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Multifunctional super-fine stainless wires reinforced reactive powder concrete for smart structures

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ABSTRACT

Super-fine stainless wires (SSWs) with microscale diameter and high aspect ratio were used to improve the mechanical, electrically conductive and self-sensing capability of reactive powder concrete (RPC). The mechanical behaviors and conductive characteristics of SSWs reinforced RPC and their responses to different external loading are investigated. The calculation models of flexural strength and toughness of SSWs reinforced RPC are established based on the microstructure analysis and composite theory, and the conductive mechanisms of composites are revealed through electrochemical impedance spectroscopy and intrinsic conductivity analysis. The results demonstrated that the addition of 1.5 vol. % of SSWs can increase the flexural strength and fracture energy of RPC by 103.2% and 442.2% respectively. The percolation occurs and polarization disappears in RPC containing 0.5 vol.% of SSWs in diameter of 20 μm. The gauge factor of RPC reinforced with SSWs in diameter of 8 μm can reach up to 22.5, 94.9 and 43.6 under cyclic compression, monotonic compression and flexure, respectively. The microstructure analysis indicates that the strengthening and toughening effects of SSWs on RPC result from the extensive reinforcing network, the inhibition on micro-cracks development and the pull-out and stripping of SSWs under loading. The conductivity of SSWs reinforced RPC mainly depends on the formation of SSWs conductive network.

Smart structure refers to a structure that can monitor itself without the need of embedded, attached or remote sensors. It can be developed by using intrinsic self-sensing concrete, which is fabricated through incorporating some functional fillers such as carbon fibers (CFs), carbon nanotubes (CNTs), steel fibers and nickel powders (NPs) into conventional concrete to increase its ability to sense the strain, stress, crack or damage in itself while maintaining or even improving its mechanical properties and durability. The intrinsic self-sensing behavior of concrete was firstly investigated in 1992 with the incorporation of CFs [1]. Up to now, the intrinsic self-sensing concrete with CFs is still one of the most extensively and comprehensively studied composites [2-8]. However, the cement-based materials and carbonic fillers have a poor compatibility, so the effective dispersion technology and dispersing agents are needed [9-10]. This complicates the composite preparation process, reduces the performance stability, and increases the material cost. In contrast, steel fibers have greater advantages than CFs in the following aspects. First, the bond strength between steel fibers and concrete is currently accounted for 0.7-1.0 MPa, slightly lower than that between steel reinforcing bar and concrete. Second, steel fibers have the similar temperature linear expansion coefficient with cement-based materials, reducing thermal stress in composites. Third, the alkaline environment caused by cement hydration products can inhibit the corrosion of steel fibers [11]. Previous studies have shown that the bond strengths between steel fiber and cement matrix increases with the compressive strength increase of cement-based materials. Therefore, the enhancement of steel fibers on high-strength cement-based materials is more obvious, which is a good foundation for the application of steel fibers in reactive powder concrete (RPC) [12-13]. Steel fibers used for RPC in previous research include hooked, twisted and smooth types. Their diameter is normally around 0.15-0.50 mm, and their length is usually between 6-16 mm. The addition of the above steel fibers has certain improvement effect on the mechanical properties of RPC. However, there is higher porosity and more micro-cracks in interface transition zone of concrete matrix surrounding steel fiber [14,15]. The weak interface between steel fibers and concrete matrix greatly limit the improvement effect on mechanical performance of RPC.

