Electrically conductive behaviors and mechanisms of short-cut super-fine stainless wire reinforced reactive powder concrete

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Abstract:

The incorporation of short-cut super-fine stainless wire (SSSW) is an effective way to improve the electrically conductive and self-sensing capability of reactive powder concrete (RPC) composed of cement, silica fume, fly ash and silica sand. The conductive characteristics of SSSW reinforced RPC and their responses to external loading are investigated. The conductive mechanisms are revealed through electrochemical impedance spectroscopy and intrinsic conductivity analysis. The results show that the percolation occurs and polarization disappears in SSSW reinforced RPC containing 0.5 vol.% of SSSW in diameter of 20 μm , and the electrical resistivity of which measured by using four-electrode-DC method drops to 44 $\Omega\cdot\text{cm}$ from $20.8\times 10^4 \Omega\cdot\text{cm}$. The gauge factor of RPC reinforced with SSSW 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 conductivity of SSSW reinforced RPC mainly depends on the formation of SSSW conductive network.

Key words: Short-cut super-fine stainless wire; Reactive powder concrete; Electrical resistivity; Piezoresistive response; Conductive mechanism

1 Introduction

Structural Health Monitoring (SHM), which can provide real-time data on the conditions of infrastructures, is necessary for large concrete structure in the life cycle. The intrinsic self-sensing concrete provides a new sensing approach for SHM. It is fabricated through adding such functional fillers as carbon fibers, steel fibers, carbon nanotubes (CNTs), and nickel powders into conventional concrete to generate ability of sensing the strain, stress, crack, damage, or temperature in itself while maintaining or even improving its mechanical properties [1-9]. Meanwhile, this multi-functional and smart concrete has been applied to a wide range of situations, such as electrical grounding, electrical contacts for cathodic protection, deicing, electromagnetic interference (EMI) shielding, and antistatic flooring [10, 11]. The intrinsic self-sensing behavior of concrete was firstly investigated in 1992 with the incorporation of short carbon fibers [12]. Since then, much research work has been done on sensing behaviors, mechanisms and structural application of intrinsic self-sensing concrete with different functional fillers under different loadings and environments [7]. Up to now, the intrinsic self-sensing concrete with chopped carbon fiber is still one of the most extensively and comprehensively studied composites. Fu et al. [13] observed that the change in electrical resistance of concrete with 0.51% ozone-treated carbon fiber can reach 45%. Shi et al. [14] found that the strain sensitivity (gauge factor, i.e. fractional change in electrical resistivity per unit strain) of concrete containing a small amount (typically 0.2-0.5 vol.%) of short carbon fibers is as high as 700. The self-sensing concrete with carbon fibers is also effective for

sensing impact damage under impact stress [15]. Compared to carbon fibers, the extremely high aspect ratio, hollow structure and low density of CNTs make them easy to form a conductive and mechanical reinforcement network inside concrete with a CNT concentration level as low as 0.05 wt.%. Yu et al. [16] investigated the piezoresistive property of the CNTs/cement composite to explore its feasibility as a stress sensor for civil structures such as roadways, levees and bridges. They found that the fractional change in electrical resistance of cement with 0.1 wt.% multi-walled CNTs can reach 11.4% under 8.2MPa of cyclic compressive loading. Azhari et al. [17] investigated the sensing ability of electrical conductive cement-based composites containing carbon fibers and CNTs. They found that the composites, containing a combination of carbon fibers and CNTs, provide better quality signal, improved reliability and increased sensitivity over composites carrying carbon fiber alone. Materazzi et al. [18] explored the applicability of CNTs cement-based sensors for measuring dynamically varying strain in concrete structures.

However, the cement-based material and carbonic filler have a poor compatibility, so the effective dispersion technology and dispersing agents are needed [7-8, 19]. This complicates the composite preparation process, reduces the performance stability, and increases the material cost. Furthermore, the matrix of intrinsic self-sensing concrete now being studied is mainly cement paste or cement mortar. This cannot meet the requirement of high strength and durability of important infrastructures. Meanwhile, carbonic fibers could not withstand bending under shear stress because of their brittleness. Therefore, the bridging carbonic fibers are bent

sharply, which makes the damage sensing become difficult [20].

