Microstructure related mechanical behaviors of short-cut super-fine stainless wire reinforced reactive powder concrete

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Abstract:

Short-cut super-fine stainless wire (SSSW) with super-fine diameter and high aspect ratio is used to reinforce reactive powder concrete (RPC). The mechanical behaviors of SSSW reinforced RPC (SSSWRRPC) cured at different regimes are investigated under different loading conditions. The calculation models of flexural strength and toughness of SSSWRRPC are established based on the microstructure analysis, the composite theory, the expression of bond strength between SSSWs and RPC matrix, and the effective coefficient of SSSWs numbers. The results demonstrate that, by incorporating only 0.5 vol. % of SSSW, the mechanical strength and toughness of RPC has been significantly increased. The 1.5 vol. % of SSSW can increase the flexural strength and fracture energy 103.2% and 442.2% respectively. The reinforcing effect of SSSWs in aspect ratio of 500 and diameter of 20 μm is superior to that of SSSWs in aspect ratio of 1250 and diameter of 8 μm . The improvement of mechanical behavior is closely related to curing condition. The microstructure analysis indicates that the strengthen effect of SSSW on RPC results from the extensive reinforcing network, the inhibition on micro-cracks development and the pull-out, contortion and stripping of SSSWs under loading.

Key words: Reactive power concrete; Short-cut super-fine stainless wire; Fiber reinforcement; Mechanical properties; Flexural toughness; Microstructure.

1 Introduction

Due to the development of modern civil engineering applications, high-performance cement-based materials are in an urgent need. However, typical cement-based materials are associated with low fracture toughness, tensile strain and impact resistance, which limit their application. The addition of discontinuous short fibers can significantly reduce the brittleness of cement-based materials and alter the mode of failure, because that the fibers can cross the paths of potential cracks and transmit stress between the fibers and the matrix through the interfacial bond [1, 2]. There are various fibers used for reinforcing cement-based material, such as polymer fiber, steel fiber, carbon fiber and plant fiber. Steel fiber has greater advantage than others. First, the bond strength between steel fiber and concrete is currently accounted for 0.7-1.0 MPa [3], slightly lower than that between steel reinforcing bar and concrete. Second, steel fiber has the similar temperature linear expansion coefficient with cement-based material. Thus, thermal stress is trivial in the composites. Third, the alkaline environment caused by cement hydration product can inhibit the corrosion of steel fiber [4]. Previous studies have shown that the higher the compressive strength of cement-based materials, the higher the bond strength between steel fiber and cement matrix. Therefore, the enhancement of steel fiber on high-strength cement-based materials is more obvious, which is a good foundation for the application of steel fiber in reactive powder concrete (RPC) [5, 6]. Steel fibers used for RPC in previous research include hooked, twisted and smooth types [7, 8]. Their diameter is normally around 0.15-0.25 mm, and their length is usually between 6-16 mm [9-19]. The research of Park et al. [7] shows that the addition of micro-fibers (with diameter of 0.2 mm and length of 13 mm) is favorable for strain hardening and micro-cracking behavior. Two short brass-coated micro-steel fibers (length of 6 and 13 mm) with diameter of 0.16 mm were used in the research of Aldahdooh et al. [9]. Abbas [10] et al. investigated the effect of copper coated steel fiber lengths (8 mm, 12 mm and 16 mm, with a constant diameter of 0.2 mm) and dosages (1%, 3% and 6%) on the mechanical properties of

ultra-high performance fiber reinforced concrete (UHPFRC). A 37% increase in the flexural peak load is observed for the beam incorporating 1% of 16 mm fibers compared to that of the control specimens. However, at similar fiber dosage, short fibers are better on capturing the growth of micro-cracks, yielding more inhibition effect on macro-crack formation. Yu et al. [13] investigated the static properties and impact resistance of hybrid fiber reinforced ultra-high performance concrete. The largest compressive strength of the composite with 1.5 vol.% long steel fibers (length of 13 mm and diameter of 0.2 mm) and 0.5 vol.% short steel fibers (length of 6 mm and diameter of 0.16 mm) is 117.1 MPa after curing for 28 days, which is 18.3% higher than that of composites without fibers. The flexural strength increases up to 70.1% at 28 days. Yu et al. [14] also studied the multiple effects of nano-silica and hybrid fibers on the properties of UHPFRC incorporating waste bottom ash (WBA). When the steel fiber content (length of 13 mm, diameter of 0.2 mm) is 2% in volume, the compressive strength and the flexural strength are increased by 35.8% and 74.1% compared with that of composites without fiber, respectively. Micro steel fibers with a length of 13 mm and a diameter of 0.2 mm were used in the study on UHPFRC by Yoo et al. [15]. The highest compressive strength is found to be 207.2 MPa for the specimen with 3% micro steel fibers. The flexural strength of the composite with 4% fibers is found to be 35.1 MPa.

