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Effect of matrix cracking on electrical resistivity of high performance fiber reinforced cementitious composites in tension

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HIGHLIGHTS

- The damage sensing ability of HPFRCCs in tension significantly depended upon matrix cracking and fiber matrix debonding.
- The change of electrical resistivity during fiber pullout was monitored with change of pullout resistance.
- The crack sensing ability decreased as the gauge length between two electrodes increased.

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ABSTRACT

The effect of matrix cracking on the electrical resistivity of high performance fiber reinforced cementitious composites (HPFRCC) was investigated by performing multi-steel fiber pullout tests combined with electrical resistivity measurement. The electrical resistivity of the HPFRCCs fell immediately after the matrix cracking and then started to increase after full debonding of the fibers during fibers pullout processing. The specimens with the two pre-designated cracks exhibited a higher reduction in the electrical resistivity than those with the one pre-designated cracks or pre-crack. The source of the sensing damage of HPFRCC in tension significantly depends upon matrix cracking and fiber matrix debonding.

1. Introduction

There has been considerable interest in structural health monitoring (SHM) systems because of the rapid deterioration of the load-carrying capacities of civil infrastructure and buildings, which could ultimately lead to their catastrophic failure. Current SHM systems mostly utilize embedded or attached sensors; however, such sensors can only be used to detect localized damage owing to their high cost and low durability.

To overcome the limitations of the current generation of sensors, various smart construction materials incorporating electrically conductive materials, e.g., cementitious composites incorporating carbon fiber, carbon nanotubes, graphene, graphite nano fibers, and steel fiber, have been developed [1–12]. Self-sensing steel-fiber-reinforced cementitious composites (SS-FRCC), a type of smart construction material, have demonstrated their superior ability to self-sense damage, in addition to having excellent mechanical resistance [9–12]. Chung [9] first reported on the self-sensing ability of steel-fiber-reinforced cementitious composites (SFRC). Wen and Chung [10] investigated the self-sensing behavior of SFRCs within the elastic range under repeated tension. They measured the electrical resistivity and tensile strain of cement paste containing 0.36 and 0.72% steel fibers, by volume, in tension.

Recently, Nguyen et al. [11] and Song et al. [12] reported on the damage-induced self-sensing responses of high performance fiber reinforced cementitious composites (HPFRCCs) with high-strength steel fibers. Unlike normal SFRCs, HPFRCCs have demonstrated a very high tensile strength and energy absorption capacity, accompanied by multiple micro-cracks [11–14]. The multiple micro-cracking behavior of HPFRCCs produces a clear reduction in the electrical resistivity in the tensile strain-hardening region [11], as illustrated in Fig. 1. Nguyen et al. [11] investigated the effects of the fiber type on the electro-mechanical response of HPFRCCs in tension, while Song et al. [12] examined the effects of the fiber volume content on the self-sensing electro-mechanical responses. Unlike those HPFRCCs with steel fibers,

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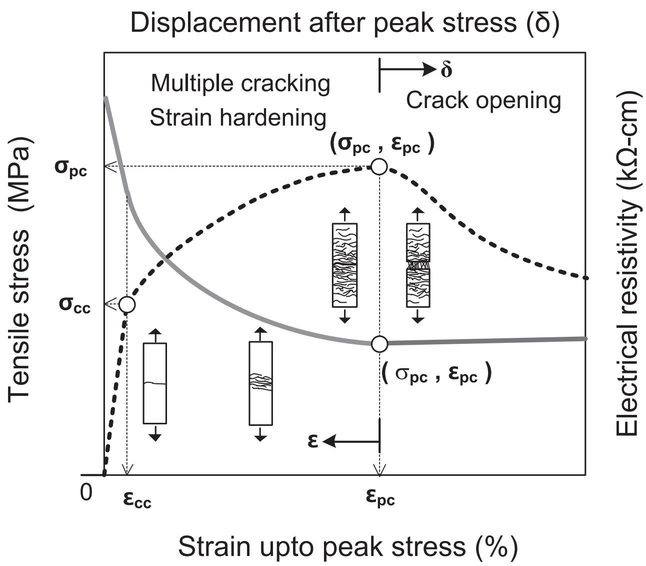

Fig. 1. Typical electromechanical behavior of HPFRCCs [10].

strain-hardening engineered cementitious composites (ECC) incorporating polyvinyl alcohol (PVA) fibers, exhibit a different tendency in their self-sensing responses [15,16]: the electrical resistivity of ECCs has been found to increase with the tensile strain, accompanied by multiple micro-cracks.

