Construction and Building Materials 150 (2017) 547–557

Contents lists available at ScienceDirect

Construction and Building Materials

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

Preparation and properties of electrically conductive aggregate made using magnetically separated fly ash

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HIGHLIGHTS

- A new kind of conductive aggregate was prepared by magnetically separated fly ash.
- The conducive aggregate has very good conductivity.
- Rust stain of conductive aggregates used to investigate iron particle distribution.

ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form 24 May 2017
Accepted 26 May 2017
Available online 14 June 2017

Keywords:
Magnetically separated fly ash
Conductive aggregate
Electrical resistivity
Iron particles

ABSTRACT

A new type of conductive aggregate was prepared by the calcination of magnetically separated fly ash (MSFA). The effects of the calcination atmosphere, calcination temperature, and iron oxide content on the electrical resistivity were studied. Experimental results show that the optimal calcination conditions are a reducing atmosphere and a temperature of 1150 °C. Iron oxides were reduced to iron by the reducing atmosphere and formed a continuous electrical path; the conductive mechanism is electron conduction. The water absorption and apparent density of the optimal conductive aggregate were 5%, and ~2.0 g/cm^3. The new series of conductive aggregates provided good electrical conductivity (volume resistivity of all conductive aggregates < 10 Ω-cm).

1. Introduction

Trends in the processes related to concrete include structural-functional integration, with electrically conductive concrete being one development direction. Conductive concrete can be used in smart engineering structures, to enable the de-icing of roads and airport runways, and to provide electromagnetic shielding [1–7]. Unlike ordinary concrete, conductive concrete has a very low electrical resistivity. Generally, the cement matrix is enhanced by the addition of conductive phases, such as carbon black, steel slag, carbon fiber, and steel fiber. To form an interconnected conductive network, the conductive phases must occupy a certain space, but because of the limitations of the conductive phase content, to date the space that those conductive phases occupy in conductive concrete has been very limited [8]. However, the aggregate, which takes up most of the space in the concrete, is non-conductive and harmful to the conductivity of the conductive concrete. Therefore, the development of a new type of conductive aggregate would significantly improve the conductivity of a conductive concrete.

The iron oxide content of the fly ash produced in southwest China is about 15%, which is higher than that of fly ash produced elsewhere. Some iron oxide can be easily separated from the fly ash by using a magnetic separator, producing an iron oxide content of more than 30% after magnetic separation [9]. As an industrial solid waste, fly ash with a high iron oxide content was considered to be a low-activity component which would adversely affect the strength of the concrete. Magnetic separation is an easy method of improving the level of utilization of fly ash in building materials. Ferroferric oxide has an electrical resistivity of 4.0×10^{-5} Ω-cm, which is in the same order of magnitude as that of polyacrylonitrile (PAN)-based carbon fibers and can be used as a conductive phase [10]. In a previous work, magnetically separated fly ash (MSFA) was used as a mineral admixture to prepare conductive concrete. The amount of admixture was very limited (about 30 wt%). The space occupied by the MSFA was also very small, such that a conductive network could not be formed [11,12]. The main object of the present study was to prepare a new type of conductive aggregate by calcining MSFA and investigating the three main factors

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.210
0950-0618/

affecting the conductivity of the aggregates: the calcination atmosphere, calcination temperature, and conductive phase content.

2. Experimental

2.1. Raw materials

Fly ash was acquired from the Luohuang Power Plant in Chongqing. As shown in Figs. 1 and 2, MSFA was prepared by wet separation using magnetic bars with magnetic field intensities of 6000–12,000 Gs. MSFA-a was separated from the Luohuang fly ash (LHFA) using a 12,000-Gs magnetic bar, MSFA-b was separated from MSFA-a using a 10,000-Gs magnetic bar, MSFA-c was separated from MSFA-c using an 8000-Gs magnetic bar, and MSFA-d was separated from MSFA-c using a 6000-Gs magnetic bar. The chemical compositions of the LHFA and MSFAs are listed in Table 1. Fig. 3 shows the size distributions of the fly ash. The particle size of the MSFAs increases after magnetic separation. This is probably related to the size of the magnetic particles, given that these are larger than the others, with a larger number of magnetic particles leading to a larger mean diameter.

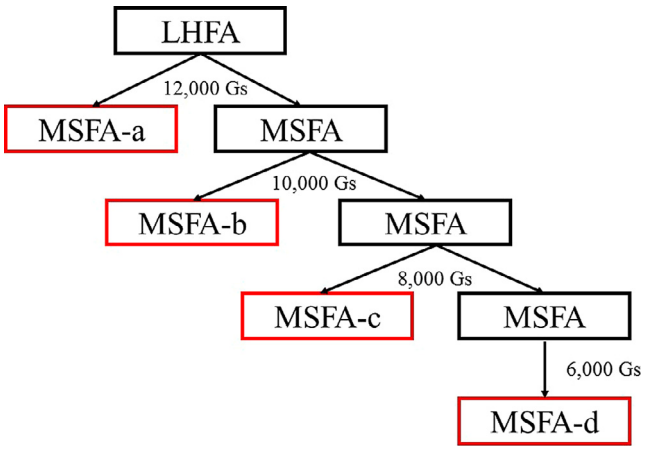

Fig. 2. Flow of magnetic separation.