Micro steel/stainless fiber (having comparative diameter with carbon fiber) has excellent dispersion capability, toughness and interfacial bond strength with concrete matrix compared with carbonic fiber, in favor of sensing damage and crack propagation. In addition, the high aspect ratio makes it easy to form conductive network, thus further improving the conductivity of cement-based materials. However, the research on the conductivity of micro steel/stainless fiber reinforced cement-based materials is limited. Banthia et al. [2] found that the conductivity of cement mortar could be improved about one order of magnitude by incorporation of steel fibers with diameter of 25 μm and length of 3 mm. The piezoresistivity of stainless steel fiber (in diameter of 60 μm , length of 5 mm and amount of 0.1 vol.%) reinforced cement paste under compression was researched by Chung et al. [21]. Chung [3] also studied the conductive behavior of cement paste containing 0.36 vol.% and 0.72 vol.% of short stainless steel fibers processed by polyvinyl alcohol binder with a diameter of 8 μm . The results showed that the resistivity of the cement paste composites can reach $57\pm 4 \Omega\cdot\text{cm}$ and $16\pm 1 \Omega\cdot\text{cm}$ respectively, which are far lower than that of cement paste with 0.5 vol.% carbon fibers. Teomete et al. [22] observed that the highest gauge factor (which is defined as the ratio of fractional change in electrical resistivity to splitting tensile strain) of copper coated steel fiber (length of 6mm) reinforced cement-based composite under tensile strain is 5195, 2600 times higher than that of commercial metal strain gages, but the diameter of the steel fiber was not mentioned. Except for strain sensing [23], the micro steel/stainless fiber reinforced concrete is more effective

for electrical grounding, electromagnetic interference and deicing [24]. Wen et al. [25] found that the EMI shielding effectiveness of cement paste with 0.72 vol.% of stainless steel fibers (diameter of 8 μm and length of 6 mm) reaches up to 70 dB at 1.5 GHz. Based on the above studies, the combination of high aspect ratio and unique mechanical properties makes micro steel/stainless fiber become ideal multi-functional filler for cement-based materials. Meanwhile, the full realization of composition effect of micro steel/stainless fiber needs uniform and compact matrix structure, especially high-performance concrete such as reactive powder concrete (RPC).

The first study of RPC was conducted by Richard et al. in 1995 [26]. RPC, also sometime referred to ultra-high performance fiber reinforced concrete, is usually composed of cement, ultra-fine powders such as crushed quartz and silica fume, superplasticizer and short steel fibers (the commonly used diameter is 150-250 μm and aspect ratio is 60-80). Compared to common cement-based materials, RPC has compact microstructures, low porosity and less interfacial transition zone [26-29]. The mechanical properties of RPC are excellent. For example, the compressive strength can reach up to 150-200 MPa, the fracture energy is up to 1200-40000 J/m^2 , and the ultimate tensile strain can be on the order of 1% [30-33]. Nowadays, RPC is regarded as a promising material for special prestressed and precast concrete members, including those used in nuclear waste storage facilities [34, 35]. With the development of structure health monitoring technology, the intrinsic self-sensing RPC will certainly become research hotspot in the future, especially for long-span and durable infrastructures. However, the common-used carbonic fibers can bring negative effect

or can only have limited improvement on the mechanical behaviors of concrete because of their poor dispersion. In addition, the compact and homogenous microstructures of RPC are beneficial for forming extensive three-dimensional overlapping network of micro steel/stainless fiber. Therefore, the introduction of micro steel/stainless fiber is an effective way to help RPC become conductive, self-sensing, and more ductile material. In order to differ from the commonly used steel fiber of RPC, this kind of micro stainless/steel fiber having comparative diameter and length with carbon fibers is called short-cut super-fine stainless/steel wire. Research results indicate that the short-cut super-fine stainless wire (SSSW) can effectively improve the mechanical properties of RPC [36]. However, the research about the functional properties of SSSW reinforced RPC has not been carried out.

In this study, the SSSW with diameter of 8 μm and 20 μm and length of 10 mm was introduced into RPC as conductive filler. The electrical resistivity of SSSW reinforced RPC was measured by using three methods including two-electrode-AC, two-electrode-DC and four-electrode-DC. The resistivity responses of SSSW reinforced RPC under cyclic compressive loading, monotonic compressive loading and flexural loading were investigated. The electrochemical impedance spectroscopy (EIS), equivalent circuit and intrinsic conductivity were used to analyze the conductive mechanisms of SSSW reinforced RPC.

