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Hybrid effects of steel fiber and carbon nanotube on self-sensing capability of ultra-high-performance concrete

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HIGHLIGHTS

- Mechanical performance of UHPC with CNTs are significantly improved by adding 2% steel fibers.
- Compressive behaviors are not properly monitored by FCR measurement.
- Unintended FCR data noise of UHPC with CNTs is significantly mitigated by adding 2% steel fibers.
- Tensile behavior of UHPFRC with CNTs is well simulated based on FCR measurement.
- Using micro steel fiber is more effective in increasing tensile GF than using macro steel fiber.

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ABSTRACT

This study aims to examine the feasibility of using steel fibers and carbon nanotubes (CNTs) on developing self-sensing ultra-high-performance concrete (UHPC). For this, four steel fiber types with two different shapes (straight vs. twisted) and three different aspect ratios from 65 to 100 were considered at a fiber volume fraction of 2%. 0.5% by volume of CNTs were simultaneously added. A plain UHPC with only 0.5% CNTs was also fabricated and tested as a control specimen. Test results indicated that the addition of 2% steel fibers was effective in enhancing compressive strength, elastic modulus, tensile strength, and strain capacity of the plain UHPC. The compressive behaviors of UHPC and ultra-high-performance fiber-reinforced concrete (UHPFRC) with CNTs were not predicted based on a fractional change in resistance (FCR) measurement, whereas the total tensile behaviors in terms of both stress-strain and stress-crack opening displacement (COD) curves were quite well simulated based on the FCR measurement and curve-fitting equations suggested. The unintended noise in the FCR of the plain UHPC was largely mitigated by adding the steel fibers, while the highest gauge factor (GF) under tensile load was found for the plain UHPC with CNTs. Using micro steel fibers was more effective in increasing the GF than using macro steel fibers, and better predictive results were obtained for the UHPFRC with straight steel fibers as compared to that with twisted steel fibers.

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1. Introduction

Ultra-high-performance fiber-reinforced concrete (UHPFRC) was developed in the mid-1990s [1] to overcome some drawbacks of ordinary concrete, such as low strength-to-weight ratio, low tensile strength, high brittleness, and poor durability. UHPFRC employs granular materials with optimized sizes and includes only fine ingredients without coarse aggregate. Steam curing with heat (90 °C) is generally applied to achieve a very high compressive strength, greater than 150 MPa, and to accelerate strength development. The inclusion of a high volume fraction of steel fibers can also remedy the shortcomings (low tensile strength and high brittleness) of ordinary concrete due to the fiber bridging effect, which causes strain- or deflection-hardening behavior with the formation of multiple microcracks. As a result, the addition of steel fiber has begun to attract much attention from researchers and engineers, and practical applications of UHPFRC to buildings and infrastructure like long span bridges have increased [2,3]. However, since this is a novel construction material recently developed and exhibits greatly different material properties with ordinary concrete, monitoring of its structural integrity during service life is required to guarantee the safety and reliability.

Structural health monitoring (SHM) based on non-destructive testing has been actively developed to ensure the integrity of

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buildings and infrastructure. This technique can continuously acquire data and monitor the safety of structures from measurements of stress and strain states. SHM has been applied using commercially available strain gauges, such as piezo-ceramic transducers, Fiber Bragg Grating (FBG) sensors, and piezoelectric sensors based on a lead zirconate titanate (PZT). However, using commercial sensors has some disadvantages, such as local assessment of structural state, structural weakness due to heterogeneity between the sensor and concrete, and uncertain coupling between the attached sensor and structural surface. To overcome such problems, various types of cement-based sensors have been introduced by previous researchers [4–14]. Since cement itself is not a conductive material, the main themes of previous studies were the development of conductive cement composites having various carbon-based materials. These conductive cement-based sensors have some advantages, i.e., low price of production, high durability, and continuous SHM of structural integrity. In general, the stress and strain variations of concrete structures are interpreted by the change in electrical resistance of cement-based sensors, so that it is important to accurately simulate the stress and strain of concrete under both compression and tension based on a measurement of electrical resistance and theoretical models.

