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Investigation on electrically conductive aggregates produced by incorporating carbon fiber and carbon black

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HIGHLIGHTS

- Electrically conductive aggregates (ECAs) are fabricated by pelletization technique.
- Carbon fiber and/or carbon black are well dispersed by semi-dry mixing method.
- The threshold percolation of carbon fiber and carbon black are identified for ECAs.
- ECAs exhibit excellent resistivity, acceptable strength and water absorption.

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ABSTRACT

This paper reports on an investigation of newly developed electrically conductive aggregates (ECAs) through the semi-dry mixing method and the pelletization technique. Carbon fiber and carbon black were incorporated into the aggregates as conductive fillers, while ordinary Portland cement and fly ash were used as matrix materials. The effects of carbon fiber and/or carbon black dosages on the electrical resistivity, water absorption and crushing strength of ECAs were studied. For ECAs with carbon fiber only, the threshold percolation of carbon fiber was identified to be 1.0% by volume. The ECAs with 1.0% carbon fiber exhibited 3.4 Ω·m electrical resistivity, 13.08% water absorption and 1.57 MPa crushing strength. Moreover, the effect of carbon black content was investigated when the content of carbon fiber was kept at 0.5 vol.%. The threshold percolation of carbon black for ECAs with 0.5 vol.% carbon fiber was 2.0% by weight. These ECAs possessed 7.34 Ω·m resistivity, 24.41% water absorption and 0.95 MPa crushing strength. Scanning electron microscope was employed to study the conductive network formed by two conductive components, which helped to illustrate the conductive mechanism of carbon fiber and carbon black inside the ECAs.

1. Introduction

Electrically conductive concrete is a cement-based composite that contains electronically conductive components to achieve a stable and relatively low electrical resistivity [1]. It is a relatively new type of functional material which has drawn much attention due to its good performance in electrical conductivity and mechanical properties [2,3]. With the function of electrical conductivity, electrically conductive concrete has been proposed for the applications of deicing, antistatic flooring, electromagnetic shielding, cathodic protection of steel reinforcement in concrete structure and health monitoring of buildings [3–6]. Since the electrical conductivity of normal concrete is very low due to the very limited conductivity of C-S-H and the highly tortuous pore structure [7,8], electrically conductive concrete is normally developed through adding a certain portion of conductive fillers, including steel slag, stainless steel fiber, graphite, carbon fiber, carbon black, etc. Several studies have already focused on the optimization of conductive fillers to reduce the electrical resistivity of concrete [9–18].

Conduction of electricity in the hardened concrete mainly depends on the movement of electrons, which requires a good contact between conductive components. Monteiro et al. [9] prepared a cement-based composite for structural monitoring through adding carbon black particles. Test results showed that the resistivity could be significantly decreased as the increase of the carbon black dosage, which enhanced the accuracy of resistivity monitoring. However, the authors also reported that the carbon black was

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seldom exclusively used in the conductive concrete. Dong et al. [10] incorporated short-cut super-fine stainless wire (SSSW) in reactive powder concrete to improve the electrical conductivity. The optimal content of SSSW in the reactive powder concrete was identified to be 0.5 vol.% for achieving an excellent conductivity of 0.44 Ω·m. Al-Dahawi et al. [11] compared the influence of carbon fiber length on the electrical properties of cementitious composites and revealed that the cementitious composites with the longer carbon fibers exhibited better electrical conductivity than composites with the short ones. Xie et al. [12] also reported that the longer fibers in the non-conductive matrix were more effective to conduct electricity than shorter ones. Thus, the dosage of fibers could be minimized to achieve a certain conductivity value. Chung [1] compared the effectiveness of various electrically conductive components, including steel fibers, steel dust, carbon fibers, carbon nanofiber, coke powder and graphite, on the electrical conductivity of cement-based materials. It was found that steel fiber with 8 μm diameter was the most effective conductive filler for lowering the electrical resistivity. In respect to carbon-based materials, carbon fiber with 15 μm diameter was more effective than carbon nanofiber, coke powder or graphite powder in improving the electrical conductivity.

