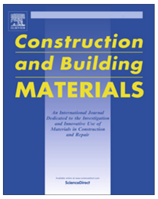
Construction and Building Materials 186 (2018) 978–985

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



The influence of curing methods on the strength of MSWI bottom ash-based alkali-activated mortars: The role of leaching of OH^- and free alkali

Guodong Huang [a,b,c,*], Yongsheng Ji [a,c,*], Linglei Zhang [a,c], Jun Li [a,c], Zhihui Hou [a,c]

[a] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 21116, Jiangsu, China
[b] School of Civil Engineering and Construction, Anhui University of Science and Technology, Huainan 232001, Anhui, China
[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 21116, Jiangsu, China

HIGHLIGHTS

- Standard room curing is not suitable for alkali-activated materials.
- The resulting OH^- and free alkali leaching severely affects strength development.
- Seal curing effectively prevents the leaching of OH^- and free alkali.

ARTICLE INFO

Article history:
Received 14 March 2018
Received in revised form 23 July 2018
Accepted 27 July 2018

Keywords:
Curing methods
Municipal solid waste incineration bottom ash
Granulated blast-furnace slag
Alkali-activated
Mortar
Free alkali
OH^-

ABSTRACT

This study investigated the influence of different curing methods on the strength development of municipal solid waste incinerator bottom ash alkali-activated mortars. The results showed that standard room curing is not suitable for alkali-activated materials. The main reason for this is the humidity > 95% in the curing room, which causes wet sample surfaces. This leads to OH^- and free alkali leaching, which severely affects strength development. Soaking curing further aggravates this effect. However, seal curing effectively prevents the leaching of OH^- and free alkali and thus maintains high alkalinity, which benefits the strength development. Therefore, the method of seal curing is more suitable for alkali-activated materials.

1. Introduction

Alkali-activated materials are a novel type of inorganic nonmetallic material developed during recent years [1]. These are high-strength binding materials produced in a reaction where strong alkali activates the silicate or aluminosilicate either at room temperature or in a state of steam curing [2]. Compared to Portland cement, alkali-activated materials consume less energy, cause almost no pollution, and require no consumption of limestone resources [3]. Consequently, this is an environmentally friendly green building material [4], offering the possibility to replace Portland cement in the future.

To ensure that the strength of alkali-activated materials achieves the desired level after preparation, curing is often applied. However, in the absence of in-depth studies of curing methods and the strength development mechanism of alkali-activated materials, often, the same curing applicable to Portland cement concrete is adapted to cure alkali-activated materials [5–8]. However, whether this curing method is suitable for alkali-activated materials remains unknown, although this type of curing method achieves a certain strength. Relevant studies have shown that the hydration mechanism of Portland cement differs strongly from the polymerization mechanism of alkali-activated materials [9]. Hydration reactions require a specific amount of water to continue and cement hydration generates a large amount of $Ca(OH)_2$ to maintain

---

* Corresponding authors at: State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 21116, Jiangsu, China.

E-mail address: jysbh@126.com (Y. Ji).

https://doi.org/10.1016/j.conbuildmat.2018.07.224

a specific alkalinity (pH value 13.0) within the cement slurry, which is beneficial to the development of strength. As a result, water is very important to cure cement concrete and the curing method of cement concrete engineering is often used in large area continuous sprinkler curing [10]. However, the polymerization of alkali-activated materials needs to be conducted under high alkalinity conditions (pH value 13.9) and the entire polymerization process does not require water [11]. The high alkalinity condition is beneficial for the leaching of active substances from alkali-activated materials and it further promotes the polymerization of active substances, thus achieving high strength [12]. Since the curing method of Portland cement concrete is adopted to cure alkali-activated materials, this will lead to a continuously wet state of the external sample surface. This will reduce the pH value within the sample and the active substances will leach out of the alkali-activated materials, which is unfavorable for the development of strength. This indicates that the curing method of Portland cement concrete is not particularly suitable for alkali-activated materials [9,13,14]. Establishing and validating suitable curing methods for alkali-activated concretes remains a major obstacle of their commercial adoption for challenging structural applications [15]. Therefore, to evaluate the impact of different curing methods on the strength development and to develop a reliable curing method for alkali-activated materials under different engineering environments is an important issue that needs to be addressed [16–18].

In this study, the method of seal curing in the curing room was adopted to remit the decline of alkalinity as well as the leaching of active substances. At the same time, seal curing was compared to natural curing, standard curing room curing, and soaking curing. Furthermore, the influence of different curing methods on the strength development of samples was analyzed, using the change law of compressive strength. The distribution law of the pH value within samples was measured via pre-embedded pH detectors in the samples during preparation. Moreover, microanalyses of inductively coupled plasma mass spectrometry (ICP-MS), X-ray diffraction (XRD), X-ray fluorescence (XRF), and Fourier transform infrared spectroscopy (FT-IR) were conducted to analyze the leaching law of free alkali and the transformation law from free alkali to union alkali and compound alkali under different curing methods.

