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Strain sensing ability of metallic particulate reinforced cementitious composites: Experiments and microstructure-guided finite element modeling

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ABSTRACT

This paper evaluates the capability of waste iron powder-reinforced cementitious matrices as self-sensing materials in lieu of more expensive carbon fiber and nanoparticle reinforced matrices. Electrical impedance spectroscopy coupled with equivalent circuit modeling is used to determine the bulk resistance of the composite beams containing up to 40% by volume of iron particulates under flexural loading. The fractional change in resistance and the gage factor, as functions of the applied stress, increases with increasing iron particulate content, demonstrating the ability of these composites in self-sensing. A microstructure-guided electro-mechanical finite element model is used to simulate the strain sensing response of these composites. The 2D microstructure is subjected to different applied tensile stresses, and the deformed geometry subjected to an electrical potential to simulate the change in resistance. Debonding at the inclusion-paste interface under load, which is found to significantly influence the fractional change in resistance, is accounted for by using a bilinear softening model. The model is found to correlate well with the experimental data, and has the potential to facilitate microstructural design of materials to achieve desired degrees of self-sensing.

1. Introduction

In the recent past, conductive concretes have attracted interest because of several novel qualities that electrical conductivity endows to conventional portland cement concretes, which are generally poor electrical conductors. The novel applications include strain and stress sensing, damage detection [1–4], deicing concrete surfaces [5], traffic monitoring [6], and electromagnetic shielding [7]. Among these applications, the sensing of strain and stress is valuable towards structural health monitoring (SHM). The self-sensing ability is based on the principle of piezoresistivity (change in electrical resistance with applied strain); the resistivity decreases reversibly under compression, and increases reversibly under tension [8]. Electrical methods for SHM have not received enough attention. Most electrical property-based studies on cementitious systems were intended to track hydration and microstructure [9,10], predict strength [11], identify and quantify corrosion of reinforcing steel [12,13], and evaluate moisture ingress into and distribution in concrete [14,15]. AC impedance-based measurements, though not as simple as DC measurements, is the preferred method in strain sensing because it can account for the influence of frequencies on the electrical response.

Carbon fibers, steel fibers, and carbon nanotubes/nanofibers are commonly used to enhance the electrical conductivity of cement-based materials to facilitate strain sensing [16–20]. An additional advantage of using these materials in cementitious systems is their contribution in generally enhancing mechanical properties. The conductive fiber volume fraction and its percolation are known to influence the strain sensing response of such composites. The self-sensing ability of carbon fiber reinforced cements under tension and compression has been reported [8]. Self-sensing of flexural damage and strain in carbon fiber reinforced cement has been demonstrated using the four-probe method by measuring the responses in the compression and tension faces [21]. Electrical impedance tomography which is a distributed sensing method, has been used to sense strain fields in fiber reinforced concrete and image cracks [22].

Carbon fiber or carbon nanotube reinforced cementitious composites are generally much more expensive, limiting their application in structures. In order to develop a family of economical self-sensing cementitious composites, this paper explores the use of waste iron particulates ($\sim 100\,\mu m$ maximum size; aspect ratio generally > 4) from short-blasting operations as an inclusion in cement-based materials. Previous work has explored the mechanical properties of such composites in detail, has showed that the compressive and flexural strengths of cementitious matrices containing up to 40% by volume of these

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particulates are comparable to, or higher than that of the unmodified matrix [23]. The presence of tough iron particulate inclusions significantly enhances the crack resistance of these composites. In this study, cement pastes containing iron particulate inclusions are evaluated for their self-sensing ability through the determination of fractional change in resistance with applied strain (or stress) in the elastic regime. A computational electro-mechanical modeling scheme, which is generic so as to be applicable to any heterogeneous material, is developed for the first time in order to predict the self-sensing ability of these matrices based on their microstructural organization and phase properties. The model is expected to help the microstructural design of particulate- or fiber-reinforced composites to achieve desired degrees of self-sensing.

2. Experimental program

2.1. Materials and mixtures

A commercially available Type I/II ordinary portland cement (OPC) conforming to ASTM C 150 was used to prepare the cementitious composites in this study. The particulate reinforcement used was a metallic waste iron powder obtained from an industrial shot-blasting operation. The median particle size of the OPC was 10 µm and that of the iron powder 19 µm as obtained from the particle size distribution measured using laser particle size analyzer, which are shown in Fig. 1(a). The iron powder consists of 88% iron and 10% oxygen (due to some amount of atmospheric oxidation) along with trace quantities of Cu, Mn, and Ca as determined from particle induced X-ray emission spectroscopy (PIXE) [24]. Fig. 1(b) shows a backscattered scanning electron (BSE) micrograph of iron particles in a cement paste, showing the angular iron particles (bright white). The BSE micrographs were obtained by grinding and polishing the sample encapsulated in an epoxy medium using abrasives of various sizes [25]. The fiber-like morphology of the particulates is evident from this figure.

