Cement and Concrete Composites 72 (2016) 48–65

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Electrically conductive behaviors and mechanisms of short-cut super-fine stainless wire reinforced reactive powder concrete

Sufen Dong [a, b], Baoguo Han [a, *], Jinping Ou [a, c], Zhen Li [a], Linyang Han [a], Xun Yu [d, e]

[a] School of Civil Engineering, Dalian University of Technology, Dalian, 116024, China
[b] School of Architectural and Civil Engineering, Inner Mongolia University of Science and Technology, Baotou, 014010, China
[c] School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China
[d] Department of Mechanical Engineering, New York Institute of Technology, New York, NY 11568, USA
[e] School of Machinery and Automation, Wuhan University of Science and Technology, Wuhan, 430081, China

ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form
17 February 2016
Accepted 27 May 2016
Available online 28 May 2016

Keywords:
Short-cut super-fine stainless wire
Reactive powder concrete
Electrical resistivity
Piezoresistive response
Conductive mechanism

ABSTRACT

The incorporation of short-cut super-fine stainless wire (SSSW) is an effective way to improve the electrically conductive and self-sensing capability of reactive powder concrete (RPC) composed of cement, silica fume, fly ash and silica sand. The conductive characteristics of SSSW reinforced RPC and their responses to external loading are investigated. The conductive mechanisms are revealed through electrochemical impedance spectroscopy and intrinsic conductivity analysis. The results show that the percolation occurs and polarization disappears in SSSW reinforced RPC containing 0.5 vol% of SSSW in diameter of 20 μm, and the electrical resistivity of which measured by using four-electrode-DC method drops to 44 Ω cm from 20.8 × 10^4 Ω cm. The gauge factor of RPC reinforced with SSSW in diameter of 8 μm can reach up to 22.5, 94.9 and 43.6 under cyclic compression, monotonic compression and flexure, respectively. The conductivity of SSSW reinforced RPC mainly depends on the formation of SSSW conductive network.

1. Introduction

Structural Health Monitoring (SHM), which can provide real-time data on the conditions of infrastructures, is necessary for large concrete structure in the life cycle. The intrinsic self-sensing concrete provides a new sensing approach for SHM. It is fabricated through adding such functional fillers as carbon fibers, steel fibers, carbon nanotubes (CNTs), and nickel powders into conventional concrete to generate ability of sensing the strain, stress, crack, damage, or temperature in itself while maintaining or even improving its mechanical properties [1–9]. Meanwhile, this multifunctional and smart concrete has been applied to a wide range of situations, such as electrical grounding, electrical contacts for cathodic protection, deicing, electromagnetic interference (EMI) shielding, and antistatic flooring [10,11]. The intrinsic self-sensing behavior of concrete was firstly investigated in 1992 with the incorporation of short carbon fibers [12]. Since then, much research work has been done on sensing behaviors, mechanisms and structural application of intrinsic self-sensing concrete with different functional fillers under different loadings and environments [7]. Up to now, the intrinsic self-sensing concrete with chopped carbon fiber is still one of the most extensively and comprehensively studied composites. Fu et al. [13] observed that the change in electrical resistance of concrete with 0.51% ozone-treated carbon fiber can reach 45%. Shi et al. [14] found that the strain sensitivity (gauge factor, i.e. fractional change in electrical resistivity per unit strain) of concrete containing a small amount (typically 0.2–0.5 vol%) of short carbon fibers is as high as 700. The self-sensing concrete with carbon fibers is also effective for sensing impact damage under impact stress [15]. Compared to carbon fibers, the extremely high aspect ratio, hollow structure and low density of CNTs make them easy to form a conductive and mechanical reinforcement network inside concrete with a CNT concentration level as low as 0.05 wt%. Yu et al. [16] investigated the piezoresistive property of the CNTs/cement composite to explore its feasibility as a stress sensor for civil structures such as roadways, levees and bridges. They found that the fractional change in electrical resistance of cement with 0.1 wt% multi-walled CNTs can reach 11.4% under 8.2 MPa of cyclic compressive loading. Azhari et al. [17] investigated the sensing ability of electrical conductive

* Corresponding author.
E-mail addresses: hithanbaoguo@163.com, hanbaoguo@dlut.edu.cn (B. Han).

http://dx.doi.org/10.1016/j.cemconcomp.2016.05.022

cement-based composites containing carbon fibers and CNTs. They found that the composites, containing a combination of carbon fibers and CNTs, provide better quality signal, improved reliability and increased sensitivity over composites carrying carbon fiber alone. Materazzi et al. [18] explored the applicability of CNTs cement-based sensors for measuring dynamically varying strain in concrete structures.

However, the cement-based material and carbonic filler have a poor compatibility, so the effective dispersion technology and dispersing agents are needed [7,8,19]. This complicates the composite preparation process, reduces the performance stability, and increases the material cost. Furthermore, the matrix of intrinsic self-sensing concrete now being studied is mainly cement paste or cement mortar. This cannot meet the requirement of high strength and durability of important infrastructures. Meanwhile, carbonic fibers could not withstand bending under shear stress because of their brittleness. Therefore, the bridging carbonic fibers are bent sharply, which makes the damage sensing become difficult [20].