2 Experimental schemes

2.1 Raw material and mix proportion

The materials used in this study mainly include short-cut super-fine stainless

wire (SSSW), cement, fly ash, silica fume, quartz sand, water and water reducer. The SSSW used is 316L stainless wire in diameter of 8 μm and 20 μm and length of 10 mm. The elongation of the SSSW is more than 1%, and the tensile strength can reach up to 1200-1800MPa. Their morphologies are shown in Fig.1. The cement used is P·O 42.5R provided by Dalian Onoda Cement Co. Ltd., China. The silica fume used is 920D silica fume provided by Shanghai Tian Kai Silicon Fume Co. Ltd., China. The fly ash used is the secondary fly ash provided by Dalian Daokete Building Materials Co. Ltd., China. The size range of quartz sand used in this study is from 0.12-0.83 mm. The water reducer used is RHEOPLUS 411 polycarboxylate superplasticizer provided by BASF's Chemical Building Materials (China) Co. Ltd. The solid content of the superplasticizer is 44%.

Based on the proportion proposed by Richard et al. [26] in 1995, the ratio of cement: silica fume: quartz sand: water was equal to 1:0.25:1.1:0.3. The content of superplasticizer was adjusted according to the amount of SSSW to achieve a good workability of concrete mixture. In order to improve the mobility of RPC and reduce the cement content per cube, 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. The SSSW reinforced RPC was marked as W0, W08 (W0805, W0810, W0815), and W20 (W2005, W2010, W2015).

2.2 Specimen preparation

The cement mortar mixer was used to stir SSSW reinforced RPC, at low speed of 140 ± 5 r/min and high speed of 285 ± 10 r/min. Firstly, cement, silica fume, fly ash,

SSSW, water and half of superplasticizer were put into mixing pans together, and then the cement mortar mixer was started to stir the mixture for one minute at low speed and four minute at high speed separately. Secondly, quartz sand was put into the slurry, and low-speed stirring was continued for one minute. Thirdly, the other half of superplasticizer was put into the SSSW reinforced RPC, and high-speed stirring was continued for four minute. During the experiment, low-speed stirring can prevent the spilling of powder, while high-speed stirring is conducive to SSSW dispersion.

There were two sizes of molds in this study. The mixtures after stirring were put into oiled molds for a one-time. Then, they were vibrated for 1 minute. Next, for two-electrode-AC resistance, two-electrode-DC resistance and EIS measurements, two stainless steel gauze electrodes (with size of 40 mm × 40 mm × 60 mm) were embedded in the corresponding positions of 40 mm × 40 mm × 160 mm specimens (10 mm measured from one side of specimens); for four-electrode-DC resistance measurement, four stainless steel gauze electrodes (with size of 40 mm × 40 mm × 60 mm) were embedded in the corresponding positions of 30 mm × 30 mm × 60 mm specimens (the outer two for passing current with 10mm measured from one side of specimens, the inner two for voltage measurement spaced 20 mm apart) (as shown in Fig.2). Then, the specimens were vibrated once again until shaking to an extent of oozing slurry on the surface of specimens. All specimens were put in standard curing chamber and demolded after 24 hours. In order to study the effect of curing environment, a series of specimens of 40 mm × 40 mm × 160 mm 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 Experimental tests of electrical property

The electrical resistances of SSSW reinforced RPC at the curing ages of 1, 3, 7, 14 and 28 days were measured. Specimens after water curing for certain ages were taken out from water and dried with cloth and then measured immediately. Meanwhile, specimens after natural curing for certain ages were directly tested. The electrical behavior of SSSW reinforced RPC was compared by using methods of two-electrode-AC, two-electrode-DC and four-electrode-DC. The test results were uniformly referred to “resistance”. The two-electrode-AC resistance was measured using handheld LCR meter (at the frequency of 100 KHz, U1733C, Agilent Technologies, Inc., USA) which can collect ten data real-timely, and then the average value of this ten data was the AC resistance of each specimen. The two-electrode-DC and four-electrode-DC resistance which were measured by using Keithley 2100 Digital Multimeter (supplied by Keithley Instruments Inc.) increased with the increase of test time, and the value in the steady phase was taken as the DC resistance of each specimen. The electrical resistivity is calculated according $\rho = RS/L$ (where ρ is electrical resistivity, R is electrical resistance, S is cross sectional area, L is the distance between two electrodes). Three specimens of each type of composites were tested for average value.