Five different mixtures were prepared, containing 0%–40% volume fraction of iron powder in the system, in increments of 10%. The water-to-cement ratio used for the preparation of the mixtures was 0.40 (mass-based). The desired proportion of the powders was hand-mixed for 2 min, after which the desired amount of water was slowly added while the blend was being mixed in Hobart mortar mixer until a uniform consistency was achieved. The mixture was poured in molds for electrical or mechanical testing. After 24 h, the specimens were removed from the molds and cured in a chamber at > 98% RH and 23 ± 2 °C for 28 days before testing. Past studies have shown that such mixtures have comparable compressive strength to plain OPC mixtures, and a higher flexural strength, attributable to the presence of strong and stiff metallic inclusions [23]. The compositions used in this study (volume fractions of iron powder in the range of 0–40%) had 28-day compressive strengths in the 35–40 MPa range, and flexural strengths in the 3.6–4.6 MPa range.

2.2. Test methods

The electrical properties of the mixtures were evaluated using electrical impedance spectroscopy (EIS). A Solartron 1260 gain phase analyzer operating in the 1 Hz to 1 MHz frequency range was used, with a 250 mV AC signal. Five measurements were collected in each decade of frequency. The real and imaginary parts of the impedance were used to extract several electrical properties of the composites.

For the strain sensing experiments, two copper plates, 25 mm × 25 mm in size, were attached to the ends of the beam samples (25 mm × 25 mm cross section, and 65 mm long). The copper plates were soldered together with the open end of an alligator clip to create the electrode. Conductive gel was used between the specimen and the electrodes to ensure proper electrical contact. The sample ends along with the electrodes were sealed using insulating tape to hold the set up in position. The length of the wire that connected the electrode plates was kept small to minimize lead wire impedance effects. The loading head and the supports were covered with an insulating tape to ensure that the metallic components of the test frame do not electrically interfere with the impedance analysis. The beam specimen was then carefully placed in the loading frame. The specimen was loaded gradually in three-point loading to a load of P_1, at which time, the load was held constant and a potential sweep was carried out using the impedance analyzer to determine the electrical properties under this load. The load was then increased to P_2 and the process repeated. The electrical response of the specimens corresponding to four different loads (P_{max} = 100 N) were recorded. Only a monotonic, displacement controlled loading sequence was carried out, at a rate of 0.38 mm/min. The vertical deflections at the center of the beam were also recorded at different loads using a linear variable differential transducer (LVDT). During the electrical measurements, the load is maintained on the samples, and any effect of creep is ignored in the analysis of the test results.

3. Strain sensing capability of the matrices

3.1. Electrical response of the matrices under load

In this section, the electrical response of particulate reinforced cementitious composites is discussed. As described in the previous section, electrical impedance spectra of the specimens were recorded at different load (stress) levels. Nyquist plots were generated for the composites containing different amounts of iron powder, at different

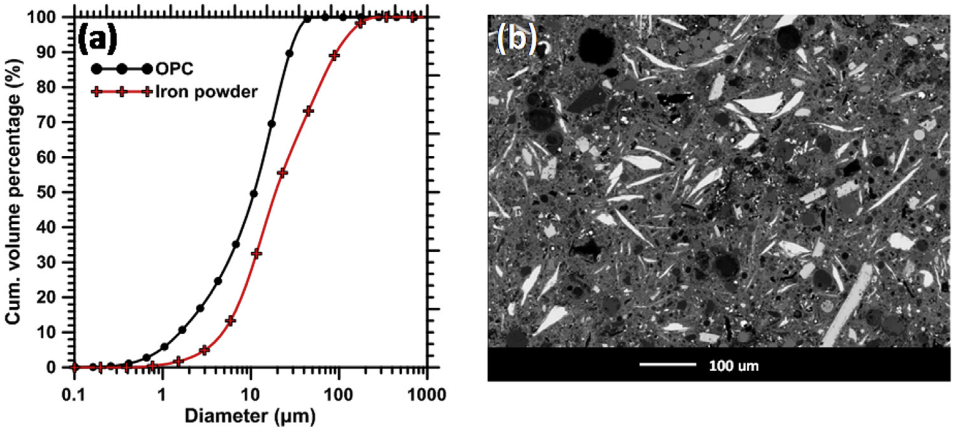

Fig. 1. (a) Particle size distributions of OPC and iron powder, and (b) backscattered electron micrograph of cement paste containing iron particulates (bright phases), showing their fiber-like morphology.