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Comparative electromechanical damage-sensing behaviors of six strain-hardening steel fiber-reinforced cementitious composites under direct tension

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ABSTRACT

This research investigates the electromechanical damage-sensing behavior of strain-hardening steel fiber-reinforced cement composites (SH-SFRCs) with six types of steel fibers (1.5% volume fraction content) within an identical mortar matrix (90 MPa). The six types of steel fibers studied are long twisted (T30/0.3), long smooth (S30/0.3), long hooked (H30/0.375), medium twisted (T20/0.2), medium smooth (S19/0.2), and short smooth (S13/0.2) steel fibers. The damage-sensing behavior was evaluated by measuring the changes in the electrical resistance during direct tensile tests. The electrical resistivity of the SH-SFRCs clearly decreased as the tensile strain increased until the post-cracking point, owing to the generation of multiple micro-cracks during strain-hardening. All the SH-SFRCs investigated had nominal gauge factors ranging between 50 and 140; these values are much higher than the commercially conventional gauge factor, which involves metal and is around 2. Both T30/0.3 and T20/0.2 produced the highest gauge factor, i.e., the best damage-sensing capacity, whereas S13/0.2 produced the highest electrical conductivity.

1. Introduction

Structural health monitoring (SHM) refers to the implementation of damage detection strategies for engineering structures, such as changes to their material and/or geometric properties, which adversely affect the structures' performances. Numerous researches have been performed on SHM to detect damage to civil infrastructure due to rapid deterioration, as well as to evaluate the current ability of the infrastructure to perform its intended functions over a long term. Further, the techniques for monitoring structural health have rapidly developed. Nevertheless, the sensors used in the system have the disadvantages of high cost and low durability; moreover, the use of sensors leads to the degradation of the load-carrying capacity of the structural members embedding them [1].

To overcome these limitations, cement-based strain sensors were developed, and their sensing abilities were successfully improved by incorporating electrically conductive fibers [2–7], conductive nano particles [8–14], and conductive metals [15] or their combinations [16–20]. Self damage-sensing construction materials are currently classified as multifunctional or smart materials [21].

A few researchers have also reported the self-sensing behavior of steel-fiber reinforced concrete. Chung [16] and Wen and Chung [17] investigated the piezoresistivity of cement-based materials containing steel fibers and reported the self-sensing capacity of steel fiber-reinforced cementitious composites (SFRCs). However, their results were limited in the elastic region because the SFRCs they studied could not exhibit tensile strain-hardening behavior that requires some conditions for reinforcing fibers [22,23]. Nevertheless, their results led to considerable interest in the self-sensing capacity of cement-based materials containing steel fibers. Strain-hardening steel fiber-reinforced cementitious composites (SH-SFRCs) are characterized by tensile strain-hardening behavior accompanied with multiple micro-cracks. Further, they have demonstrated much higher load carrying and energy absorption capacities than normal concrete [24,25]. If SH-SFRCs could exhibit self damage-sensing behavior as well, they would be more attractive to civil engineers as multifunctional materials for the development of robust, tough, and durable civil infrastructure.

However, there is very little information regarding the factors that influence the electromechanical behavior of SH-SFRCs. Among the influential factors, the type of fiber is expected to significantly

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influence the electrical resistivity versus strain responses as well as the tensile stress versus strain responses of SH-SFRCs under direct tension. The electromechanical behavior of SH-SFRCs under direct tension strongly depends on the interfacial bond strength between the fiber and matrix, which is a function of the properties of the fiber [26]. Hence, the effects of fiber type on the electromechanical behaviors of SH-FRCCs should be understood to develop the sensing capacity of SH-SFRCs as a self damage sensor.

This situation has motivated us to carry out experimental studies on the self damage-sensing capacities of SH-SFRCs with various high-strength steel fibers under direct tension. The objectives of this paper are to (1) investigate the effects of fiber type on the electrical conductivity of SH-SFRCs, (2) discover the effects of fiber type on the self damage-sensing capacity as well as the tensile resistance of SH-SFRCs, and (3) understand the correlation between the electrical and mechanical behaviors of SH-SFRCs.

2. Electromechanical behavior of strain-hardening steel fiber-reinforced cementitious composites (SH-SFRCs) under direct tension

Direct tensile behavior of steel fiber reinforced cementitious composites can be classified into strain-hardening and strain-softening behavior according to the tensile response after the first cracking point. The condition for tensile strain-hardening behavior is that the post-cracking tensile strength (point B) should be higher than the first-cracking strength (point A) [33] as shown in Fig. 1. The point A is the limit of proportionality in the curve while the point B is the peak stress point. The tensile stress and strain at point A were notated as σ_{cc} and ε_{cc}, while those at point B were notated as σ_{pc} and ε_{pc}, respectively.