Super-fine stainless wires (SSWs) have the same excellent characteristics as the above commonly used steel fibers such as high mechanical property, good dispersion in concrete, and similar linear expansion coefficient with concrete. Owing to the micron diameter and high aspect ratio, SSWs can form three-dimensional overlapping network at low volume fraction, which will be helpful to further improve the strength, toughness and deformation capacity and alter the failure criterion of RPC under loading [16-19]. Meanwhile, the micron diameter of SSWs can also improve the microstructure of RPC and weaken the adverse effect of interface transition zone caused by commonly used steel fiber. Even more, the addition of SSWs has potential to endow RPC with excellent functional characteristics due to the good electrically and thermally conductivity of SSWs [20]. Therefore, SSWs with microscale diameter (8 μm and 20 μm, with volume fraction of 0.5%, 1.0% and 1.5%) and high aspect ratio (the length of SSW is 10 mm) is used to improve the mechanical, electrically conductive and self-sensing capability of RPC. The mechanical behaviors and conductive characteristics of SSWs reinforced RPC and their responses to different external loading are investigated. The calculation models of flexural strength and toughness of SSWs reinforced RPC are established based on the microstructure analysis and composite theory, and the conductive mechanisms of composite are revealed through electrochemical impedance spectroscopy and intrinsic conductivity analysis.

The experimental design and property measurements can be found in the references of [21-25]. The main results are as follows. The flexural strength increases with the increase of SSWs' content and diameter. When the SSWs content is 1.5 vol.% (with diameter of 20 μm), the flexural strength of RPC can be increased by 100.7% compared to that of RPC without SSWs. Meanwhile, the flexural strength of RPC with SSWs in diameter of 8 μm is raised by 68.9% (Fig. 1). The fracture energy of RPC reinforced with SSWs in volume fraction of 1.0 vol.% and 1.5 vol.% and diameter of 20 μm is increased by 111.7% and 173.0% after water curing for 28 days respectively, while the increments can reach up to 442.2% as the curing ages are 3 days. These increments can be attributed to the following effect of SSWs: inhibition effect on the initiation and convergence of microcracks, shielding effect on the crack tip stress, pull-out, contortion and stripping effect on bridging macrocracks, thus leading to the improvement of mechanical properties, toughness and deformation of RPC. The flexural strength and toughness of SSWs reinforced RPC can be theoretically calculated according to composite theory and pull-out energy of fibers.

The results of electrical resistivity of SSWs reinforced RPC measured by using two-electrode-DC method showed that the electrical resistivity decreases with the increase of SSWs' content. The electrical resistivity of RPC with SSWs in diameter of 8 μm is considerably higher than that of RPC with SSWs in diameter of 20 μm, indicating that the dispersal uniformity of SSWs in diameter of 20 μm is better than that in diameter of 8 μm at the same content. The percolation phenomenon has already appeared when the content of SSWs in diameter of 8 μm is 1.5 vol.%, and the conductive pathway has shift from RPC matrix to SSWs network. The percolation phenomenon of RPC with SSWs in diameter of 20 μm already exists when the content of SSW is only 0.5 vol.%. The test results also showed that the electrical resistivity of RPC is less affected by curing ages, which can be attributed to that the SSWs play an important role in the conductive pathway of RPC with SSWs in diameter of 20 μm.

The relationships between cyclic compressive stress/strain, monotonic compressive stress/strain and flexural loading and the fractional change in electrical resistivity (FCR) of SSWs reinforced RPC are established. The results indicated that the SSWs reinforced RPC has piezoresistive response under cyclic compressive loading within the elastic regime. However, the characteristics of piezoresistive response vary with SSWs content and diameter. The gauge factor of RPC with SSWs in diameter of 8 μm and volume fraction of 1.0 vol.% can reach 41.9 under cyclic compressive loading within elastic regime (Fig. 2). The fractional change in electrical resistivity first increases slowly and then rapidly with the increase of monotonic compressive stress/strain, and this can be attributed to the variation of conductive network and specimen deformation under loading. The resistivity fractional changes of RPC with SSWs in diameter of 8 μm and volume fraction of 1.0 vol.% under peak monotonic compressive failure stress is 41.1%, and the corresponding gauge factor is 143.1. Under flexural loading, the bottom part of specimens is tensioned, and the SSWs in this area move away from each other even are pulled-out. This phenomenon leads to the increase of electrical resistivity. The top part of specimens is compressed and the SSWs tend to close to each other even contact with each other, which leads to the decrease of the electrical resistivity. Therefore, the electrical resistivity of SSWs reinforced RPC under flexural loading presents offset phenomenon. Therefore, the incorporation of SSWs makes the fractional change in electrical resistivity of SSWs reinforced RPC correspond to the combined effect of compression and tension under flexure. The gauge factor of RPC with SSWs in diameter of 8 μm and volume fraction of 1.5% under flexural loading is 36.9. The conductive mechanisms of SSWs reinforced RPC revealed is closely related to the formation of SSWs conductive network. The SSWs in diameter of 20 μm is more suitable to be used as conductive fillers for RPC compared to SSWs in diameter of 8 μm. Therefore, strain, stress (or external force), crack and damage of SSWs reinforced RPC can be monitored through measuring the change of electrical resistivity of the composites.

