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Anisotropic electrical and abrasion-sensing properties of cement-based composites containing aligned nickel powder

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ABSTRACT

The electrical properties of aligned nickel powder-filled cement-based composites and the abrasion-sensing properties of these composites, as evaluated based on the change in their resistance at varying abrasion depths, were investigated in this paper. Micrograph characterization of nickel powder distribution indicates that the electrical conduction path preferentially forms along the direction of the nickel powder alignment, which leads to increasingly anisotropic electrical properties under greater magnetic field strengths. The level of anisotropy was also determined to be strongly dependent on the nickel powder content. The maximum anisotropic electrical properties were achieved at the percolation threshold content of the nickel powder, which is the critical point for the formation of an effective conductive network. Based on the cement-based composites anisotropic electrical properties and a sectionalized electrode design, the composites filled with aligned nickel powder demonstrated good abrasion-sensing properties, with humidity and temperature self-compensation abilities.

1. Introduction

Infrastructures usually suffer from fatigue load, environmental corrosion and such disasters as earthquakes, which may cause the degradation of the infrastructure's health state. Therefore, the health monitoring of infrastructures is of increasing importance [1–3]. In a normal health-monitoring system, stress/strain and the structure vibration parameter are the most common types of information that require measurement [4–6]. For structures in a special service environment, certain other important factors should also be monitored. In particular, scouring is one of the major causes of damage to hydraulic structures, such as piers. The washing away of a structure's surfacial concrete not only decreases its bearing capacity but also accelerates the invasion of chloride into the structure and causes rapid corrosion of the steel bar [7–15]. Therefore, scouring must be monitored to evaluate the health state of concrete structures built in aquatic environment.

Cement-based sensors are a new type of sensor and are suitable for concrete structure health monitoring due to their advantageous compatibility with concrete matrix [16,17]. Benefiting from this compatibility, cement-based sensors exhibit behavior matching that of the concrete matrix, which may suffer from loading, scouring or other environmental effects. Most of the previous studies focused on strain-sensing properties that were based on the change in the resistance of cement-based composites under varying amounts of strain (i.e., based on piezoresistivity), and the electrical conductivity of the cement-based composites was typically improved through the addition of conductive fillers, such as carbon fibers, carbon black, carbon nanotubes and nickel powder [18–25]. The previous studies demonstrated that humidity- and temperature-based compensation should be performed because the resistance of the cement-based composites is dependent on these environmental factors [26–28]. This paper examined the scouring abrasion-sensing properties of cement-based composites based on the change in their resistance with various abrasion depths.

In general, conductive fillers are randomly distributed in a composite and form an isotropic conductive network. Accordingly, the electrical properties of the generated composites are isotropic. This paper proposes an innovative approach to improving the scouring abrasion-sensing properties, as well as temperature and humidity self-compensation abilities, of cement-based sensors,

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which requires the electrical properties of the cement-based composites to be anisotropic. The recently developed method of inducing nickel filler alignment using a magnetic field allows the conductive network of composites to be controlled [29–31]. This paper describes the use of a magnetic field to align nickel powder in cement-based composites and the evaluation of the characteristics and mechanism of the composites' anisotropic electrical properties. Then, the scouring abrasion-sensing properties of an optimized cement-based composite and its potential self-compensation abilities were studied by employing its anisotropic electrical properties.

2. Anisotropic electrical properties of cement-based composites filled with aligned nickel powder

2.1. Materials and experimental methods

The nickel powders used in this study were purchased from Wuxi Shunda Metal Powder Co., Ltd. in China. According to the supplier, the as-received nickel powder has an average diameter of 3 μm, whose morphology is shown in Fig. 1. The resistivity of the nickel powder was $7.0 \times 10^{-6}\,\Omega$ cm. The cement used in this study was Portland cement (P.O. 42.5) from Harbin Cement Company (Harbin, China). The surfactant 12-aminododecanoic acid (0.2% by weight of cement) was used to disperse the nickel powder. Composites containing 5%, 10%, 15%, 17%, 18%, 19%, 20% and 23% nickel powder by overall volume were used, and the corresponding mixtures were termed Ni5, Ni10, Ni15, Ni17, Ni18, Ni19, Ni20 and Ni23, respectively.

The surfactant was first dissolved in water. Then, nickel powder was added to the solution and stirred in a shear blender at a high speed of 600 rpm for 5 min to disentangle the large aggregates. Subsequently, the mixture was sonicated (400 W and 40 kH) for 1 h to generate a uniformly dispersed suspension. Next, cement was added and mixed by shear stirring for 5 min. The mixture was then placed in a vacuum chamber for 10 min to remove any air bubbles. Finally, the prepared mixtures were poured into molds to form prisms of 10 × 10 × 36 mm.

