Cement and Concrete Composites 72 (2016) 27–38

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Mechanical properties of lightweight concrete made with coal ashes after exposure to elevated temperatures

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

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daehak-ro 291, Yuseong-gu, Daejeon 34141, South Korea

ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form 28 March 2016
Accepted 31 May 2016
Available online 1 June 2016

Keywords:
High temperature
Lightweight concrete
Mechanical properties
Fly ash
Bottom ash

ABSTRACT

This study investigated the thermal resistance of lightweight concrete with recycled coal bottom ash and fly ash. Specimens were exposed to temperatures up to 800 °C then cooled to room temperature before conducting experiments. Compressive strength test, FF-RC test, TG analysis, and XRD analysis were performed to analyze the physicochemical effects of coal ashes on the thermal resistance of concrete. Test results indicated that both bottom ash and fly ash were associated with a substantial increase in the residual strength of thermal exposed concretes. The results were attributed to the surface interlocking effect and the smaller amount of SiO_2 for bottom ash. For fly ash, the formation of pozzolanic C-S-H gel and tobermorite retained water at high temperatures, and the consumption of $Ca(OH)_2$ lowered stress from rapid recrystallization after exposure to 600 °C. It was concluded that the incorporation of coal ashes allows for lightweight concrete with good thermal resistance.

1. Introduction

In response to the persistent pursuit of taller, longer, and larger structures around the world, the search for technologies that allow lighter and cheaper construction materials has attracted attention for decades now. One such technology is structural lightweight concrete, which has close to 20% lower density compared to normal weight concrete, and exhibits strength that is adequate enough for many structural purposes. The primary advantage of lightweight concrete is the reduction in the dead load of structures, allowing smaller cross-sections and less reinforcing materials. Lightweight concrete is also used because of its low transportation cost, resistance to earthquake loading, easier handling, and low overall cost [1].

Lightweight concrete, which can be in a form of polymer concrete or lightweight aggregate concrete, can achieve a greater strength-to-density ratio than ordinary concrete and only slightly compromises the strength of ordinary concrete [2]. The most commonly used lightweight aggregates are artificially calcined aggregates, such as expanded shale, expanded clay and expanded vermiculite, and natural lightweight aggregates, such as scoria and pumice [3]. These aggregates have many benefits but also drawbacks, including relatively high cost, the large environmental impact of the energy-intensive calcination process, or limited local availability of material. One prospective material to overcome the drawbacks is coal bottom ash, a byproduct of the coal-fired electrical power plant. This chemically stable material is very affordable, abundant worldwide with one million tons produced annually in South Korea alone [4], and does not require any additional energy for production. In addition, recycling bottom ash will prevent serious ground and water pollution caused by the common practice of landfill; it has been verified in previous studies that heavy metals along with other pollutants from bottom ash can be solidified in cementitious forms [5–8]. Bottom ash accounts for 10–30% of total coal ash, with the rest mainly comprised of fly ash. The pozzolanic reaction of fly ash, along with its many advantages as a cementitious binder, has been extensively studied [9–13].

One of the most destructive causes of concrete failure is fire [14]. Fire, unlike many other threats to concrete, may cause complete failure with a single case of exposure, making it difficult to take necessary measures when a threat or the resulting damage is first detected. The application of lightweight concrete must therefore be conducted with a good understanding of its behavior at elevated temperatures, especially in relation to the properties of the aggregates and binder used. Numerous studies have been conducted on moisture flow, heat flow, and the main causes of spalling,

* Corresponding author.
E-mail address: haengki@kaist.ac.kr (H.K. Lee).

http://dx.doi.org/10.1016/j.cemconcomp.2016.05.028
0958-9465/

especially inside normal and heavy-weight concrete [15–20]. However opinions vary on how concrete density, water content, and thermal conductivity affect its thermal resistance. For example, Sakr and EL-Hakim reported that dense matrix of concrete increased residual strength of concrete subjected to elevated temperature, whereas Hossain and Lachemi concluded otherwise [21,22]. In addition, Li et al. reported that oven-dried specimens showed lower strength than air-dried specimens after exposure to 800 °C, whereas Lau reported that higher moisture contents resulted in greater strength loss [23,24]. Most importantly, although numerous studies have investigated the application of coal ashes in lightweight concrete, little attention has been given to its effect on thermal resistance.

This study focused on the thermal resistance of lightweight concrete using recycled coal ashes, with bottom ash as aggregate, and fly ash as a portion of the binder. The behavior of the lightweight concrete with coal ashes at elevated temperatures was investigated in comparison with the behavior of lightweight concrete with expanded shale, a commonly used lightweight aggregate. A comparative analysis was conducted in terms of physical changes in the interface between aggregate and paste, the chemical composition of paste, and the degradation process of paste through dehydration and phase transformation. It is projected that the results of this study can deepen the understanding of lightweight concrete with coal ashes, leading to safer design and application of this technology.