The cyclic compressive loading was exerted on the 30 mm × 30 mm × 60 mm specimens by using universal testing machine WDW-200E, as shown in Fig.2 (a). The maximum value of the cyclic compressive loading is 20 kN (determined by

compressive tests, within an elastic regime) and the loading rate is 0.4 mm/min. Two strain gauges were fixed to the opposite sides of specimens along the loading direction to test the longitudinal strain. Dynamic strain indicator DC-204R provided by Tokyo Sokki Kenkyujo Co., Ltd. was employed to measure the strain. At the same time, the four-electrode-DC resistance measurement was carried out by using Keithley 2100. The monotonic compressive loading was exerted on the 30 mm × 30 mm × 60 mm specimens with a loading rate of 1.2 mm/min after cyclic compressive test. The longitudinal strain and four-electrode-DC resistance were all collected during the monotonic compression test. The average strain calculated with the measured two strain values was used to describe the relationship between the fractional change in electrical resistivity and cyclic/monotonic compressive strain/stress.

Based on the research of Wen et al. [37], the oblique surface resistance is the best indicator of the combined effect of strain and damage under flexure, but it is relatively insensitive to interior damage. Therefore, the embedded electrode method was used for the strain sensitivity test of SSSW reinforced RPC under flexural loading in this study. The flexural loading was exerted on the 40 mm × 40 mm × 160 mm specimens by using WDW-200E with a loading rate of 0.05 mm/min. The distance between the bearing points was 100mm. The flexural-tensile strain of the bottom mid-span was obtained by using strain gauges, and the resistance measured by using two-electrode-DC method was collected, as shown in Fig.2 (b).

The fractional change in electrical resistivity is calculated as $\Delta\rho = 100\% \times (\rho_{min} - \rho_0)/\rho_0$ (where ρ_0 is the resistivity without loading, ρ_{min} is the resistivity

under loading). The strain sensitivity, i.e. gauge factor, is defined as the fractional change in electrical resistivity per unit strain. The sampling frequencies for stress, strain and resistance were all 2 Hz. The curve of stress/strain vs. fractional change in electrical resistivity under loading was analyzed based on the one, which was most nearly to the average of three specimens.

The EIS was obtained using electrochemical analyzer produced by Shanghai Huachen Chemical Factory. During the test, one side of stainless steel gauze of 40 mm × 40 mm × 160 mm specimens was considered as working electrode and the other side of stainless steel gauze was considered as counter electrode. The test electrode power output and sense input of electrochemical analyzer were linked to working electrode, and the reference electrode input and counter electrode output were linked to counter electrode. A wide range of frequency (from 10^{-2} Hz to 10^6 Hz) and a low-amplitude AC excitation of 10mv were used for EIS test in this study. Each frequency generates a single current response datum, which has both real and imaginary component. The EIS and DC resistivity polarization analysis was also conducted on the one, which was best approximated to the average of three specimens.

3 Electrical resistivity of SSSW reinforced RPC without loading

3.1 Electrical resistivity of SSSW reinforced RPC measured by using two-electrode-AC method

The electrical resistivity of SSSW reinforced RPC measured by using two-electrode-AC method is shown in Fig.3. As can be seen from Fig.3, the

incorporation of SSSWs significantly lowers the electrical resistivity of RPC, and the electrical resistivity values have been reduced from $9.4 \times 10^4 \Omega \cdot \text{cm}$ for RPC without SSSW to $10.4 \times 10^2 \Omega \cdot \text{cm}$ and $19.8 \Omega \cdot \text{cm}$ for W0815 and W2015 respectively after natural curing for 28 days. The electrical resistivity of SSSW reinforced RPC increases with curing ages, which can be attributed to the development of cementitious material hydration. Meanwhile, the electrical resistivity decreases with the increase of SSSW content, due to the more and more connection between the adjacent SSSWs. It is worth noting that the electrical resistivity of SSSW reinforced RPC after natural curing for 28 days decreases abruptly when the contents of SSSW in diameter of 8 μm and 20 μm are 1.5% and 1.0%, respectively. However, this phenomenon for W08 after water curing for 28 days occurs at the content of 1.0%. The experiment results also show that the electrical resistivity of W20 is far lower than that of W08, and the electrical resistivity of W2005 is already lower than that of W0815.

Compared Fig.3 (a) to Fig.3 (b), the electrical resistivity of SSSW reinforced RPC after water curing for 28 days is smaller than that of composites after natural curing for 28 days. The difference is particularly obvious for SSSW reinforced RPC with low content of SSSWs, because that the ionic conduction plays an important role in the conductive pathway of these composites. Meanwhile, the two-electrode method is easily affected by the contact resistance between electrode and cement matrix [38]. Therefore, the moistening of electrode surface caused by water curing partly contributes to the decrease of the electrical resistivity.

