Construction and Building Materials 79 (2015) 173–181

Contents lists available at ScienceDirect

Construction and Building Materials

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

A novel eco-friendly porous concrete fabricated with coal ash and geopolymeric binder: Heavy metal leaching characteristics and compressive strength

J.G. Jang, Y.B. Ahn, H. Souri, H.K. Lee *

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daehak-ro 291, Yuseong-gu, Daejeon 305-701, South Korea

HIGHLIGHTS

- A novel type of porous concrete made solely with industrial byproducts was developed.
- Heavy metal leaching characteristics and compressive strength were studied.
- Characteristics of geopolymer affected the diffusion of heavy metals from bottom ash.
- The porous concrete showed acceptable compressive strength and leaching behavior.

ARTICLE INFO

Article history:
Received 21 September 2014
Received in revised form 8 January 2015
Accepted 10 January 2015
Available online 22 January 2015

Keywords:
Coal ash
Porous concrete
Heavy metals
Geopolymer
Void ratio
Compressive strength

ABSTRACT

This study focuses on the development of a novel type of eco-friendly porous concrete made solely with industrial by-products. Coal bottom ash was used as a coarse aggregate and geopolymer as a binder. Experimental evaluations of heavy metal leaching behavior and compressive strength were conducted. The test results showed the concentrations of heavy metals which leached from the bottom ash in porous concrete were below the selected criteria, and the characteristics of geopolymer dominantly affect the diffusion of heavy metals from bottom ash. In addition, a significant correlation was observed among the paste thickness, measured total void ratio and compressive strength, and an empirical formula to express the relationship between the void ratio and compressive strength was derived. It is concluded that the porous concrete developed in this study can effectively immobilize heavy metals as solidified/stabilized products.

1. Introduction

Porous concrete is a construction material that contains large interconnected voids. These voids are created by omitting fine aggregate from conventional normal concrete. This allows porous concrete to have numerous characteristics and capabilities, such as water permeability, acoustic absorption, water purification, SO_x and NO_x adsorption, humidity control, and even functions related to vegetation [1–6]. Unlike piled earth materials, which also have permeability and other benefits, porous concrete can be fabricated into various shapes and strengths. Moreover, it is highly durable. Due to these numerous advantages and its wide range of applications, porous concrete has recently attracted a considerable amount of attention as an eco-friendly construction material that is in harmony with nature.

Coal ash is an industrial by-product of coal-fired power plants that can be divided into fly ash and bottom ash. The generated amounts of fly ash and bottom ash differ between power plants, though fly ash usually accounts for 70–90% of the total amount of coal ash, whereas bottom ash accounts for 10–30% [7,8]. Fly ash has been actively recycled as cement and concrete admixtures [8]. On the other hand, the recycling of bottom ash remains rare even with a guideline for bottom ash recycling as a road base material, sub-base aggregate and structural fill material [9,34]. The chemical composition and physical properties of bottom ash differ from those of fly ash, and bottom ash generally contains more heavy metals as compared to fly ash [10]. Therefore, sending hazardous bottom ash to landfills incurs the risk of ground water pollution due to heavy metal leaching while also requiring large tracts of land. The proper recycling of bottom ash is urgent, and several studies have found that the solidification of bottom ash with cementitious materials reduces the amount of heavy metals which

* Corresponding author. Tel.: +82 42 350 3623; fax: +82 42 350 3610.
E-mail address: haengki@kaist.ac.kr (H.K. Lee).

http://dx.doi.org/10.1016/j.conbuildmat.2015.01.058
0950-0618/

leach from it to below many environmentally acceptable criteria by both physical and chemical means [7,11].

Over the past few decades, much studies dealing with the effects of the void ratio, water-to-cement ratio, coarse aggregate characteristics, and cement paste characteristics on the strength and functionality of porous concrete have been conducted [6,7,12–15]. Although typical mix proportions for porous concrete fabricated with ordinary cement paste and gravel have been made available in recent years, there are only a few studies dealing with the utilization of coal bottom ash as a coarse aggregate material for use in the formulation of porous concrete. Park et al. [7], investigated the toxicity of bottom ash and the mechanical properties of porous concrete fabricated with bottom ash and Portland cement paste, and concluded that mixing with reinforcing element was necessary to improve the strength of porous concrete using bottom ash, as the mechanical strength tended to decrease as the bottom ash mixing ratio increased. In addition, Park et al. [7] reported that porous concrete using bottom ash coarse aggregate satisfied environmentally acceptable criteria for heavy metals.

On the other hand, geopolymers represent a type of alkali-activated binder which is considered to be a more eco-friendly counterpart of cementitious materials which may also offer high strength and remarkable durability [16–20]. The main materials used to make geopolymers consist of recycled ingredients such as coal fly ash, blast furnace slag, and metakaolin, which are hardened in an alkaline environment created by waterglass, NaOH, KOH, or a combination of these alkali-activators [19]. Therefore, it is expected that porous concrete fabricated with coal ash and geopolymeric binder, a novel type of porous concrete developed in this study, will provide the following advantages. First, coarse aggregate and cementitious binder, the major parts of porous concrete, can be completely composed of recycled industrial by-products, enabling a more effective use of our resources. Second, it will be more cost-effective compared to normal porous concrete, as the production of porous concrete is possible on-site, where the fly ash and bottom ash are generated. Third, geopolymers generally create fewer capillary pores than Portland cement paste. For this reason, less heavy metal leaching from bottom ash can be expected.