The three-dimensional network of fibers can restrict the generation, propagation and convergence of internal micro-cracks, consequently improving the mechanical properties of cement-based materials [10, 13]. For some applications such as highway road surface, however, some measures (e.g. opening the leveling beam of concrete paver or three-roller-axle unit) should be taken to ensure that steel fibers in concrete layer are not upright and upwarp, meeting the requirement of road surface use safety. In addition, exposed fibers are easy to rust. If the fiber diameter is reduced by one order of magnitude on the basis of previous research and the texture shifts from steel to stainless, the above problems could be avoided. Meanwhile, this super-fine

fiber material, named short-cut super-fine stainless wire (SSSW), is easier to form extensive three-dimensional enhancement network, and is expected to improve the toughness of RPC further. Other studies have shown that the abrasion resistance of concrete increases obviously with the increase of compressive strength [20]. That is to say, if the incorporation of SSSWs can improve the compressive strength of RPC, the SSSW reinforced RPC (SSSWRRPC) will get better abrasion resistance as well. There are no relevant reports about the mechanical properties of SSSWRRPC so far.

Based on the above analysis, different contents of SSSW with diameter of 8 μm and 20 μm were introduced to prepare wire reinforced RPC in this study. The effects of SSSWs on mechanical strength and toughness of RPC were investigated. The bonding state between SSSWs and RPC matrix and the wire dispersion were studied through microstructure analysis. The reinforcing mechanism of SSSW to RPC was explored and the **phenomenological** calculation models of flexural strength and toughness **that rely on parameter fittings** were established.

2 Experimental schemes

2.1 Raw material and mix proportion

The Portland cement (P·O 42.5R) produced by Dalian Onoda Cement Co. Ltd. in China was used in this study. Silica fume used was a commercially available product of Shanghai Tian Kai Silicon Fume Co. Ltd. in China. The secondary fly ash provided by Dalian Daokete Building Materials Co. Ltd. in China was used. Quartz sand with a size range of 0.12-0.83 mm was used. The SiO_2 and Fe_2O_3 content of quartz sand is more than 99-99.5% and less than 0.005% respectively. RHEOPLUS 411 (BASF) was used as a superplasticizer to adjust the workability of the concrete mixtures. Short-cut super-fine stainless wire (SSSW) with diameter of 8 μm and 20 μm and length of 10 mm was employed in this study. The elongation of the SSSW is more than 1%, and the tensile strength can reach up to 1200-1800 MPa.

The proportioning used in this study was based on that proposed by RICHARD [21] in 1995,

and the ratio of cement (C), silica fume (SF), quartz sand (QS), water (W) was equal to 1:0.25:1.1:0.3. The content of superplasticizer (SP) was adjusted according to the amount of SSSW, ensuring that the concrete mixture can be easily molded and there is no bleeding after vibration. In order to improve the mobility of RPC and reduce the cement content per cubic meter, the fly ash was used to replace 20% of cement. The SSSW was added in the amount of 0, 0.5%, 1.0% and 1.5% by volume of RPC, which is equivalent to 0, 3.99kg/m³, 7.98kg/m³ and 11.97kg/m³. The SSSW reinforced RPC (SSSWRRPC) was marked as W0, W08 (W0805, W0810, W0815), and W20 (W2005, W2010, W2015).

2.2 Specimens preparation

The cement mortar mixer was used to stir SSSWRRPC, at low speed of 140±5r/min and high speed of 285±10r/min. First, cement, silica fume, fly ash, SSSW, water and half of superplasticizer were put into mixing pans together, stirring one minute at low speed and four minute at high speed separately. Second, quartz sand was put into the slurry, stirring one minute at low speed. Third, the other half of superplasticizer was put into the SSSWRRPC, stirring four minute at high speed. During the experiment, low-speed stirring can prevent the spilling of powder, while high-speed stirring is conducive to wire dispersion.

The mixtures after stirring were put into oiled molds. They were put onto the vibrating table until shaking to an extent of oozing slurry on the surface of specimens. Next, all specimens of 40 mm × 40 mm × 160 mm were put in standard curing chamber and then demolded after 24 hours. In order to study the effect of curing environment, a series of specimens were cured in water at 20 °C until certain curing ages, and the other specimens were exposed to air after water curing for 14 days (called “natural curing” in this study).