The change of electrical resistivity of SH-SFRCs under direct tensile load is shown in Fig. 2: Fig. 2a shows the typical change in the electrical resistivity of SH-SFRCs owing to electrical polarization before applying tensile load whereas Fig. 2b shows the typical change in the electrical resistivity of SH-SFRCs under direct tension. As shown in Fig. 2a, under electric current without tensile load, the electrical resistivity rapidly increased for the first 10 min owing to the electrical polarization and became stable after 20 min. Dielectric materials including cement-based composites generally produced the electrical polarization under an applied DC electrical field: when the polarization-induced electrical field and the applied DC electrical field are opposite in direction, the polarization increased the electrical resistivity with time [30,36]. Many researchers have reported about the electrical polarization of cement pastes as well as cementitious composites [27–32,36]. The tensile load would be applied after stabilizing the electrical resistivity to avoid the effect of polarization on the measured resistivity.

The electrical resistivity can be calculated from the measured electrical resistance, using Eq. (1), that is depending on the geometry of the specimens.

$$\rho = R \cdot \frac{A}{L} \tag{1}$$

where ρ is the electrical resistivity; R, the electrical resistance; A, the cross-sectional area; and L, the length between the two inner electrodes, which is also the gauge length of the specimen.

The electrical resistivity can be recognized as a material property that is not dependent on the geometry of the specimen, whereas the electrical resistance is influenced by the area of the section and the length of the specimen between two inner electrodes.

A gauge (or strain) factor is defined as the fractional changes in the electrical resistance per unit strain and is applied to evaluate the self damage-sensing capacity of SH-SFRCs. For a strain-hardening cement-based material, the nominal gauge factor (GF) would be evaluated based on the difference in the electrical resistance between the start of loading and post-cracking point. Eq. (2) can be applied to calculate the GF of SH-SFRCs as the tensile strain changes from zero to the post-cracking strain (ε_{pc}).

$$GF = \frac{\Delta R/R_0}{\Delta\varepsilon} = \frac{(R_0 - R_{pc})/R_0}{(\varepsilon_{pc} - 0)} = \frac{(R_0 - R_{pc})}{R_0 \cdot \varepsilon_{pc}} = \frac{(\rho_0 - \rho_{pc})}{\rho_0 \cdot \varepsilon_{pc}} \tag{2}$$

where R_0 (or ρ_0) and R_{pc} (or ρ_{pc}) are the corresponding electrical resistance (or resistivity) at the start of loading and post-cracking point, respectively.

3. Experiments

An experimental procedure was conducted to investigate the effects of fiber types on the electrical conductivity and electromechanical behavior of SH-SFRCs under direct tension. The following six types of steel fibers were investigated: long twisted (T30/0.3), long smooth (S30/0.3), long hooked (H30/0.375), medium twisted (T20/0.2), medium smooth (S19/0.2), and short smooth (S13/0.2) steel fibers. The content of the steel fibers was 1.5% by volume in all the specimens.

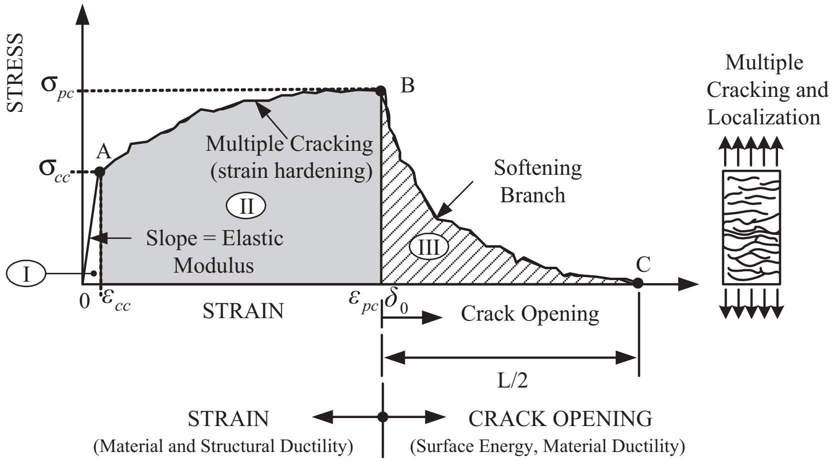

Fig. 1. Typical tensile strain-hardening behavior of SH-SFRCs [33].