Construction and Building Materials 187 (2018) 699–707

Contents lists available at ScienceDirect

Construction and Building Materials

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

Multi-functional properties of carbon nanofiber reinforced reactive powder concrete

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HIGHLIGHTS

- Mechanical properties of CNF-RPC were presented.
- CNF-RPC showed excellent electrical and piezoresistive performances.
- CNF-RPC behaved a good deicing ability when CNFs contents reached 1.0%.

ARTICLE INFO

Article history:
Received 15 March 2018
Received in revised form 24 June 2018
Accepted 27 July 2018

Keywords:
Carbon nanofiber
Reactive powder concrete
Mechanical properties
Piezoresistivity
Deicing performance

ABSTRACT

This paper aimed to develop carbon nanofiber (CNF) reinforced reactive powder concrete (CNF-RPC) with multi-functional properties. Water to binder ratio (w/b) was kept at 0.2 and CNFs dosage ranged from 0% to 2% by volume of the total cementitious materials. Flexural and compressive strengths of CNF-RPC were determined for each dosage of CNFs. Piezoresistive performance of CNF-RPC was investigated while the piezoresistivity of CNFs added cement paste and mortar were also performed. Moreover, deicing performance of CNF-RPC was experimentally researched and numerally simulated using finite element analysis. Results indicated that RPC with appropriate content of CNFs performed favorable mechanical properties and excellent self-sensing performance. While CNFs content was close to the post-percolation threshold zone, CNF-RPC presented an obvious deicing performance. When CNFs content was in the percolation threshold zone, resistance of CNF-RPC rarely changed with measurement time. RPC containing CNFs (CNF-RPC) was more conductive and demonstrated a higher sensitivity and linearity of self-sensing performance than CNFs added cement paste and mortar samples.

1. Introduction

Reactive powder concrete (RPC) is produced with the maximum compactness theory. Quartz sand with optimized particle size distribution is used as fine aggregate instead of coarse aggregate and ordinary river sand. RPC usually contains a high percentage of mineral admixtures [1]. The mineral admixture can enhance the activity of RPC matrix, thus increasing the compactness of multi-size particle system. Therefore, RPC presents ultra-high strength, high toughness and excellent durability [1,2].

RPC matrix filled with conductive fillers can serve as multi-functional materials [3,4]. Multi-functional RPC with ultra-high strength can be used as concrete structural materials for major engineering such as long-span concrete bridge, marine concrete structures and infrastructure of high-speed rail. Additionally, RPC combined with functional fillers can serve as intrinsic self-sensing materials, providing real-time monitoring for large-scale building structures [4]. Moreover, this type of concrete can be applied to electromagnetic interference (EMI) shielding, deicing and electric heating systems [5–7].

Carbon nanofibers (CNFs) whose surface modified by oxidizer are easily dispersed in cement matrix [8]. This type of carbon nanofibers (CNFs) possesses excellent conduction and mechanical properties. Therefore, the addition of CNFs can decrease the resistivity and enhance the mechanical behavior of composites [9]. Cement-based materials with CNFs showed improvements of mechanical properties, conductivity and specific functional properties [10,11]. When being compared with short-cut carbon fibers (CFs), CNFs are more easily dispersed in cement matrix. Besides, the inner defects of CNFs are less than CFs. In comparison to carbon

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https://doi.org/10.1016/j.conbuildmat.2018.07.229
0950-0618/

nanotubes (CNTs), CNFs show numerous exposed edge planes along the surface. These exposed edge planes of CNFs possess advantageous chemical or physical interactions. Moreover, CNFs are produced at lower cost than CNTs. Being compared with metal fillers, CNFs show excellent corrosion resistance. Consequently, CNFs are regarded as excellent conductive fillers for making functional concrete [12].

Previous research pointed out that low water cement ratios lead to the decreased porosity for cement-based materials. Moreover, the conductive network of CNF-RPC was possibly improved by decreasing the water to cement ratio (w/c). Therefore, CNF-RPC with water cement ratios of less than 0.3 shows an obviously improved conductivity [9]. On the other hand, the addition of silica fume was useful to disperse CNFs due to the small particle size effect and the improved interfacial interaction between CNFs and RPC matrix [13]. Above all, RPC reinforced with CNFs may present ultra-high strength and excellent functional performance. However, little attention has been paid to the development of multi-functional RPC materials.

This paper investigated the multi-functional performance of CNF-RPC when CNFs was added by 0%, 0.25%, 0.5%, 1.0%, 1.5% and 2.0% of volume of the total binder. The measured properties included flexural and compressive strength, electrical resistivity, piezoresistivity and deicing performance. Finally, finite element analysis was applied to simulating the deicing process of CNF-RPC.