2.3 Measurement of mechanical properties

The flexural strength was measured by universal electronic testing machine WDW-200E, according to <Method of testing cements-determination of strength-ISO> GB/T17671-1999 of

China. The distance between supports was equal to 100 mm, and the loading rate was 0.05 mm/min. During the loading, the bottom midspan flexural-tensile strain was measured by use of strain gauges (BX120-50AA, provided by Zhejiang Huangyan Test Instrument Co. Ltd., China) perpendicular to the loading direction for flexural-tensile stress-strain analysis. The strain signals were collected using a strain reader DC-204R provided by Tokyo Sokki Kenkyujo Co. Ltd.. The middle deformation parallel to loading was measured by a deformation sensor for toughness analysis. The final value of flexural strength and flexural-tensile strain were the average of three specimens.

The compressive strength was also measured according to <Method of testing cements-determination of strength-ISO> GB/T17671-1999 of China. The specimens of 40 mm × 40 mm × 160 mm were broken in two near the middle after flexural test. The two pieces were measured by using compression testing machine YAW-2000D provided by China Jinan Era Assay Testing Machine Co. Ltd. and using test fixture with contact area of 40 mm × 40 mm. The loading rate was 1.2 mm/min. The average of six specimens was used to evaluate compressive strength of the composites. Meanwhile, the vertical deformation was also collected by a deformation sensor for load-deformation analysis.

The microstructure of SSSWRRPC was observed and photographed using a scanning electron microscope (NOVA NANOSEM450 provided by FEI Inc., USA).

3 Results and analysis of mechanical behaviors

3.1 Flexural behaviors

3.1.1 Flexural strength

The flexural strength of SSSWRRPC is shown in Fig.1. It can be seen from Fig.1 that the flexural strength increases with the increase of SSSW content and diameter. When the SSSW content is 1.5%, the flexural strength of W20 is increased by 100.7%, 70.5% and 103.2% for specimens after water curing for 3 days, water curing for 28 days and natural curing for 28 days

respectively, compared to that of RPC without SSSWs. Meanwhile, the flexural strength of W08 is raised by 68.9%, 47.6% and 77.1%, respectively. Under flexural loading, micro-cracks initiate randomly at the bottom side of RPC, and then propagate and converge quickly, generating a negative effect on the flexural strength. The incorporation of SSSWs can inhibit the coalescence of the micro-cracks, which in turn resists the propagation of crack and shield the crack tip stress.

Fig.1 The effect of SSSW content and diameter on the flexural strength of SSSWRRPC cured at different regimes

Fig.2 The effect of curing regimes on the flexural strength of SSSWRRPC

Fig.2 show that the flexural strength of SSSWRRPC changes with curing regimes. The flexural strength of W0 increases with water curing ages, but decreases with natural curing ages. This phenomenon mainly depends on the hydration product characteristic of RPC, which is dominated by C-S-H gel and has less calcium hydroxide crystals. As a result, the micro-cracks are easily to be generated due to volume shrinkage in dry condition [22]. When the SSSW content is low, the restriction is too small to prevent the development of shrinkage cracks, and the incorporation of SSSWs makes the porosity larger than that of composites without wires. These are why the flexural strength after natural curing for 28 days falls significantly from that after water curing for 3 days (numbers illustrated in Fig.2). However, for W0815 and W2015, the SSSWs are close enough to prevent crack convergence. The flexural strength of them after water curing for 28 days is slightly lower than that after water curing for 3 days, within the error of 10%. This can be attributed to the effect of high porosity due to the incorporation of SSSWs.

3.1.2 Analysis of flexural load-deformation

The fracture energy of fiber reinforced cement-based materials characterized the flexural toughness of composites is represented by the area under load-deformation curve. The load-deformation curves and the corresponding fracture energy of SSSWRRPC are shown in Fig.3. In this study, the load-deformation curves include a load adjustment process because of specimen size and experimental condition. It can be seen from Fig.3 that the load-deformation curve of W0 falls sharply after reaching the ultimate load, which represents typical brittle fracture. The incorporation of W08 does not change the brittleness. When the contents of 20 μm SSSW are 1.0% and 1.5%, the load-deformation curves decrease slowly, i.e. the W2010 and W2015 still have a certain carrying capacity in the case of large deformation. This means that the fracture behavior of SSSWRRPC is transforming from brittleness to plasticity.

