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Developing Multifunctional Ultra-High Performance Concrete via Incorporating Hybrid Steel Wires and Fibers

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Abstract. *Stainless steel wires (SSWs) with micro diameter and stainless steel fiber (SFs) with millimeter diameter were incorporated together to develop multifunctional ultra-high performance concrete (UHPC) in this study. The addition of 0.2 vol.% of SSWs can already improve interface between matrix and SFs, reduce the microcracks in UHPC caused by shrinkage and initial load, increase SFs' distribution and orientation with their high flexibility, thus enhancing the flexural toughness and resulting in the occurrence of multiple cracking flexural failure mode of UHPC with less than 2.0 vol.% SFs. The hybrid SWs and SFs reinforced UHPC possesses low electrical resistivity and can sense its initial cracking, residual flexural loading and cracking development by the measured fractional change in electrical resistivity. This is mainly coming from the inhibition effect of SWs on microcracks and the extensively conductive pathway formed by both SWs and SFs. The multiple cracking failure mode under flexural load and the self-sensing capacity to monitor crack initiation and propagation of UHPC with low content hybrid wires and fibers is important to develop multifunctional UHPC, thus providing a new approach for maintaining sustainable development of infrastructures.*

Keywords: *Stainless steel wires; Ultra-high performance concrete; Multiple cracking failure; Crack development monitoring function*

Introduction

Based on the excellent strength, toughness, and durability of UHPC, it will definitely play an important role in fabricating large-scale infrastructures represented by super-high and large-span structures. The design characteristics of UHPC include improving the fineness and activity of raw material, adopting thermal curing to promote hydration reaction, removing coarse aggregate, using superplasticizer to ensure low water-binder ratio, and incorporating steel fibers (SFs) to increase toughness [Park et al. 2012]. It is worthwhile to note that the conventional SFs with diameter larger than 0.12 mm mainly play the role of bridging effect across macroscopic cracks, and they cannot modify the electrically conductive property to endow UHPC with self-sensing property[Meng et al. 2017 and Smith et al. 2020]. Meanwhile, the initial microcracks under loading propagate rapidly and multiple cracking failure mode under flexural/tensile load is still not available in UHPC as the total SFs content is 2.0 vol.% [Larsen and Thorstensen 2020]. This can be attributed to that SFs have no significant modification effect on UHPC matrix and they cannot form widely distributed network at low content level. High content of SFs seriously reduces the workability, increases the density, and raises the cost of UHPC [Wu et al. 2017 and Fan et al. 2021].

Owing to the high aspect ratio, high tensile strength, strong bond strength with concrete matrix, remarkable electrical conductivity, and great dispersibility, stainless steel wires (SSWs) with micro diameter arrange a widely distributed overlapping network in UHPC at their low contents, leading to that the microcracks in UHPC matrix induced by hydration heat temperature gradient, shrinkage, and initial load can be effectively controlled, and the conductivity and self-sensing property of UHPC are improved [Dong et al. 2020, 2021a and b]. Meanwhile, the formation of complete SSWs' network is expected to exert a favorable influence on the SFs' distribution. SSWs have potential to simultaneously enhance UHPC matrix and form synergistic improvement/conductive network together with SFs to optimize flexural properties and failure state of UHPC and endow UHPC with high electrically conductive and self-sensing properties, thus reducing the content of SFs and maximizing the effectiveness of both wires and fibers.

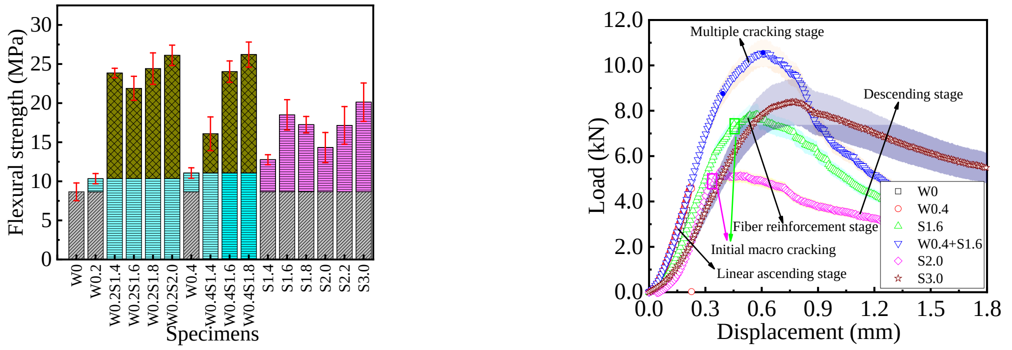
Therefore, the flexural, electrical, and self-sensing properties of UHPC incorporating hybrid SSWs and SFs were investigated in this study, and the synergistic modification mechanisms of SFs and SSWs were revealed.

2. Method

The experimental design and property measurement methods can be found in the references of [Dong et al. 2022, Wang et al. 2022].