In the present study, a novel type of porous concrete utilizing coal ash and geopolymeric binder was developed. Bottom ash from a coal-fired power plant was employed as a coarse aggregate material and geopolymeric binder (alkali-activated fly ash/slag paste) was used as the cementitious binder material for the fabrication of the porous concrete. The present study aims to investigate the heavy metal leaching characteristics and the compressive strength of porous concrete fabricated with coal bottom ash and the aforementioned geopolymeric binder through a series of characterization tests. An experimental evaluation of the macro- and microstructures, heavy metal leaching, void ratio, and compressive strength of the porous concrete was conducted for this purpose. In addition, the experimental results of porous concrete fabricated with the geopolymeric binder were compared to the results of porous concrete made with the ordinary Portland cement paste.

2. Experimental procedure

2.1. Raw materials

Fly ash and ground granulated blast furnace slag (BFS) were used as geopolymeric binder materials. The slag-to-binder ratio of 0.5 was determined to synthesize geopolymeric binder. The chemical composition and specific surface areas of the fly ash and BFS used in this study are listed in Table 1. The fly ash and BFS were synthesized at room temperature using an alkali-activator which was made with a 4 M NaOH solution and waterglass (SiO_2/Na_2O = 2.16, water content = 61.5 wt%, specific gravity = 1.38). The mass ratio of the NaOH solution/waterglass for the alkali-activator is 2. Detailed information pertaining to the preparation of the alkali-activator and the geopolymeric binder can be found in Jang et al. [16]. In addition, Type I Portland cement was used as a reference material.

Table 1
Chemical composition and specific surface areas of the fly ash and BFS.

Chemical composition (%)	Fly ash	BFS
SiO_2	42.10	35.17
Al_2O_3	28.60	13.93
CaO	6.26	42.47
Fe_2O_3	14.40	0.58
MgO	2.60	4.12
K_2O	2.40	0.46
SO_3	0.61	2.03
Na_2O_3	–	0.15
Specific surface areas (m^2/kg)	290	485

The coal bottom ash used in this study is from the Seocheon thermoelectric power plant in South Korea. It was first sieved using 2.5 mm, 5 mm, and 13 mm sieves to obtain two groups of bottom ash, one with a grading of 2.5–5 mm, and the other with a grading of 5–13 mm. The two groups were then washed well to remove the fine powder of the bottom ash as well as other impurities. The chemical composition of the bottom ash used in this study was determined by X-ray fluorescence (XRF) using MiniPal 2 from PANanalytical. These results are listed in Table 2. The XRF analysis shows that SiO_2, Al_2O_3, and Fe_2O_3 comprise nearly 90% of the bottom ash for both sizes. The amounts of heavy metals in the bottom ash, fly ash and BFS, in this case chromium, copper, arsenic, lead, cadmium and mercury were investigated with inductively coupled plasma (ICP) using the iCPA-6300 Duo ICP-OES and ICP/MS 7700X spectrometers. These results are listed in Table 3. The test samples for the ICP analysis were pretreated using a microwave sample digestion system (operating condition: 210 °C, microwave power range of 1000 W) manufactured by Milestone Inc. with nitric acid and hydrochloric acid, after which they were diluted with ultrapure water. The physical properties of the bottom ash were determined through a series of experiments in accordance with the procedure described in ASTM C127-12 [33]. The details of the physical properties of the bottom ash are given in Table 4. The obtained apparent specific gravity (ASG), bulk specific gravity (BSG), and water absorption ratio (WAR) values were calculated by Eqs. (1)–(4) [33].

$$ASG = W_{OD}/(W_{OD} - W_{UW}) \quad (1)$$

$$BSG_{OD} = W_{OD}/(W_{SSD} - W_{UW}) \quad (2)$$

$$BSG_{SSD} = W_{SSD}/(W_{SSD} - W_{UW}) \quad (3)$$

$$WAR = (W_{SSD} - W_{OD})/W_{OD} \times 100\% \quad (4)$$

Here, W_{OD} is the weight of the oven dried (OD) aggregate, W_{UW} is the apparent weight of the aggregate under water, and W_{SSD} is the weight of the surface-saturated dried (SSD) aggregate. In addition, a measurement method for the absolute volume ratio of bottom ash can be found in JIS A 1104 [38].

Porous concrete has a small amount of mixing water and a large amount of coarse aggregate; thus, it is necessary to consider whether or not the water content on the surface of the aggregate is stable. Therefore, air-dried bottom ash aggregates, with controlled water content levels of approximately 3–5%, were used to eliminate the effect of the water contained within the bottom ash and to minimize the absorption of the cement paste resulting from the drying of the bottom ash.

2.2. Mix proportion and fabrication method of the porous concrete

Four types of paste were used for the fabrication of the porous concrete. The mix proportion of the cement paste and the geopolymer paste used in this study is listed in Table 5. The water-to-cement (w/c) ratios of the cement paste were determined to be 0.25 and 0.3, which are commonly used w/c ratios for fabricating porous concrete. Alkali-activator-to-binder (a/b) ratios of 0.5 and 0.6 were utilized for the geopolymer paste. The mix proportion of the geopolymer paste used in this

Table 2
Chemical composition of the bottom ash.

Chemical composition (%)	2.5–5 mm	5–13 mm
SiO_2	49.90	50.10
Al_2O_3	29.30	26.90
CaO	1.64	3.95
Fe_2O_3	10.50	10.80
K_2O	4.69	4.22
TiO_2	2.83	2.52
ZrO_2	0.15	0.14
Cl	0.57	1.10