Fig.3 (b), (d) and (e) show that the fracture energy of SSSWRRPC decreases significantly with the curing ages from 3 days to 28 days either water curing or natural curing, which can be

attributed to the effect of water erosion and shrinkage micro-cracks. The results also show that the fracture energy increases with the increase of SSSW content. Compared to W0, the fracture energy of W2010 and W2015 is increased by 272.2% and 442.2% after water curing for 3 days respectively, 111.7% and 173.0% after water curing for 28 days respectively, and 142.2% and 293.2% after natural curing for 28 days respectively. These increments can be attributed to the pull-out effect of SSSW.

(a) Load-deformation, water curing for 3 days

(b) Fracture energy, water curing for 3 days

(c) Load-deformation, water curing for 28 days

(d) Fracture energy, water curing for 28 days

(e) Load-deformation, natural curing for 28days

(f) Fracture energy, natural curing for 28 days

Fig.3 The flexural load-deformation curves and fracture energy of SSSWRRPC

Fig.4 Crack development and SSSWs

The pull-out process of SSSW is an energy-consuming process [7, 23], which can be represented by Fig.4 [24]. Fig.4 shows the interaction between crack development and SSSW bridging. Under flexural loading, the cracks first appear at the bottom midspan of specimens, then a small part of SSSWs debonds from cement matrix but most of them still can bridge micro-cracks. After that, the stress re-distribution appears and the SSSWs are beginning to be pulled out. The pull-out of SSSWs increases the load of neighboring wires across cracks, which results in that more SSSWs are pulled out from the matrix. As the flexural loading increases, fracture energy continues to increase with more formation of cracks.

3.1.3 Analysis of flexural stress-strain

Under flexural loading, the relationship between the bottom midspan flexural-tensile stress and strain is shown in Fig.5. Fig.5 shows that the initial ascending stage of the flexural-tensile stress-strain curves does not vary with the SSSW incorporation, which represents that SSSW has no effect on the tensile modulus of RPC. After the elastic stage, the rising rate of stress-strain curves decreases, and the curves gradually close to x axial, showing the specimens have gone into plastic deformation region. With the increase of SSSW content and diameter, the linear stage i.e. proportional limit increases, and the distance between proportional limit and peak stress increases too. Meanwhile, the descending stage of the flexural-tensile stress-strain curves becomes slow. The experimental results also show that the peak stress of SSSWRRPC increases with the

increase of wire content. For W0815, W2010 and W2015, the peak strain increases significantly. Compared to W0, the peak strains are increased by 47.8% and 95.1% for W0815 after water curing and natural curing for 28 days respectively. Meanwhile, the ratios of increment can reach up to 69.8% and 39.7% for W2010, and they are 118.3% and 144.6% for W2015 respectively. The peak strains of W0815 and W2015 after natural curing for 28 days are larger than that after water curing for 28 days due to the micro-cracks generated by shrinkage.

(a) Flexural-tensile stress-strain curves, water curing for 28 days

(b) Flexural-tensile peak strain, water curing for 28 days

(c) Flexural-tensile stress-strain curves, natural curing for 28 days

(d) Flexural-tensile peak strain, natural curing for 28 days

Fig.5 Flexural-tensile stress-strain curves and peak strain of SSSWRRPC

During the experiments, the W0 specimens suddenly part into half after peak stress, but the SSSW reinforced specimens still remain intact after failure, with one main large crack on the bottom. With the increase of SSSW content, the development path of the main large crack becomes longer. Additionally, there is a tendency for multiple cracking to appear. This phenomenon is consistent with the change rule of stress-strain curves, and represents the

transformation of SSSWRRPC fracture behavior. By comparison, the SSSW has more significant influence on the fracture energy than flexural strength and flexural-tensile peak strain.

3.2 Compressive behaviors

3.2.1 Compressive strength

The compressive strength of SSSWRRPC is shown in Fig.6. Fig.6 shows that the compressive strength increases with the increase of SSSW content. This can be attributed to that the SSSWs restrict the internal material deterioration and crack propagation by absorbing the developed stress at the SSSW's tip [10]. The results also show that the compressive strength of W20 is higher than that of W08. When the content of SSSW in diameter of 20 μm is 1.5 vol. %, the compressive strength is increased by 25.1% and 18.9% after water and natural curing for 28 days respectively. Compared to Fig.1, the rangeability of compressive strength is far lower than that of flexural strength, which is in accordance with previous research [16].