Azhari et al. [6] reported that adding carbon fiber and carbon nanotubes (CNTs) is effective in improving the electrical conductivity and piezoresistive sensing capability of concrete under compression. Gao et al. [4] noted that carbon nanofibers can improve both the electrical properties and the strength of cement composites when they are properly dispersed. However, a strength reduction in concrete with carbon nanomaterials was also reported by Hardy et al. [5] because of the aggregation of the nanomaterials. Fu and Chung [7] have investigated the strain sensitivity of carbon fiber-reinforced cement composites and found that a change in load in the cement composites with carbon fibers can lead to a change in resistance. The carbon fibers added increased the tensile strength, whereas they reduced the compressive strength of cement composites. According to a previous study performed by Banthia et al. [8], the carbon fiber itself was not less conductive than the steel fiber and the electrical conductivity of cement composites reinforced with carbon fibers was significantly higher than that with steel fibers. Han et al. [10] experimentally evaluated the effect of water-to-cement (W/C) ratio on the electrical and piezoresistive properties of cement composites using CNTs. According to their test results, better piezoresistive sensing capacity was obtained when the W/C ratio was 0.6 as compared to 0.45, and similar experimental results have been reported by You et al. [9]. Lee et al. [11] noted that the cement composite with hybrid use of 0.1% carbon fibers and 0.5% CNTs provided similar electrical and piezoresistive sensing properties to that containing 1% CNTs. Also, Yoo et al. [12] examined the effects of carbon nanomaterials on the electrical conductivity and self-sensing capability of cement composites using CNTs, graphite nanofibers, and graphene and noted that using the CNT was most effective in enhancing the electrical properties of cement composites at an identical volume fraction of 1%. Monterio et al. [14] developed a self-sensing concrete using carbon black. Using three-point bending tests, they found that: (i) the carbon black content affected the mechanical and electrical properties of concrete, (ii) adding up to 4% (by weight) carbon black improved the mechanical properties, and (iii) a carbon black amount ranging from 7 to 10% is more effective for self-sensing. Azhari and Banthia [13] simulated tensile behaviors of cement composites under cyclic tensile loads using carbon fibers. They [13] effectively decreased data noise by adding a high amount of carbon fibers and simulated the tensile strains.

Likewise, numerous studies [4–14] have been published regarding the development of conductive or self-sensing cement-based materials thus far. The previous results on ordinary cement-based sensors are not able to be directly applied and extended to UHPFRC because of its greatly different mechanical properties with ordinary mortar. For instance, some properties of UHPFRC, such as very high strength characteristics, strain-hardening and multiple cracking behaviors, etc., are not observed in ordinary mortar. The ordinary cement-based sensors have much lower strength and poorer post-cracking tensile performance compared to those of UHPFRC. So, if the ordinary cement-based sensors are applied to UHPFRC elements, this can cause the weakest part in the section and thus not applicable. Therefore, for their health monitoring of structural integrity, a UHPFRC-based sensor needs to be developed. Most of the previous studies were conducted for ordinary cement paste and mortar having normal or high strength, and only few studies [9,15–18] have been published in very recent years regarding the development of self-sensing UHPFRC, showing very high strength of about 180 MPa and dense microstructures. Sun et al. [16] used 0.5% brass-coated micro straight steel fibers in ultra-high-performance concrete (UHPC) and evaluated its piezoresistive capacity under compression. They found a smooth change of its resistance under repeated compression and the repeatability and sensitivity were greatly improved by applying oven drying. As the developed UHPFRC sensor was embedded in ultra-high-strength concrete column for SHM, its sensitivity was reduced, compared to the sensor itself in the uniaxial stress state. For developing conductive UHPFRC, Dong et al. [17] have adopted short-cut super-fine stainless wire with high aspect ratio. Its sensing capability under compression and flexure was evaluated, and four orders of electrical resistivity of plain UHPC could be reduced by incorporating 0.5% stainless wires with 20-μm diameter. Kim et al. [18] have used hybrid short and medium-length straight steel fibers at 2% by volume and evaluated the self-sensing capacity of UHPFRC under direct tension. From their study, the electrical resistivity of UHPFRC decreased with tensile force and a higher matrix strength led to a higher resistivity and longer polarization time. The electrical resistivity of UHPFRC was quite high as much as 973.3 KΩ cm. However, based on a study performed by You et al. [9], the incorporation of only short steel fibers up to 3% can decrease the electrical resistivity of plain UHPC, but insufficient to impart piezoresistive property of UHPC. In addition, by including a small amount of CNTs, i.e., 0.3% or more, an excellent self-sensing capacity of UHPFRC under flexure along with significantly lower resistivity of about 323–393 Ω cm could be achieved, which is about two orders of magnitude smaller than that given by Kim et al. [18]. Thus, the hybrid use of steel fibers and CNTs is very effective in reducing the resistivity and enhancing self-sensing capacity of UHPC. However, as compared to ordinary cement composites, the self-sensing capability of UHPFRC is still in its infancy. In addition, to the best of our knowledge, only very limited study [15] has published regarding the hybrid effect of steel fibers and CNTs on self-sensing capability of UHPFRC under tension and there is no published study evaluating the effects of steel fiber geometry and CNT on the electrical properties and self-sensing capacity of UHPFRC under both compression and tension.

Accordingly, the electrical and self-sensing properties of UHPC and UHPFRC with 0.5% CNTs were examined under both monotonic compressive and tensile loads. This is because, as compared to the previous suggestions, the hybrid use of steel fiber and CNT is expected to give better conductivity and self-sensing capacity to UHPC matrix. To evaluate the effect of steel fiber type on these properties, three straight steel fibers with different aspect ratios (l_f/d_f) of 65, 97.5, and 100 and a twisted steel fiber with an l_f/d_f of 100 were considered, where l_f is the fiber length, and d_f is the fiber diameter. The tensile stress-strain and stress-crack opening displacement (COD) curves were simulated based on the measured fractional change in resistivity (FCR) and curve fitting equations obtained. Lastly, the fracture energies of UHPC and UHPFRC with

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