



Study on improvement of carbonation resistance of alkali-activated slag concrete



Juan He^{a,*}, Qie Gao^a, Yonghua Wu^a, Junhong He^b, Xiaolin Pu^a

^a College of Materials and Mineral Resources, Xi'an University of Architecture and Technology, Xi'an 710055, China

^b Mathematics Department, Baoji University of Arts and Sciences, Baoji 721013, China

HIGHLIGHTS

- Technical approaches are used to improve carbonation resistance of AAS concrete.
- Addition of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ slightly increases the pH value of solid dispersed phase.
- Addition of $\text{Ca}(\text{OH})_2$ and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ can significantly reduce the carbonation depth.
- Additional component has little effect on compressive strength.
- Additional component has little effect on hydration and carbonation products.

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ABSTRACT

Carbonation resistance of Alkali-Activated Slag (AAS) concrete is poor. The main reason is that the main hydration product of AAS is calcium silicate hydrate and no calcium hydroxide crystal exists. Two technical approaches were used to improve carbonation resistance of AAS concrete. One method is to add some components that can react with CO_3^{2-} , so $\text{Ca}(\text{OH})_2$, $\text{Zn}(\text{OH})_2$ and ZnCl_2 were added to AAS concrete mixture to absorb CO_2 . The other method is to increase the diffusion resistance of CO_2 in concrete, so air-entraining agent and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ were added to AAS concrete. The results show that $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ slightly increases and ZnCl_2 obviously reduces the pH value of solid dispersed phase. Other additional components have little effect on the basicity of solid dispersed phase. The carbonation degree of AAS concrete is significantly reduced by $\text{Ca}(\text{OH})_2$ and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ within the carbonation ages from 3 days to 28 days. Additional components have little effect on the compressive strength of AAS concrete and also have little effect on the hydration and carbonation products of AAS cement.

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1. Introduction

Alkali-activated slag (AAS) binder is getting more and more attention from concrete researchers. AAS binder is known as an environment-friendly cementitious material because of its lower costs, lower energy and CO_2 emissions [1–4]. Moreover, AAS binder shows high mechanical properties, low permeability and good resistance to chemical erosion [5–8].

However, previous studies have shown that carbonation resistance of AAS concrete is poor. This hinders the popularization and application of AAS concrete. Palacios and Puertas [9,10] studied the carbonation of AAS pastes and AAS mortars. The authors [9,10] observed that in AAS pastes, carbonation occurs only in the C-A-S-H gel. Carbonation of AAS mortar is more serious than

ordinary Portland cement (OPC) mortar. In OPC mortar, only a slight carbonation was observed. While up to 10 mm carbonated front was recorded in WG-activated mortar and only 3 mm was recorded in NaOH-activated mortar. After carbonation, mechanical strength of WG-activated mortar decreased because of the decrease of cohesion in the matrix and the increase of porosity. While mechanical strength of NaOH-activated mortar increased because of the increase of compaction.

Research results of Bakharev et al. [11] also show that AAS concrete carbonated more serious than OPC concrete. AAS concrete showed higher strength loss than OPC concrete. Bernal et al. [12,13] studied the carbonation characteristics of alkali-activated (AA) metakaolin (MK) and slag blends, and AA fly ash (FA) and slag blends. They achieved that as carbonation proceeded, compressive strength decreased roughly linearly. Carbonation caused a highly polymerised alumina-silicate gel in AA slag in which C-A-S-H gel formed. While in AA FA an N-A-S-H gel formed.

* Corresponding author.

E-mail address: hjxd@aliyun.com (J. He).

He and Yang [14,15] studied the carbonation behavior of AAS paste, analysed the carbonation products and microstructure. The results show that when AAS paste was carbonated, specific surface area and cumulative pore volume increased, and average pore diameter and most probable pore diameter reduced. Three variants of calcium carbonate, which are calcite, aragonite and vaterite, all existed in carbonated specimens. The amount of aragonite and vaterite increased with the increase of carbonation age. After carbonation, the C-A-S-H gel rich in silicon was generated, and its degree of polymerization increased. Carbonation behavior of AAS paste didn't increase its dry shrinkage.

According to Ning Li et al. [16], decalcification of C-S-H was the main reaction in carbonation of AAS. AAS mortars demonstrated a lower CaCO_3 formation compared to Portland cement mortars. Calcite and vaterite were the major CaCO_3 polymorphs produced by carbonation.