Fig.6 The effect of SSSW content and diameter on the compressive strength of SSSWRRPC cured at different regimes

Fig.7 The effect of curing regimes on the compressive strength of SSSWRRPC

It can be seen from Fig.7 that the compressive strength of SSSWRRPC increases with curing ages, while the compressive strength after natural curing for 28 days is higher than that after water curing for 28 days. This indicates that the micro-cracks mentioned previously have no adverse effect on compressive strength. However, the water curing has a negative impact on compressive strength, especially for W0810 and W0815. Because of high aspect ratio, the molding becomes slightly difficult and the compactness is relatively lowered when the SSSW content is high. Therefore, the W0810 and W0815 tend to be more influenced by water erosion. The compressive strength of W0 after water curing is increased by 83.5% with the ages from 3 days to 28 days, which can be attributed to the increase of the hydration products and structure compactness. By comparison, the change of compressive strength is mainly determined by RPC matrix.

3.2.2 Analysis of compressive load-deformation

The compressive load-deformation curves of SSSWRRPC are shown in Fig.8. The area under compressive load-deformation curve is called compressive toughness [25]. It can be seen from Fig.8 that the SSSWRRPC is mostly in elastic stage when it is subjected to relatively small compressive loading. With the loading increase, the ascending stage of load-deformation curves moves toward x axial gradually, showing the SSSWRRPC enters into plastic deformation stage. The compressive load-deformation curve of W0 drops sharply after failure, and the specimens

fall into pieces momentarily. The load-deformation curves for wire reinforced specimens exhibit ductile behavior, with steadier drop of load carrying capacity. This can be attributed to the lateral expansion restriction of wires, resulting in high tolerance to axial deformation.

(a) Compressive load-deformation curves, water curing for 3 days

(b) Compressive toughness, water curing for 3 days

(c) Compressive load-deformation curves, water curing for 28 days

(d) Compressive toughness, water curing for 28 days

(e) Compressive load-deformation curves, natural curing for 28 days

(f) Compressive toughness, natural curing for 28 days

Fig.8 The compressive load-deformation curves and compressive toughness of SSSWRRPC

Fig.8 (b), (d) and (f) show that the compressive toughness of SSSWRRPC has a substantial

increase because of the addition of SSSW. The toughness of the composite with SSSW in diameter of 20 μm is better than that of the composite with SSSW in diameter of 8 μm . The toughness of SSSWRRPC after water curing for 28 days is higher than that after natural curing for 28 days. That is to say, erosion generated by water curing has no adverse impact on the toughness of SSSWRRPC, although it has negative effect on the compressive strength. However, the micro-cracks generated by natural curing limit the increase of compressive toughness.

During the experiment process, the SSSWRRPC specimens make a big noise when approaching the peak load and the deformations become gradually larger, until completely crushed. The specimens of W0 break into pieces after failure, while the SSSW reinforced specimens show an insignificant fragmentation due to the confinement effect of SSSWs.

4 Microstructure analysis and calculation models of flexural strength and toughness

4.1 Microstructure analysis

SEM images of RPC matrix after water and natural curing for 28 days are presented in Fig.9. Fig.9 shows that the RPC matrix is very compact and essentially composed of hydration products resembling C-S-H gel, with fewer CH and AFt crystals due to the poor formation conditions [26]. Unhydrated fly ash particles are easy to be found, and have compact interface with cement hydration products. Fig.9 (a) shows that the loose structure is observed in water curing specimens due to water erosion. Meanwhile, Fig.9 (b) shows that the more micro-cracks exist in natural curing specimens. This is why the flexural strength of SSSWRRPC at 28 days is lower than that at 3 days.

Fig.10 shows the interface state of SSSWs in SSSWRRPC. It can be seen from Fig.10 that the SSSW surface is covered by hydration products, mainly C-S-H gel. As a result, the SSSWs have high bond strength with cement-matrix, which are not subjected to SSSW parameter and curing regimes. Fig.11 shows the reinforcement mechanism of SSSW in RPC. The pull-out, contortion and stripping of SSSWs can be observed in Fig.11, and the above process needs to

overcome shear friction and consume energy. The SSSW crossing cracks is rarely observed, which means that the reinforcement mechanism of SSSW on cement-based materials is different from that of steel fiber with diameter in millimeter.

(a) Water curing for 28 days

(b) Natural curing for 28 days

Fig.9 Microstructure of RPC matrix

(a) W0810, water curing for 28 days

(b) W2005, natural curing for 28 days

Fig.10 The surface of SSSW

(a) Pull-out of SSSWs

(W2005, water curing for 28 days)

(b) Contortion and stripping of SSSWs

(W0810, water curing for 28 days)

Fig.11 The pull-out, contortion and stripping of SSSWs in SSSWRRPC

Fig.12 The dispersion of SSSWs (water curing for 28 days)

It can be seen from Fig.12 that the dispersion of SSSW in diameter of 20 μm is superior to that of SSSW in diameter of 8 μm . More stripping traces are observed in the microscopic images of W08 due to the limited enhancement. Because of high aspect ratio, the distance between SSSWs is small, and the phenomenon of curling, bending and clustering is easy to emerge. This limits the exertion of bridging and stress transfer of SSSW, especially for W08.