Micro steel/stainless fiber (having comparative diameter with carbon fiber) has excellent dispersion capability, toughness and interfacial bond strength with concrete matrix compared with carbonic fiber, in favor of sensing damage and crack propagation. In addition, the high aspect ratio makes it easy to form conductive network, thus further improving the conductivity of cement-based materials. However, the research on the conductivity of micro steel/stainless fiber reinforced cement-based materials is limited. Banthia et al. [2] found that the conductivity of cement mortar could be improved about one order of magnitude by incorporation of steel fibers with diameter of 25 μm and length of 3 mm. The piezoresistivity of stainless steel fiber (in diameter of 60 μm, length of 5 mm and amount of 0.1 vol%) reinforced cement paste under compression was researched by Chung et al. [21]. Chung [3] also studied the conductive behavior of cement paste containing 0.36 vol% and 0.72 vol% of short stainless steel fibers processed by polyvinyl alcohol binder with a diameter of 8 μm. The results showed that the resistivity of the cement paste composites can reach $57 \pm 4\ \Omega$ cm and $16 \pm 1\ \Omega$ cm respectively, which are far lower than that of cement paste with 0.5 vol% carbon fibers. Teomete et al. [22] observed that the highest gauge factor (which is defined as the ratio of fractional change in electrical resistivity to splitting tensile strain) of copper coated steel fiber (length of 6 mm) reinforced cement-based composite under tensile strain is 5195, 2600 times higher than that of commercial metal strain gages, but the diameter of the steel fiber was not mentioned. Except for strain sensing [23], the micro steel/stainless fiber reinforced concrete is more effective for electrical grounding, electromagnetic interference and deicing [24]. Wen et al. [25] found that the EMI shielding effectiveness of cement paste with 0.72 vol% of stainless steel fibers (diameter of 8 μm and length of 6 mm) reaches up to 70 dB at 1.5 GHz. Based on the above studies, the combination of high aspect ratio and unique mechanical properties makes micro steel/stainless fiber become ideal multi-functional filler for cement-based materials. Meanwhile, the full realization of composition effect of micro steel/stainless fiber needs uniform and compact matrix structure, especially high-performance concrete such as reactive powder concrete (RPC).

The first study of RPC was conducted by Richard et al., in 1995 [26]. RPC, also sometime referred to ultra-high performance fiber reinforced concrete, is usually composed of cement, ultra-fine powders such as crushed quartz and silica fume, superplasticizer and short steel fibers (the commonly used diameter is 150–250 μm and aspect ratio is 60–80). Compared to common cement-based materials, RPC has compact microstructures, low porosity and less interfacial transition zone [26–29]. The mechanical properties of RPC are excellent. For example, the compressive strength can reach up to 150–200 MPa, the fracture energy is up to 1200–40000 J/m^2, and the ultimate tensile strain can be on the order of 1% [30–33]. Nowadays, RPC is regarded as a promising material for special prestressed and precast concrete members, including those used in nuclear waste storage facilities [34,35]. With the development of SHMtechnology, the intrinsic self-sensing RPC will certainly become research hotspot in the future, especially for long-span and durable infrastructures. However, the common-used carbonic fibers can bring negative effect or can only have limited improvement on the mechanical behaviors of concrete because of their poor dispersion. In addition, the compact and homogenous microstructures of RPC are beneficial for forming extensive three-dimensional overlapping network of micro steel/stainless fiber. Therefore, the introduction of micro steel/stainless fiber is an effective way to help RPC become conductive, self-sensing, and more ductile material. In order to differ from the commonly used steel fiber of RPC, this kind of micro stainless/steel fiber having comparative diameter and length with carbon fibers is called short-cut super-fine stainless/steel wire. Research results indicate that the short-cut super-fine stainless wire (SSSW) can effectively improve the mechanical properties of RPC [36]. However, the research about the functional properties of SSSW reinforced RPC has not been carried out.

In this study, the SSSW with diameter of 8 μm and 20 μm and length of 10 mm was introduced into RPC as conductive filler. The electrical resistivity of SSSW reinforced RPC was measured by using three methods including two-electrode-AC, two-electrode-DC and four-electrode-DC. The resistivity responses of SSSW reinforced RPC under cyclic compressive loading, monotonic compressive loading and flexural loading were investigated. The electrochemical impedance spectroscopy (EIS), equivalent circuit and intrinsic conductivity were used to analyze the conductive mechanisms of SSSW reinforced RPC.

2. Experimental schemes

2.1. Raw material and mix proportion

The materials used in this study mainly include short-cut super-fine stainless wire (SSSW), cement, fly ash, silica fume, quartz sand, water and water reducer. The SSSW used is 316L stainless wire in diameter of 8 μm and 20 μm and length of 10 mm. The elongation of the SSSW is more than 1%, and the tensile strength can reach up to 1200–1800 MPa. Their morphologies are shown in Fig. 1. The cement used is P·O 42.5R provided by Dalian Onoda Cement Co. Ltd., China. The silica fume used is 920D silica fume provided by Shanghai Tian Kai Silicon Fume Co. Ltd., China. The fly ash used is the secondary fly ash provided by Dalian Daokete Building Materials Co. Ltd., China. The size range of quartz sand used in this study is from 0.12 to 0.83 mm. The water reducer used is RHEOPLUS 411 polycarboxylate superplasticizer provided by BASF's Chemical Building Materials (China) Co. Ltd. The solid content of the superplasticizer is 44%.

Based on the proportion proposed by Richard et al. [26] in 1995, the ratio of cement: silica fume: quartz sand: water was equal to 1:0.25:1.1:0.3. The content of superplasticizer was adjusted according to the amount of SSSW to achieve a good workability of concrete mixture. In order to improve the mobility of RPC and reduce the cement content per cube, the fly ash was used to replace 20% of cement. The SSSW was added in the amount of 0, 0.5%, 1.0% and 1.5% by volume of RPC. The SSSW reinforced RPC was marked as W0, W08 (W0805, W0810, W0815), and W20 (W2005, W2010, W2015).