For the electrically conductive concrete with a single conductive component, conductive fiber was more effective for conducting electricity than conductive filler. However, the combined use of conductive fibers and fillers had been recognized to produce a more efficient conductive system in the electrically conductive concrete. Wen and Chung [13] reported that a 50% replacement of carbon fiber by carbon black in the cement matrix composites could maintain the electrical conductivity of the system with 100% carbon fiber, but it reduced the strain sensing effectiveness. Tuan and Yehia [14] developed electrically conductive concrete for bridge deck deicing through adopting steel fiber, steel shaving and carbon-based materials. Carbon and graphite materials were recommended to replace steel shavings due to their drawbacks in consistency of size and composition. The resulting conductive concrete has been demonstrated to work well in deicing. Garcia et al. [15] examined the conductivity of asphalt mortar produced with graphite and steel wool. The conductive fibers were more effective for conducting electricity than the conductive fillers. Comparatively, a combination network consisting of fibers to reach the optimum conductivity and a small volume of filler to stabilize the resistivity were suggested. Wu et al. [16] investigated the effects of filler type, filler content and mixed fillers on the electrical resistivity of the asphalt concrete. It was found that the asphalt conductive concrete produced with pure carbon fiber exhibited the best conductive performance. However, the authors recommended the combined use of small amounts of expensive carbon fibers and large amounts of cheap carbon black or graphite as a cost-effective conductive system for asphalt concrete. Ding et al. [17] proposed the use of nano-carbon black and carbon fiber in developing the electrically conductive concrete as conductive components. The degree of strain and damage of the beam cast by the developed electrically conductive concrete was successfully correlated with electrical properties. Wu et al. [18] developed a three-phase composite conductive concrete containing steel fiber, carbon fiber and graphite for pavement deicing. Dispersion of carbon fiber and concrete voids were identified as the main factors affecting the conductivity of concrete. An optimal mix formulation containing 1.0 vol.% steel fiber, 0.4 vol.% carbon fiber and 4.0 wt.% graphite achieved an electrical resistivity of 3.22 Ω·m. Generally, the electrically conductive concrete with combined conductive components exhibited superior performance in terms of efficient and stable electrical conductivity.

Conduction of electricity requires the continuous contact of conductive components within the concrete. Conventional aggregates occupying 50–70% volume of concrete may inhibit the conductive of the media, as they are nonconductive. The electrical resistivity of common coarse aggregates ranged from 300 Ω·m to 1500 Ω·m [3]. Thus, the combination of conductive coarse aggregates with the conventional conductive paste may produce a more continuous, and thus more conductive concrete. In addition, replacing small amount of conventional aggregates by lightweight aggregates would not significantly affect the mechanical properties of concrete [19]. Thus, replacement of normal aggregates with conductive aggregates might be promising to fabricate conductive concrete. Currently, few studies have considered coarse aggregates to be electrically conductive. He et al. [20] manufactured the conductive aggregates by sintering clay with the incorporation of graphite powder. It demonstrated that the resistivity of conductive aggregate mortar was much lower than that of conventional mortar. Unfortunately, the conductive aggregates prepared in the study had a tablet shape which was significantly different from natural coarse aggregates. Moreover, the calcination process to produce conductive aggregates in their study consumed quite a bit of energy. Thus, it is of great interest to produce electrically conductive coarse aggregates with proper manufacturing methods and satisfactory properties. Application of waste materials in producing conductive aggregates would also positively impact environment and cost.

In this paper, a pelletization technique was employed to produce conductive coarse aggregates, using a process of agglomeration of fine particles into pellets. Prior to this, a semi-dry mixing method was used to disperse the carbon fibers in the matrix. Ordinary Portland cement and fly ash were used as the matrix materials for pelletization. Carbon fiber and carbon black were incorporated into the matrix materials as the conductive components. Physical, mechanical and electrical properties were estimated and compared for the conductive aggregates. Conductive aggregates prepared by the semi-dry mixing and the pelletization exhibited excellent electrical conductivity with satisfactory mechanical properties.

2. Experimental study

2.1. Raw materials

The main materials used to prepare aggregates in this study were ordinary Portland cement (OPC), fly ash (FA). Carbon fiber and/or carbon black were incorporated into the mix as conductive components. The OPC has the specific gravity and surface area of 3.15 and 3310 cm^2/g, respectively. The FA complying with ASTM class F ash was adopted in the study. The specific gravity and surface area of the FA were 2.31 and 3960 cm^2/g, respectively. The chemical compositions of the OPC and the FA are presented in Table 1.

Carbon fiber (CF) with diameter of 12–15 μm and length of 1.0 mm was used in this study. The density of CF was about 1.76 g/cm^3 and the volume resistivity of CF was around

Table 1
Chemical compositions of OPC and PFA.

Chemical compositions	OPC (wt.%)	PFA (wt.%)
SiO_2	19.85	55.81
Al_2O_3	3.68	23.17
CaO	65.14	7.31
SO_4	5.40	1.57
Fe_2O_3	2.90	6.68
MgO	1.78	2.27
K_2O	0.91	1.78
TiO_2	0.27	1.29
Na_2O	–	–