Based on the above analysis, the three-dimensional overlapping network of SSSWs can retard the development of micro-cracks. The pull-out, contortion and stripping of SSSWs can improve the mechanical properties, toughness and deformation of SSSWRRPC.

4.2 Calculation model of flexural strength

According to composite theory, the tensile strength of fiber reinforced cement-based composites can be calculated based on Equation (1).

$$\sigma_c = \sigma_m(1 - V_f) + \bar{\sigma}_f V_f \quad (1)$$

where σ_c is the tensile strength of composite, MPa; σ_m is the tensile strength of concrete matrix; V_f is the volume content of fiber, mm^3 ; $\bar{\sigma}_f$ is the average tensile strength of fiber.

There is a liner relation between flexural strength and tensile strength of fiber reinforced cement-based composites, as shown in Equation (2).

$$\sigma_{ct} = \alpha \sigma_c \quad (2)$$

Therefore, the flexural strength of SSSW reinforced RPC can be calculated based on Equation (3).

$$\sigma_{ct} = \alpha(\sigma_m(1 - V_f) + \bar{\sigma}_f V_f) = \sigma_{mt}(1 - V_f) + \alpha\eta_l\eta_\theta\sigma_{fmax}V_f \quad (3)$$

where $\alpha=2.0$ according to the research of Krenchel [27]; σ_{mt} is the flexural strength of RPC matrix; η_θ is the orientation factor and $\eta_\theta = 0.20$ for three-dimensional disordered SSSWs; σ_{fmax} is the maximum tensile strength of SSSW; η_l is the length factor. The length factor is closely related to the critical length and damage state of SSSW. The critical length of SSSW can be expressed as Equation (4).

$$l_f^{crit} = \frac{d_f\sigma_{fmax}}{2\tau} \quad (4)$$

where l_f^{crit} is the SSSW critical length; d_f is the SSSW diameter, mm; and τ is the bond strength between SSSWs and RPC matrix, MPa.

According to the existing research [27], if the SSSW length (l_f , mm) is larger than critical length, the damage state of SSSW will be mainly dominated by tensile failure; and on the contrary, the damage state of SSSW will be based on pull-out. As a result, the corresponding η_l can be expressed as Equations (5) and (6) respectively.

$$\eta_l = 1 - \frac{l_f^{crit}}{2l_f} \quad l_f > l_f^{crit} \quad (5)$$

$$\eta_l = \frac{l_f}{2l_f^{crit}} \quad l_f \leq l_f^{crit} \quad (6)$$

Based on microstructure analysis (as shown in Fig.11), the SSSWs are pulled out from the RPC. The Equation (6) should be chosen for the calculation of η_l . Then the flexural strength of SSSW reinforced RPC can be expressed as Equation (7).

$$\sigma_{ct} = \sigma_{mt}(1 - V_f) + \alpha\eta_\theta \frac{l_f}{d_f} V_f \tau \quad (7)$$

Meanwhile, the relationship between the flexural strength of SSSWRRPC and V_f (as shown in Fig.1 (a), (b) and (c)) can be analyzed using quadratic polynomial. The fitting results

are shown in Table 1.

Table 1 the relationship between flexural strength of SSSWRRPC (σ_{ct}) and V_f				
Curing condition	SSSW	Fitting results		R^2
Water curing for 3 days	W08	$\sigma_{ct} = 6.81 + 5.73 \times (100 V_f) - 1.73 \times (100 V_f)^2$	0.999	
	W20	$\sigma_{ct} = 6.81 + 7.01 \times (100 V_f) - 1.60 \times (100 V_f)^2$	0.999	
Water curing for 28 days	W08	$\sigma_{ct} = 7.69 + 3.92 \times (100 V_f) - 1.03 \times (100 V_f)^2$	0.999	
	W20	$\sigma_{ct} = 7.69 + 4.23 \times (100 V_f) - 0.40 \times (100 V_f)^2$	0.999	
Natural curing for 28 days	W08	$\sigma_{ct} = 6.51 + 2.13 \times (100 V_f) + 0.83 \times (100 V_f)^2$	0.999	
	W20	$\sigma_{ct} = 6.51 + 3.24 \times (100 V_f) + 0.80 \times (100 V_f)^2$	0.999	