2. Materials and experimental methods

2.1. Materials used

Materials used in this study were class F fly ash from Dang-jin thermal power plant in South Korea, bottom ash from Seo-cheon thermal power plant in South Korea, expanded shale from Hanya Raw-material, Ltd. in China, and type I Portland cement. The chemical compositions of the fly ash and bottom ash were obtained by X-ray fluorescence (XRF) using MiniPal 2 from PANanalytical, and that of expanded shale and cement were given by the manufacturer. The chemical composition of materials used in this study is presented in Table 1, which indicates that SiO_2 alone comprises 49.9% of the bottom ash and 65% of the expanded shale. Blaine finenesses of the fly ash and cement were 290 m^2/kg and 280 m^2/kg, respectively. Physical properties of the aggregate materials were tested in accordance with standard test methods including ASTM C128 for density and absorption, ASTM C29 for bulk density, and ASTM C136 for sieve analysis. The results of the standard tests are organized in Table 2. The maximum aggregate size for both bottom ash and expanded shale was 10 mm.

2.2. Specimens preparation

Six different mix proportions were designed to investigate the effect of bottom ash and fly ash on thermal resistance compared to that of expanded shale. Water-to-binder ratio of 0.635 and aggregate-to-paste ratio of 0.942 by weight were used for all mixtures. A relatively high water to binder ratio was adopted to achieve a rapid and extensive pozzolanic reaction of fly ash [25]. Viscosity modifier was used in amounts of less than 0.2 cement weight percent for adequate workability. Mix proportions of the specimens are given in Table 3.

Paste was made before incorporating aggregates to reduce the separation of materials and to lower the amount of materials absorbed into the porous aggregates [5]. Aggregates were air dried for improvement in internal curing [26] and to reduce the film of water on the aggregate surface that is accused of creating a weak interface with higher water content [13]. Cylindrical (ϕ10 cm × 20 cm) and cubic (5 cm × 5 cm × 5 cm) specimens were fabricated. Fresh specimens were wrapped in plastic wrap for a day, then demolded and cured in water at 20 °C for 28 days.

Air-dry densities of the cured specimens were measured after being dried for 24 h at room temperature, and the results are summarized in Table 4. All specimens showed significantly lower densities, corresponding to 75–80% the density of normal weight concrete (2300 kg/m^3). The incorporation of coal bottom ash and fly ash increased the air-dry density of the lightweight concrete in comparison with the incorporation of expanded shale and type I cement alone, respectively, at the same water-to-binder and aggregate-to-paste ratios. This may be explained by the Blaine fineness of fly ash, which is higher in value compared to that of cement, resulting in tighter packing.

2.3. Testing and characterization

2.3.1. Thermal exposure

Prior to thermal exposure testing, the specimens were first dried at 100 °C until a constant weight was achieved, to remove capillary water and reduce the risk of spalling. The specimens were cooled to room temperature, then placed inside a furnace, whose internal temperature was increased from room temperature to 200, 400, 600, or 800 °C at the rate of 10 °C/min. The maximum temperature was maintained for 2 h to attain thermal equilibrium at the center of the specimens [27]. After the 2 h the furnace was turned off, and the specimens were allowed to cool slowly for 24 h inside the furnace. Finally, all specimens were sealed with plastic wrap to prevent rehydration until further experiments. Weight loss during the thermal exposure was measured as an indication of the amount of water loss [28]. It is recognized that free water is evaporated at temperatures up to 200 °C, adsorbed water at temperatures up to 400 °C, and chemically bound water at temperatures up to 1500 °C [28,29].

2.3.2. Free-free resonant column test (FF-RC test)

The FF-RC test is a non-destructive testing method for estimating Young's modulus within the elastic range of a material, in which the principle of elastic wave propagation is applied [30]. A cylindrical specimen is suspended from a support frame using two pieces of string to create free-free boundary conditions, as shown in Fig. 1. One end of the specimen is hit with a small mallet, and the resonant frequency is measured and recorded by the waveform analyzer at the other end. Young's modulus is estimated using Eq. (1) [30]:

$$E = \rho \cdot (f_1 \cdot \lambda)^2, \tag{1}$$

where ρ is the unit weight of the specimen, f_1 is the resonant frequency, and λ is the first mode wavelength, which is twice the length of the specimen [30]. Using a single ρ value and using twice the length of the specimen for λ signify that the concrete is assumed

Table 1
Chemical composition of materials.

Chemical composition (%)	Fly ash	Bottom ash	Expanded shale
SiO_2	51.00	49.90	65
Al_2O_3	25.00	29.30	18
CaO	6.24	1.64	2
Fe_2O_3	12.70	10.50	7
K_2O	1.70	4.69	–
TiO_2	2.14	2.83	–
ZrO_2	0.14	0.15	–
Cl	–	0.57	–