2. Experimental materials and methods

2.1. Materials

2.1.1. MSWI bottom ash

The MSWI bottom ash (BA) that was used in this experiment was supplied from the GCL-Poly (Xuzhou) Renewable Energy Power Generation Co., Ltd. The municipal solid waste was first separated via magnetic separation and then calcined at 800 °C. The BA was washed at the recycle station and its chemical composition is shown in Table 1. In this experiment, the BA required grinding into a fine powder with a surface area of 400 m^2/kg and a specific gravity of 2.47. The particles were mainly spherical with a median particle size of 47 μm and 28% was retained on a 45 μm sieve.

2.1.2. Granulated blast furnace slag (GBFS)

The GBFS used in this experiment was S95 granulated blast furnace slag powder, which conforms to the Chinese standard GB/T 18046-2008 [19]. The surface area and specific gravity of GBFS were 416 m^2/kg and 2.89, respectively, and 35% was retained on a 45 μm sieve. Its chemical composition is shown in Table 1.

2.1.3. Activator

For alkali activated solutions, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) of 9.65% in Na_2O, 25.22% in SiO_2, and 65.13% in H_2O, respectively, were utilized. The sodium silicate solution had a modulus of 2.6. NaOH was used as solid state analytical reagent with a purity of 99.5%. The NaOH dosage and water are listed in Table 2, and a 125 ml 4.8 M NaOH solution was prepared to obtain each set of mortars. The solution was left to settle for 24 h before use.

2.1.4. Others

For the fine aggregate, the test sand used in this study had an ISO specific gravity standard of 2.58 and a fineness modulus of 2.9. Deionized water was used for the test.

2.2. Methods

2.2.1. Mix proportion of alkali-activated samples

Table 2 shows the mix proportion of BA alkali-activated mortars and all BA alkali-activated mortars have the same formulation with different curing conditions. A liquid to binder ratio of 0.6 was used, where the liquid consisted of the total mass in the NaOH, water, and sodium silicate solution. The sand to binder ratio was 3. GBFS was incorporated (40% in binder) to improve the strength of alkali-activated mortars.

2.2.2. Casting of BA alkali-activated samples

The BA alkali-activated samples were prepared in a 20 ± 2 °C controlled room. Before preparation, BA with NaOH and water (Table 2) was mixed to form a slurry, which was aged for 4 h to conduct a defoaming pre-treatment that eliminated the effects of foaming and expansion when bottom ash meets alkali. The casting procedure was then initiated by mixing the slurry and GBFS for 1 min; then, sand and a sodium silicate solution were added and stirred for 1 min. Finally, according to the "Method of testing cement--Determination of strength—ISO [20]", standard mortar samples of 40 mm × 40 mm × 160 mm were produced. All samples (except for C-6) were stored for 24 h in a curing room after casting and were subsequently demolded. The curing room was 20 ± 2 °C (>95% humidity).

2.2.3. Curing methods of BA alkali-activated samples

Table 2 shows that groups C-1 to C-6 were BA alkali-activated mortars that adopted different curing methods, which were used to examine the effects of different curing temperatures and humidity levels on the resulting strength development. Natural curing of group C-1 was conducted under natural conditions, with daily average temperatures ranging from 5 °C to 20 °C (at 60% humidity). Standard curing room curing of group C-2 was conducted in the curing room, with a constant temperature of 20 ± 2 °C (humidity > 95%), which it is the curing standard (GB50010-2010) of Portland cement concrete in the laboratory [21]. Group C-3 adopted the way of seal curing, where the sample was sealed via plastic film and placed in the curing room. The curing temperature and humidity were identical to group C-2. Group C-4 adopted steam-curing and the specific method retained the sample in the steam room for 6 h after demolding (temperature = 80 °C and

Table 1
Chemical composition of raw material (%).

Raw material	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	Zn, Pb, Ba, Sr, Cu	LOI
GBFS	31.35	34.65	18.65	0.57	9.31	–	–	–	0.7
BA	53.82	14.44	14.18	6.18	3.26	2.52	2.24	0.61	1.62

Table 2
Mix proportion of BA alkali-activated samples (g).

	BA	GBFS	Deionized water	Sodium silicate solution	NaOH	sand	Curing methods	Curing temperature	humidity
C-1	270	180	125	120	25	1350	Natural curing	5 °C–20 °C	60%
C-2	270	180	125	120	25	1350	Standard curing room curing	20 ± 2 °C	>95%
C-3	270	180	125	120	25	1350	Seal curing in curing room	20 ± 2 °C	>95%
C-4	270	180	125	120	25	1350	Steam-curing	80 ± 2 °C	100%
C-5	270	180	125	120	25	1350	Soaking curing (after 24 h)	20 ± 2 °C	100%
C-6	270	180	125	120	25	1350	Soaking curing (after preparation)	20 ± 2 °C	100%