Here, we propose that the bond strength is composed of chemical bond strength and frictional force due to confining action, according to microstructure analysis. Meanwhile, the bond strength is affected by curing condition and the confining action around SSSWs is closely related to V_f . As a result, the bond strength τ can be expressed as Equation (8).

$$\tau = A\tau_c + A\mu\sigma_n = A\tau_c + A\mu BV_f \quad (8)$$

where A is the coefficient caused by curing condition; τ_c is the chemical bond strength; μ is the frictional coefficient; σ_n is the confining pressure; B is the correlation coefficient between confining pressure and the volume content of SSSWs.

Based on Equations (7) and (8), the flexural strength expression of SSSWRRPC should be modified to Equation (9).

$$\sigma_{ct} = \alpha\eta_\theta \frac{l_f}{d_f} AB\mu V_f^2 + \left(\alpha\eta_\theta \frac{l_f}{d_f} A\tau_c - \sigma_{mt} \right) V_f + \sigma_{mt} \quad (9)$$

As a result, the bond strength corresponding to different curing condition and volume content of SSSWs can be deduced from Table 1 and Equation (9), as shown in Table 2.

Table 2 The bond strength between SSSWs and RPC matrix (MPa)					
Curing condition	SSSW	The expression of τ	The bond strength ($V_f=0.5\%, 1.0\%, 1.5\%$)		
Water curing for 3 days	W08	$\tau = 1.160 - 34.6 V_f$	0.987	0.814	0.641
	W20	$\tau = 3.539 - 80.0 V_f$	3.139	2.739	2.339
Water curing for 28 days	W08	$\tau = 0.799 - 20.6 V_f$	0.696	0.593	0.490
	W20	$\tau = 2.153 - 20.0 V_f$	2.053	1.953	1.853
Natural curing for 28 days	W08	$\tau = 0.439 + 16.6 V_f$	0.522	0.605	0.688
	W20	$\tau = 1.652 + 40.0 V_f$	1.852	2.052	2.252

Table 2 shows that the bond strength between SSSWs and RPC matrix mainly depends on chemical bond strength, which is also affected by curing condition and volume content of SSSWs. By comparison, the effect of curing condition on friction force is the same as that on compressive strength of SSSWRRPC. Meanwhile, the effect of curing condition on chemical bond strength is the same as that on flexural strength. This indicates that the interface bond state between SSSWs and RPC matrix has important influence on the flexural behavior of SSSWRRPC. The expression of bond strength can be used to calculate flexural toughness.

4.3 Calculation model of flexural toughness

Pigott [28] proposed that the flexural toughness of short fiber reinforced cement-based composites is mainly determined by fiber pull-out, and they also proposed the fiber pull-out energy calculation methods, which depend on fiber length and damage state. The fiber pull-out energy is equal to the increment value of fracture energy. Fig.11 shows that the damage state of SSSWs is pull-out. Therefore, the calculation method of the pull-out energy of SSSWs is shown as Equations (10) - (12), based on Pigott's theory.

The average pull-out energy of one single SSSW can be expressed as Equations (10).

$$\overline{W_P} = \frac{1}{24} \pi d_f \tau l_f^2 \quad (10)$$

SSSW numbers per unit volume can then be described by Equations (11).

$$N = \frac{V_f}{l_f A_f} \quad (11)$$

The pull-out energy of SSSWs in SSSWRRPC can be given by Equations (12).

$$W_P = C \cdot N \cdot \overline{W_P} = C \cdot \frac{V_f}{l_f A_f} \cdot \frac{1}{24} \pi d_f \tau l_f^2 = C \frac{1}{6} \frac{l_f}{d_f} \tau V_f \quad (12)$$

The parameter C is put forward as the effectiveness coefficient of SSSW numbers caused by the cluster of SSSWs, which is determined mainly by wire distance S and aspect ratio. The SSSWs are easy to cluster with the decrease of wire distance and the increase of aspect ratio,

representing the decrease of effective coefficient. The wire distance S can be calculated using the formula proposed by Romualdi et al. [29], and $S = 13.8 \frac{d_f}{\sqrt{V_f}}$. As a result, we propose that the effective coefficient is expressed as Equation (13).

$$C = \frac{13.8 \frac{d_f}{\sqrt{V_f}}}{K(\frac{1}{100V_f d_f} + \varepsilon)} \times 1000 \quad (13)$$

where K is determined by curing condition and volume content; $\varepsilon = 80$, which is determined by the conventional aspect ratio (60~80) of fiber; 1000 is the unit conversion factor.