3. Results and Discussions

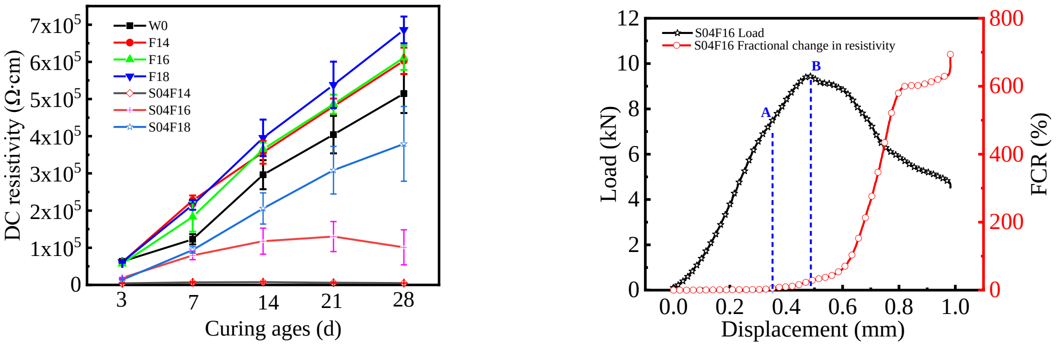
It can be found from the experimental results that the improvement effect of mono SFs on flexural strength of UHPC is better than that of mono SSWs. Incorporating 0.2 vol% SSWs increases the flexural strength of UHPC with 1.4 vol%, 1.6 vol%, 1.8 vol%, 2.0 vol% SFs by 87%, 18%, 42%, and 82%, respectively, as shown in Fig. 1(a). The flexural strength of UHPC with hybrid 0.2 vol% SSWs/1.8 vol% SFs and 0.2 vol% SSWs/2.0 vol% SFs is 24.4 MPa and 26.1 MPa, 71% and 52% higher than that of UHPC with mono 2.0 vol%/2.2 vol% SFs. Meanwhile, the flexural strength of UHPC with hybrid 0.2 vol% SSWs/1.8 vol% SFs is 22% higher than that of UHPC with hybrid 0.5 vol.% medium length (10 mm) straight mesoscale steel fibers and 1.5 vol.% long straight mesoscale steel fibers (20 mm) [Niu et al. 2021], and 6% higher than that of UHPC with 4.0 vol.% straight mesoscale steel fibers (diameter of 0.2 mm and length of 13 mm) [Yoo et al. 2017]. Meanwhile, these above two values of flexural strengths are comparable to that of UHPC with hybrid 1.0 vol.% hooked mesoscale steel fibers and 1.0 vol.% straight mesoscale steel fibers (26.5 MPa) [Yoo et al. 2017]. Fig. 1(b) shows that incorporating hybrid SSWs and SFs make the flexural load-displacement curves of UHPC have long linear ascending stage and smooth transition stage from the initial macro cracking to fiber reinforcement stage. Adding 0.4 vol% SSWs already enables the flexural load-displacement curves of UHPC with 1.6 vol% fibers possess multiple-cracking stage. This can be attributed to that SSWs and SFs work together to inhibit the initiation and propagation of cracks. According to the calculation results of crack energy and experimental observation, UHPC has no multiple cracking failure mode when the content of SFs is less than 3.0 vol%, but the multiple cracking failure mode has occurred for UHPC with UHPC with hybrid 0.2 vol.% SSWs/1.8 vol.% SFs and 0.4 vol.% SSWs/1.6 vol.% SFs.



(a) Flexural strength (b) Flexural load-displacement curves

Fig. 1 Flexural strength and load-displacement curves of UHPC incorporating hybrid SSWs and SFs

The electrical resistivity of UHPC with mono SFs can be reduced by one or two orders of magnitude by adding SSWs, as shown in Fig. 2(a). For UHPC with hybrid SSWs and SFs, SSWs play a key role in the conductive pathway. The fractional change in resistivity of UHPC with hybrid SSWs and SFs under flexural load increases linearly before initial macro cracking load, as shown in Fig. 2(b). The linear slope for this stage presents a declining trend due to the inhibiting effect of SSWs on initiation and propagation of cracks. With the flexural load increases, the fractional change in resistivity for UHPC increases non-linearly. After reaching the peak flexural load, the fractional change in resistivity presents a rapid growth trend with the decrease of flexural load and the development of macro cracks, which is mainly resulted from the disconnection of conductive fibers. Especially, the factional change in resistivity and stress sensitivity of UHPC with hybrid 0.4 vol% SSWs and 1.6 vol% SFs increase one or two orders of magnitude under peak flexural load compared to that of UHPC with mono 1.6 vol% SFs, achieving the values of 28.31% and 0.01288 %/MPa.



(a) Electrical resistivity (b) Self-sensing property

Fig. 2 Electrical resisitvity and self-sensing property of UHPC with hybrid SSWs and SFs

The modification mechanisms of SSWs on flexural, electrical and self-sensing properties of UHPC with SFs can be summarized as the following three aspects. 1) SSWs with micro diameter can modify the interface between SFs and concrete matrix, and can also modify SFs' dispersion and orientation state in UHPC through hindrance effect, reducing the defects caused by uneven dispersion and millimeter diameter of SFs and improving SFs' efficiency. 2) The hybrid using of SSWs and SFs provides a system with sufficiently small spacing to control the initiation and propagation of cracks and a high overlapped conductive network, leading to the occurrence of multiple cracking failure and stable/high self-sensing ability.

4. Conclusions

Using hybrid SSWs and SFs makes it possible to fabricating multifunctional UHPC with excellent flexural property, multiple-cracking failure code, and high sensing property simultaneously. This kind of multifunctional UHPC with hybrid SSWs and SFs integrates smartness with their excellent mechanical properties and durability, and it can actively adapt environmental change and resist external damage and has potential to optimize safety, longevity, and function of infrastructures to reduce life cycle cost, resource consumption, and environment pollution.

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