	BA1	BA2	ES		
Control	170	566	720	0	0	0	926	0
BA1-25			540	145	0	0		11.6
BA1-50			360	290	0	0		23.2
BA2-25			540	0	140	0		13.7
BA2-50			360	0	280	0		27.3
ES-25			540	0	0	141		20.1
ES-50			360	0	0	282		40.3

3.1. Microstructure

In the present study, backscattered electron (BSE) images were employed instead of conventional SEM images to analyze the microstructure of concrete and to provide visual observation of the degree of hydration of cement around the lightweight aggregate. It is well known that the hydrated part of cement can be distinguished with unhydrated part by the color contrast in BSE images. For a hardened cement matrix, unhydrated cement appears brighter than hydration products, while the pores and cracks filled with epoxy resin are dark [16].

To observe the microstructure of hardened concrete, 50 × 100 mm cylinder-type specimens were cast and cut to 5 ± 1 mm thicknesses using a diamond saw at 91st day of curing. The cut specimens were dried in the vacuum oven at 50 °C for 3 days to evaporate the water in the specimens, and were vacuum/pressure-impregnated with low-viscosity epoxy resin. Note that the epoxy impregnation of concrete specimens serves two purposes: 1) it fixes the pore system and hydration products during cutting and polishing process, and 2) it enhances the contrast of color between pores and hydration products in the BSE images [17]. The vacuuming time in the impregnation process was 1 h and the pressure range was between 1.9 and 2.1 atm (1400–1600 Torr). The detailed process of the vacuum/pressure impregnation for concrete specimens can be found in Ref. [18]. The surfaces of impregnated specimens were polished with 600-grit followed by 1000, 1500, and 4000-grit silicon carbide grinding papers. Note that the ‘grit number’ refers to the number of abrading particles per square inch of a grinding paper [16]. After each polishing, the specimens were cleaned by compressed air spraying. Polished specimens were then coated with gold to provide a conductive surface for viewing BSE images. A field emission (FE) type SEM (Magellan400) manufactured by FEI Company was used. Accelerating voltage and probe current for BSE images were 20kV and 0.4–0.8 nA, respectively. Moreover, element spatial distributions of the surface were illustrated using the energy dispersive X-ray spectroscopy (EDX) mapping function of the SEM.

3.2. Degree of hydration

The degree of hydration of each mixture was indirectly expressed as the non-evaporated water-to-cement ratio (W_{ne}/C). Generally, in the case of cement paste without any other cementitious materials, the absolute value of the degree of hydration (α) can be directly calculated from the value of non-evaporated water content (W_{ne}) [19]. In this case, the calculation process is based on the presupposition that the non-evaporated water is only caused by the hydration of cement. However, in the present study, some portion of non-evaporated water was attributed to the pozzolanic reaction between cement and bottom ash. Therefore, the value of W_{ne} was directly used as a measure of the degree of hydration in the present study, not calculated by the absolute value of the degree of hydration α based on the value of W_{ne} . The non-evaporated water-to-cement ratio (W_{ne}/C) indicated the mass ratio between water, which was consumed by both the hydration reaction of cement and the pozzolanic reaction of lightweight aggregates, and cement in mortar.

To obtain the values of W_{ne}/C in mixtures, the amount of non-evaporated water in mortar was measured by vacuum-drying evaporable water in it. It is worth mentioning that, in the present study, vacuum-drying was introduced as an alternative method to conventional oven-drying. It was intended to prevent acceleration of both hydration and pozzolanic reaction in the mortar during oven-drying at a temperature higher than 100 °C. Therefore, by applying the vacuum-drying method, it could be prohibited the decomposition and/or loss of bound water of some hydration products, e.g., ettringite and C-S-H, from 50 °C to 105 °C [20]. For the measurement, fresh mortar samples of 150 ± 20 g were poured in a plastic bag (a Ziploc bag) to less than 5 mm thickness and sealed. By use of the plastic bag, water evaporation from the samples was completely prevented. Fresh samples in plastic

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