2. Experimental

2.1. Raw materials

The PR-19-XT-LHT-OX CNFs with a density of 2.1 g/cm^3 supplied by the Pyrograf Products, Inc was used in this study. The surface of CNFs was treated with oxidizer by producers for easily dispersing in cement matrix. This type of CNFs shows an average diameter of 149 nm and average length of 19 µm. Ordinary Portland cement with strength grade of 42.5 MPa in accordance with Chinese Standard GB175-2007 was used as cementitious material [14]. Silica fume with specific surface area of 15 m^2/g was used as a mineral admixture. The SiO_2 content of silica fume is more than 96% according to Chinese standard GB/T21236-2007 [15].

Quartz sand with two kinds of particle size of 0.35–0.59 mm and 0.15–0.297 mm were applied in preparing CNF-RPC. The quartz sand is composed of 99.6% SiO_2, 0.02% Fe_2O_3 and other ingredients. River sand with fineness modulus of 2.82 was used for preparing mortar samples. The flowability of fresh cement-based materials was adjusted by adding different dosage of polycarboxylate-based, high-range water-reducing agent (SP). The particle size distribution and chemical composition of cementitious materials are shown in Tables 1 and 2. In Table 2, R2O represents Na_2O and K_2O.

2.2. Mixing proportion and specimen preparation

To determine the mechanical and electrical properties of CNF-RPC, six groups of mixtures were prepared. Water to binder ratio by weight was kept at 0.20 in this study. The addition of silica fume, fine and coarse quartz sand of each group were 0.3, 0.22 and 0.88 by mass of cement respectively. CNFs were added by 0%, 0.25%, 0.5%, 1.0%, 1.5% and 2.0% by volume of the total cementitious materials respectively. The water reducing agent was added by 1.2–2.5% of the total weight of cementitious materials. These mixture types corresponding to different CNFs dosages were named by M1, M2, M3, M4, M5 and M6 respectively as shown in Table 3. On the other hand, CNFs added mortar and paste samples with water to binder ratio of 0.4 were also prepared and the cement-sand ratio of mortar was equal to that of RPC. Water-reducing agent was used to adjust the slump flow of CNF-RPC mixtures and mortars to reach around 180 mm for obtaining a good dispersion of CNFs [9,16]. For the same purpose, the slump flow of cement pastes containing CNFs was designed at around 200 mm.

Water-reducing agent was mixed uniformly in mixing water and then CNFs were added for a 3 min high speed stirring operation to obtain a homogeneous solution. A Hobart A200C (I.T.W. Inc., Chicago, America) planetary mixer was used to prepare fresh mortars with the same procedure. Firstly, cement (and silica fume if applicable) was added into the homogeneous solution containing CNFs and water-reducing agent for 3 min mixing at speed of about 140 rmp. Then, sand was added and mixed at a speed of about 285 rmp for another 3 min [17,18]. When the mortar mixing progress was completed, the mixture was poured into the oiled molds to form prism specimens with size of 35 mm × 35 mm × 55 mm and 210 mm × 100 mm × 50 mm. Samples with size of 35 mm × 35 mm × 55 mm were used to measure resistance and piezoresistivity. And plate specimens with size of 210 mm × 100 mm × 50 mm were selected to study the deicing performance. A concrete vibrator was used to facilitate the compaction and decrease air bubbles. The consolidated specimens were covered by plastic sheets for 2 days curing at room temperature and demolded. Then specimens were transferred to a standard fog room with temperature of 20 °C and relative humidity of above 95% for another

Table 3
Mixing parameters of CNF-RPC.

Types	Water reducing agent (%)	CNFs (%, by volume)	CNFs (%, by mass)
M1	1.2	0	0
M2	1.3	0.25	0.17
M3	1.5	0.5	0.34
M4	1.8	1.0	0.68
M5	2.0	1.5	1.02
M6	2.5	2.0	1.35

Table 1
Particle size distribution of raw materials (%).

Types	Particle size/um						
	0.3	0.6	1	4	8	64	360
Cement	0	0.33	2.66	15.01	28.77	93.59	100
Silica fume	31.2	58.3	82.3	100	100	100	100

Table 2
Chemical composition of cementitious materials.

Types	Chemical composition/%						
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	R_2O
Cement	20.86	5.47	3.94	1.73	62.23	2.66	0.48
Silica fume	90	0.8	0.6	0.8	0.4	0	7.4