A set of Helmholtz coils purchased from Changchun Yingpu Magnetic-electric, Inc. was employed to align the nickel powder. The uniform magnetic field (MF) generated by these Helmholtz coils demonstrated a field uniformity of 0.1% in a cylindrical volume measuring 50 mm in length and 50 mm in diameter. The magnetic field increased linearly upon the application of a current. After the fresh cements containing dispersed nickel powder were prepared and poured into the molds, they were immediately centrally placed under the uniform cylindrical magnetic field generated by the Helmholtz coils, as shown in Fig. 2. During the first 24 h curing process at room temperature, various magnetic fields (50Gs, 100Gs or 150Gs to generate various alignment levels) were applied along the parallel or transverse direction relative to the longitudinal axis (36 mm) of the specimens. At the stage of cement paste mixture remained fluidity, the magnetic force could drive the nickel powder to move and align in the fresh mixture. Then, the cement paste hardened and the aligned nickel powders were finally fixed by the increasing amount of hydration products. The specimens were demolded after 24 h and subsequently subjected to accelerated curing in a water bath at 60 °C for four days. Afterwards, the specimens were dried in an oven at 50 °C for 24 h and then stored in an airtight container to get rid of the effects of humidity. In this paper, the nickel powder-filled cement-based composites cured under various magnetic field strengths are denoted as Ni(X)-MF(Y). For example, Ni17-MF150 refers to Ni17 cured under a magnetic field of 150 Gs.

After the specimens were prepared, DC electrical resistance measurements were performed using the two-probe method at room temperature, in which conductive silver adhesive pasted onto the two opposite surfaces of a 10 × 36 mm region served as electrical contacts. The resistance measured along and transverse to the direction of the magnetic field was termed the longitudinal resistance and transverse resistance, respectively. Three specimens for each mixture were prepared and tested. A DC circuit developed by Han [20] was used to continuously measure the resistance of the specimen. In this method, a standard reference resistor was series connected with the specimen, and the voltages of the specimen and the standard reference resistor were collected simultaneously using a data acquisition board. Since the electrical current flow in the series circuit is the same, so the resistance of the specimen was calculated as follow:

$$R_0 = U_0 \cdot R_r / U_r \quad (1)$$

where R_0 is the resistance of the specimen, U_0 is the voltage on the specimen, R_r is the standard reference resistor, U_r is the voltage on the standard reference resistor, respectively.

2.2. Results and discussion

Fig. 3 shows the electrical properties of cement-based composites filled with various nickel powder contents cured under different magnetic field strengths. For the composites cured without the application of a magnetic field, the change in resistivity with increased nickel powder content is consistent with the general electrical behavior of a conductive composite. According to the

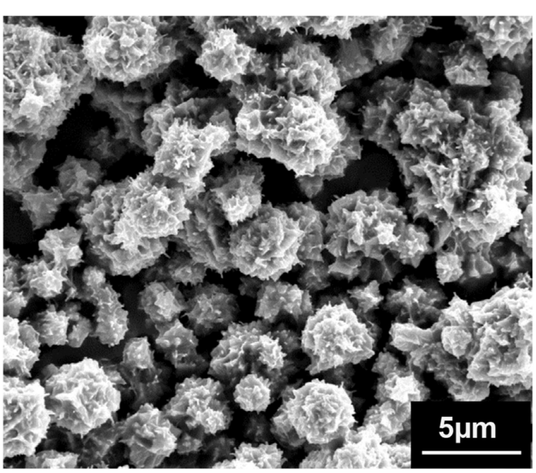

Fig. 1. The morphology of the nickel powder used in this study.

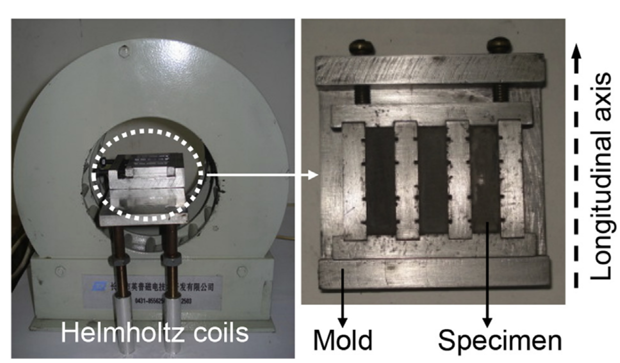

Fig. 2. Experimental set-up for the fabrication of the cement-based composite.