The change in the electrical resistivity of HPFRCCs (or ECCs) clearly occurs because of matrix cracking as well as any change in the fiber slip. This could be closely related to the interfacial electrical resistivity between the fibers and matrix at a given crack. The contact electrical resistivity is heavily dependent on the interface bonding strength between the fibers and concrete matrix [17–20]. Based on these findings, the interfacial electrical resistivity of steel fibers embedded in cement mortar should increase with the amount of slip. However, HPFRCCs with steel fibers exhibit a clear reduction in their electrical resistivity as their tensile strain increases, accompanied by the appearance of multiple micro-cracks. The reason for this reduction in the electrical resistivity is not yet fully understood.

In this study, we set out to determine the reason for the reduction in the electrical resistivity of HPFRCCs in tension. Our detailed objectives were 1) to investigate the electrical resistivity of multi-fiber pullout specimens in tension, 2) to discover the effects of matrix cracking on the electrical resistivity of HPFRCCs in tension, 3) to correlate the change in the electrical resistivity of multi-fiber pullout specimens and direct tensile specimens of HPFRCCs, and 4) to investigate effect of gauge length on the electrical resistivity.

2. Multi-fiber pullout tests

Multi-fiber pullout specimens were used to investigate the source of the reduction in the electrical resistivity of HPFRCCs, as their tensile strain (and therefore the number of cracks) increased. The pullout load, as well as the electrical resistivity, were measured simultaneously as tension was applied to the multi-fiber pullout specimens. The fiber pullout specimens consisted of both single- and double-sided bell-shaped specimens. The single-sided pullout specimens are widely used for single-fiber pullout tests since it is much easier to manufacture and test single-sided specimens than double-sided ones. However, the results of pullout tests using single-sided specimens are generally more scattered, given the range of fiber grips and the nature of the interfacial characteristics between the fibers and cement matrices [21,22]. Moreover, it is more difficult to hold the multi-fibers in multi-fiber pullout tests, giving rise to a need for special grips. Thus, double-sided pullout specimens would be more suitable than single-sided pullout specimens for multi-fiber pullout tests [21].

Fig. 2 shows examples of multi-fiber pullout specimens: the cross-section of each specimen measured 25 × 25 mm^2 and the length of each was 190 mm. Smooth steel fibers, 30 mm in length, were embedded in the middle of the specimens, with equal amounts of matrix to either side. As can be seen in Fig. 2, three types of specimens were prepared: pre-cracked specimens, one-cold-joint specimens, and two-cold-joint specimens. The specimens with the cold joints were prepared to investigate the effects of matrix cracking on the electrical resistivity. On the other hand, the pre-cracked specimens were prepared by using an embedded foam sheet (3 mm wide, 25 × 25 mm^2 cross-section) in the middle of the specimens to investigate the change in the electrical resistivity as the amount of slip increased during fiber pullout.

During the tests, the electrical resistivity was measured using a DC four-probe method. A direct current was passed through the two outer electrodes while the voltage was measured between the two inner electrodes. Electrodes, 5 mm in width, were formed on the surfaces of the specimens using copper tape and silver paint. The electrical resistivity of the specimens, which does not depend on the specimen geometry, during the pullout test, was calculated from the measured electrical resistance using Eq. (1)

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

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

The pullout response of multiple steel fibers was evaluated by calculating the pullout peak load, unit peak load, and pullout work [21]. The unit peak load was determined by dividing the pullout peak load by the number of fibers, with the pullout work being the area under the pullout load versus slip curves.

3. Experiments

An experimental program was designed to investigate the effects of matrix cracking on the electrical resistivity of HPFRCCs in tension. The three types of pullout specimens, i.e., with pre-cracking, one cold joint, and two cold joints, were prepared as shown in Fig. 2. The number of long, smooth steel fibers (30 mm in length), embedded in the specimens, was 49, which was equivalent to an approximately 1% fiber content by volume, assuming a 2D fiber distribution. Ultra-high-performance concrete (UHPC) with a strength of 180 MPa, containing 2 vol% short, smooth fibers (6 mm in length), were used as the matrix for the pullout specimens. The short fibers were added to the UHPC mortar to prevent cracking of the matrix, with the exception of the pre-designated crack position in the multi-fiber pullout specimens. The long smooth fibers were carefully embedded in the matrix using a PVC plate and foam sheets, as shown in Fig. 3a. As shown in Fig. 3b, a PVC plate (25 × 25 × 3 mm^3) with 49 holes (0.4 mm in diameter) was used to align the fibers in the foam sheets. Direct tensile specimens containing 2% short, smooth fibers and 1% long, smooth fibers in UHPC were additionally prepared to determine the correlation between the pullout electrical resistivity and the tensile electrical resistivity. In addition, the specimens with one cold joint were used in the investigation of the effect of gauge length on the electrical resistivity.