In addition, the increase of dynamic impact toughness and the decrease of damage degree under high-speed impact load are of important significance for SSWs reinforced RPC used in extreme environment especially under blast-impact load. Furthermore, the addition of 1.5 vol.% SSWs leads to 19.9% increases in damping ratio of RPC as well as 202.9% increases for electromagnetic wave shielding efficiency at the frequency of 4 GHz. The electromagnetic wave absorbing property of RPC reinforced with 1.5 vol.% SSWs exceeds 125.0% of that of RPC without SSWs in the frequency range of 17-18 GHz. The addition of SSWs can also effectively increase the thermal conductivity and wear resistance of RPC.

Owing to the good compatibility between SSWs and RPC, it is possible to obtain high performance and smart concrete with excellent strength, high toughness, favorable conductivity and self-sensing capability by using low content of SSWs. The SSWs reinforced RPC has potential to make structures smart, eco-efficient, durable and sustainable, thus improving the structure operating safety and efficiency. Therefore, it is an ideal choice for maintaining sustainable development of structures.

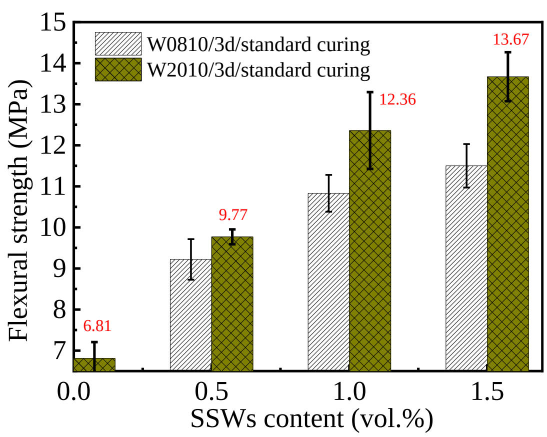

Fig. 1 Flexural strength of SSWs reinforced RPC

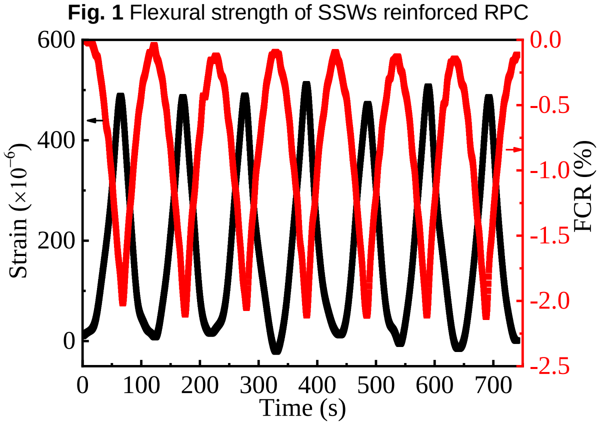

Fig. 2 Self-sensing property of RPC with SSWs in diameter of 8 µm and volume fraction of 1.0 vol.% under cyclic compressive loading

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