2.2. Sample preparation

The MSFAs were hydrothermally activated in a NaOH aqueous solution for 3 h at 80 °C; the mass ratio of the MSFA and NaOH aqueous solution was 1:1 and the concentration of the NaOH aqueous solution was 3 mol/L. The activated MSFAs were then formed into disk-shaped specimens using a tablet machine. These disk-shaped specimens were 50 mm in diameter, and 7 mm thick. After that, the specimens were calcined using a furnace with different atmospheres: (1) Air; (2) N_2; and (3) a reducing atmosphere (the specimens were buried in coke to attain a reducing atmosphere). The heating process consisted of several steps, as follows: (1) The specimens were placed in the furnace and heated from room temperature to 500 °C over 100 min and then held at 500 °C for 10 min. (2) Then, the specimens were heated from 500 °C to different final temperatures over 120 min. They were then held at the final temperature for 20 min. (3) After the completion of the heating process, the specimens were allowed to cool to room temperature in the furnace (Fig. 4). After the calcination process, a degree of constriction was observed in the specimens. The diameter was about 45 mm and the thickness was 6 mm. The disk-shaped specimens were used to acquire the necessary measurements. Some of the specimens were crushed to form particles of less than 4.75 mm for use in the apparent density and water absorption measurements.

2.3. Property tests and analytical techniques

2.3.1. Electrical resistivity of conductive aggregate

The volume electrical resistivity was measured using a FLUKE 8808A digital multimeter and ZHAOXIN PS-3005D DC power supply. The four-probe method was used. As shown in Fig. 5, the top and bottom surfaces of the specimens were polished and electrodes were attached to points 1, 2, 3, and 4 using silver paste to further enhance the electrical contact. Points 1 and 4 were connected to the DC power supply and the current was read from the DC power supply. Points 2 and 3 were connected to the digital multimeter to measure the voltage. The volume electrical resistivity was calculated as follows:

$$\rho = \frac{V_{23}}{I} \cdot 2\pi \left(\frac{1}{r_{12}} - \frac{1}{r_{24}} - \frac{1}{r_{13}} + \frac{1}{r_{34}} \right)^{-1} \quad (1)$$

where ρ is the volume electrical resistivity of the specimens, and V_{23} and I are the voltage measured between points 2 and 3 and the current, respectively. Then, r_{12}, r_{24}, r_{13}, and r_{34} are the distances between the corresponding electrodes (cm). Five specimens were tested, and the average value was calculated.

2.3.2. Apparent density, porosity and water absorption of conductive aggregate

The crushed specimens were dried at 105 °C ± 5 °C and then allowed to cool to room temperature. The cooled specimens were put into a measuring cylinder (m_c), when the measuring cylinder is full, the mass of the whole measuring cylinder was measured (m_w). The cooled specimens were weighed (m_0) and then put into a volumetric flask which was placed in water at 25 °C for 24 h. Then, water was added to the scale line and the overall weight of the volumetric flask was determined (m_1). Subsequently, the contents of the volumetric flask were discarded and the volumetric flask was filled with water at 25 °C and the mass of the volumetric flask was measured again (m_2). Thus, the apparent density, porosity and water absorption of the specimens were calculated, as follows:

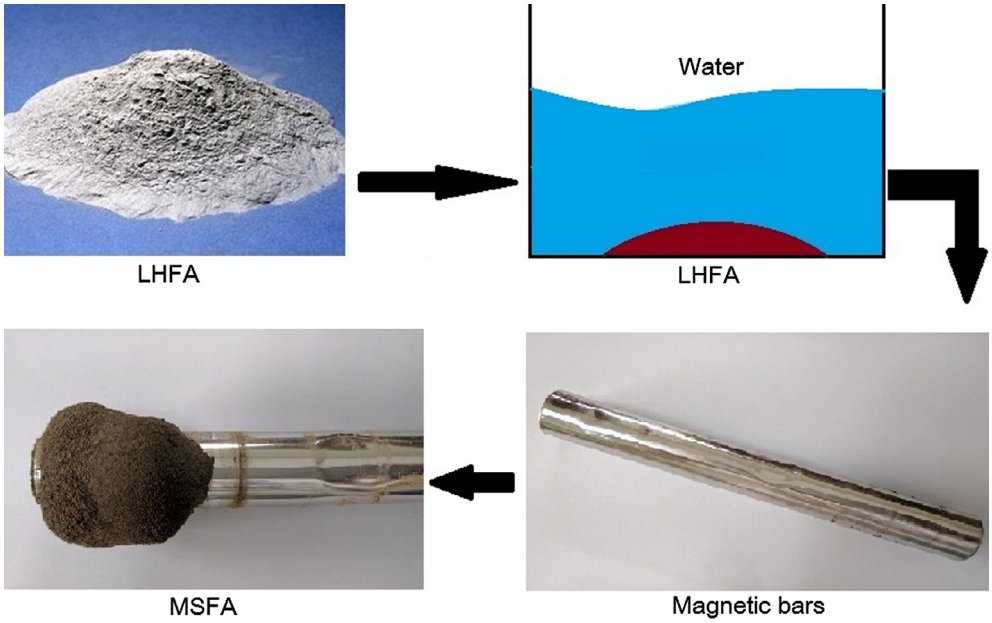

Fig. 1. Preparation of MSFA.