Curing condition	SSSW	K	Theoretical results	Experimental results	Theoretical results/ experimental results
Water curing for 3 days	W0805	$\frac{1}{200}$	77.7	68.7	1.13
	W0810		175.9	173.1	1.02
	W0815		246.8	251.8	0.98
	W2005	$\frac{1}{70}$	206.9	124.3	1.66
	W2010		475.0	466.2	1.02
	W2015		698.1	757.5	0.92
Water curing for 28 days	W0805	$\frac{1}{150}$	41.1	48.1	0.86
	W0810		96.1	83.7	1.15
	W0815		141.6	148.1	0.96
	W2005	$\frac{1}{30}$	57.9	63.7	0.91
	W2010		145.3	160.6	0.90
	W2015		236.8	248.7	0.95
Natural curing for 28 days	W0805	$\frac{1}{190}$	39.1	43.1	0.91
	W0810		124.2	125.0	0.99
	W0815		251.7	133.1	1.89
	W2005	$\frac{1}{35}$	60.0	136.9	0.44
	W2010		178.0	170.6	1.04
	W2015		335.8	351.9	0.95

Based on Equations (12) and (13) and the bond strength in Table 3, the modified theoretical increment value of fracture energy is calculated. The theoretical and experimental results are shown in Table 3. Table 3 shows that the pull-out energy of SSSWs calculated by the modified theoretical Equation (12) is in accordant with the experimental results. The error can be controlled in 15%, except only three data. The results verifies that the incorporation of SSSWs has remarkable toughening effect on RPC, retarding the crack of matrix and then improving the energy absorbing capability of SSSWRRPC due to the pull-out of SSSWs under loading. The

effective coefficient of SSSW numbers should be further proved in the follow-up experiments.

5 Conclusions

SSSWs were added into RPC to develop high-performance concrete in this paper. Due to high aspect ratio, SSSWs are more likely to form extensive three-dimensional reinforcing network at low dosages compared to ordinary macro steel fiber, and its stainless steel texture is resistant to corrosion. Meanwhile, the homogeneous microstructure of RPC makes it possible to disperse SSSW uniformly inside matrix material. The mechanical strength, toughness and stress-strain behavior of SSSWRRPC were investigated. The reinforcement mechanism was studied through microstructure analysis. The calculation models of flexural strength and toughness were also established.

The flexural behavior of SSSWRRPC has been improved significantly due to the addition of SSSW. When the content of 20 μm SSSW is 1.5 vol. %, the increase of flexural strength reaches up to 103.2%, while the maximum fracture energy increased 442.2% compared with that of composites without SSSW. The increment of flexural-tensile strain can reach up to 144.6%. Natural curing appeared to have more adverse effect on flexural strength than fracture energy and flexure-tensile strain. The compressive strength and toughness of SSSWRRPC can increase by 18.9% and 214.6% respectively after natural curing for 28 days. The curing condition has different influence on compressive strength and toughness.

The SSSW has strong interfacial bond with RPC matrix, and the dispersion of SSSWs in diameter of 20 μm is superior to that in diameter of 8 μm . The reinforcement mechanism is mainly the pull-out, contortion and stripping of SSSWs. The expression of bond strength is proposed for setting up the modified calculation model of flexural strength. The effective coefficient of SSSW numbers is put forward based on wire distance and aspect ratio for calculating the flexural toughness of SSSWRRPC.

This study verified the feasibility of composing SSSW and RPC to develop

high-performance cement-based materials. Meanwhile, the use of SSSW can avoid the detrimental effect caused by the exposure of ordinary steel fiber. The developed SSSWRRPC will be the preferred material for long-span and thin-plate construction due to its high toughness. Future work on the proposed SSSWRRPC will include investigations on dynamic behaviors, long-term mechanical performance, durability and application of the SSSWRRPC under realistic field conditions.

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Strength:

$$\sigma_{ct} = \alpha \eta_0 \frac{l_f}{d_f} AB \mu V_f^2 + \left(\alpha \eta_0 \frac{l_f}{d_f} A \tau_c - \sigma_{mt} \right) V_f + \sigma_{mt}$$

Toughness:

$$W_p = C \cdot \frac{V_f}{l_f A_f} \cdot \frac{1}{24} \pi d_f \tau l_f^2 = C \frac{1}{6} \frac{l_f}{d_f} \tau V_f$$

Theoretical models of strength and toughness