Previous researches focus on the carbonation process and the effect of carbonation on the microstructure and physical-mechanical properties of AAS concrete. Some results and consensus have been achieved. In general, AAS mortars and concretes suffer more severe carbonation than OPC mortars and concretes [17]. The type and content of slag activators all affect the carbonation process and products. He and Yang [14,15] approved that the existence of more alkali (Na^+ , K^+) in pore solution, no existence of $\text{Ca}(\text{OH})_2$ crystal in hydration product and the larger drying shrinkage of AAS concrete were the important reason for its serious carbonation. Palacios and Puertas [9] attributed this to the fact that in Portland cement paste both the portlandite and the C-S-H gel could be carbonated, whereas in alkali-activated slag pastes, only the C-(A)-S-H gel was carbonated directly.

However, there has been very limited work performed on the improvement of carbonation resistance of AAS concrete. Therefore, in this paper, AAS binders activated with water glass (WG) was used to investigate the technological approaches to improve carbonation resistance of AAS concrete.

2. Experimental

2.1. Materials

The blast-furnace slag was a granulated product ground to fineness of about $432 \text{ m}^2/\text{kg}$, and the density is $2.87 \text{ g}/\text{cm}^3$. The basicity coefficient ($M = (\text{CaO} + \text{MgO})/(\text{SiO}_2 + \text{Al}_2\text{O}_3)$) and the quality coefficient ($K = ((\text{CaO} + \text{MgO} + \text{Al}_2\text{O}_3)/(\text{SiO}_2 + \text{MnO} + \text{TiO}_2))$) of slag were 0.98 and 1.98 respectively. The activity index of 7 days and 28 days were 85% and 103% respectively. The chemical composition of slag is shown in Table 1.

AAS binder was prepared by using water glass (WG) as the activator. WG was an industrial product and its chemical composition and physical properties are shown in Table 2. NaOH was blended

with WG to adjust the modulus (M_s) of WG solution (molar ratio of SiO_2 to Na_2O) to be 1.2. Its concentration was 40%. NaOH was a commercially available industrial caustic soda, the purity of which was 99%. Fine aggregate was the river sand. Its fineness modulus was 2.8. Coarse aggregate was crushed stone. Its maximum particle size was 31.5 mm. Mixing water was tap water.

Air-entraining agent was a yellow powder-like non-ionic surfactant, the main ingredient of which was natural saponin. $\text{Ca}(\text{OH})_2$, $\text{Zn}(\text{OH})_2$, ZnCl_2 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ all were analytical pure AR reagents.

2.2. Experimental procedures

2.2.1. Experimental methods

AAS concrete specimens with two sizes were prepared: $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ and $100 \text{ mm} \times 100 \text{ mm} \times 300 \text{ mm}$ respectively. The specimens were demoulded after moulded for 24 h, and then they were cured in the standard-curing room at relative humidity (RH) of no less than 95% and $20 \pm 2 \text{ }^\circ\text{C}$. Specimens of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ were used to test compressive strength of 3 days, 7 days, 14 days and 28 days.

After 26 days of curing in standard conditions, specimens of $100 \text{ mm} \times 100 \text{ mm} \times 300 \text{ mm}$ were dried in oven at $60 \text{ }^\circ\text{C}$ for 48 h. Subsequently, except two opposite sides exposed to the accelerated carbonation environment, other sides and bottoms were coated with wax. The temperature and relative humidity in carbonation chamber were controlled at $(20 \pm 2)^\circ\text{C}$ and $(70 \pm 5)\%$, respectively. CO_2 concentration in this chamber (volume concentration) was $(20 \pm 3)\%$. At the testing date (carbonated for 3 days, 7 days, 14 days and 28 days), the specimens were taken out of the carbonation chamber and were split along the sides and cleaned, and then the freshly broken surfaces were sprayed with 1% of phenolphthalein in the solution of absolute ethyl alcohol. The carbonated portion was uncolored and non-carbonated portion was purple. The average distance from the concrete surface to the chromatic boundary was the carbonation depth. The arithmetic average of three specimens is taken as the carbonation depth value of this group of AAS concrete specimen. After carbonation depth was tested, the split surface of AAS concrete was sealed with wax to be used in the next test of carbonation depth.

Reduction rate of carbonation depth was the ratio of carbonation depth difference to reference specimen carbonation depth. Carbonation depth difference was the value of reference specimen carbonation depth minus the carbonation depth with additional component.

The pH value of solid dispersed phase was determined by PHS-3C acidity meter. Solid dispersed phase was either slag powder or the powder binder to which some additional component was added. The solid dispersed phase and distilled water were mixed at 1:2, and were stirred for 10 h continuously. Then the solution

Table 1
Chemical composition of slag.

SiO_2 (%)	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	Ignition loss (%)
32.02	16.15	38.78	0.84	8.40	0.23	0.34	0.27	0.40

Table 2
Chemical composition and physical properties of WG.

SiO_2 (%)	Na_2O (%)	M_s	Baume degree ($^\circ\text{Bé}$)	Density (g/cm^3)
24.9	9.3	2.76	40.0	1.384

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