3.2 Electrical resistivity of SSSW reinforced RPC measured by using two-electrode-DC method

The electrical resistivity of SSSW reinforced RPC measured by using two-electrode-DC method is shown in Fig.4. Fig.4 shows that the electrical resistivity decreases with the increase of SSSW content, and the electrical resistivity of W08 is considerably higher than that of W20 which indicates that the dispersal uniformity of SSSW in diameter of 20 μm is better than that in diameter of 8 μm at the same content. Fig.4 (a) shows that the electrical resistivity of W08 after water curing for 28 days is $21.8 \times 10^4 \Omega \cdot \text{cm}$, $3.9 \times 10^4 \Omega \cdot \text{cm}$ and $5.8 \times 10^2 \Omega \cdot \text{cm}$ respectively. This indicates that the percolation phenomenon has already appeared when the content of SSSW in diameter of 8 μm is 1.5%, and the conductive pathway has shift from RPC matrix to SSSW network. Fig.4 (c) shows that the electrical resistivity of W08 after natural curing for 28 days increases with curing ages and is relatively higher than that after water curing for 28 days. Fig.4 (b) and (d) show that the percolation phenomenon of W20 already exists when the content of SSSW is only 0.5% and the electrical resistivity of W20 after natural curing for 28 days is $4.5 \times 10^2 \Omega \cdot \text{cm}$, $44.0 \Omega \cdot \text{cm}$ and $22.0 \Omega \cdot \text{cm}$, respectively. The test results also show that the electrical resistivity of W20 is less affected by curing ages, which can be attributed to that the SSSWs play an important role in the conductive pathway of W20. The W2005 after natural curing for 28 days has much higher electrical resistivity than that after natural curing for 21 days, because that the overlapping wire in these specimens is less and the conductive pathway is susceptible to shrinkage crack caused by natural curing. Meanwhile, the

electrical resistivity of W2005 after water curing for 14 days decreases with the increase of curing ages because of the effect of ionic conduction on the incomplete SSSW overlapping conductive network.

It can be seen from Fig.3 and Fig.4 that the percolation phenomenon of SSSW reinforced RPC is not subject to AC and DC voltage, but the percolation threshold of W08 measured by using AC voltage is affected by water content. The electrical resistivity of W08 measured by using two-electrode-DC method is considerably higher than that of composites measured by using two-electrode-AC method, while there is little difference between the electrical resistivity of W20 measured by using these two methods. This is because that the effect of polarization caused by DC voltage on electrical resistivity is closely related to the conductivity of composites, and it is more obvious when the conductive pathway of composites is dominated by cement matrix. The effect of polarization on DC resistivity will be introduced later.

3.3 Electrical resistivity of SSSW reinforced RPC measured by using four-electrode-DC method

The electrical resistivity of SSSW reinforced RPC after natural curing for certain ages measured by using four-electrode-DC method is shown in Fig.5. Fig. 5 shows that the electrical resistivity of SSSW reinforced RPC after natural curing for 14 days decreases slightly with the increase of curing ages, except for W0 and W2510. This can be attributed to the effect of shrinkage crack and pore solution concentration. The electrical resistivity of SSSW reinforced RPC decreases with the increase of SSSW content, and the electrical resistivity of W20 after natural curing for 28 days is 44.0

$\Omega\cdot\text{cm}$, $8.5\ \Omega\cdot\text{cm}$ and $4.7\ \Omega\cdot\text{cm}$, respectively. Meanwhile, the electrical resistivity of W20 is far lower than that of W08. The percolation phenomenon has already appeared when the contents of W08 and W20 are 1.5% and 0.5% respectively. This is the same as the aforementioned results.

It can be seen from Fig.4 and Fig.5 that the electrical resistivity of SSSW reinforced RPC measured by using two-electrode-DC method is larger than that of composites measured by using four-electrode-DC method, due to the contact resistance caused by two-electrode method. The relationship between the test results measured by using four-electrode-DC method and two-electrode-AC method varies with SSSW content and diameter. The incorporation of SSSWs in diameter of $20\ \mu\text{m}$ or 1.5 vol. % SSSWs in diameter $8\ \mu\text{m}$ makes the electrical resistivity measured by using four-electrode-DC method smaller than that of composites measured by using two-electrode-AC method. This indicates that the effect of polarization on electrical resistivity is far less than that of contact resistance between electrode and cement matrix for high conductivity composites. However, the experimental results for W0 and W0805 show the contrary trend, i.e. the effect of polarization caused by DC voltage is more obvious than that of contact resistance for composites with poor conductivity.

Fig.3, Fig.4 and Fig.5 show that the resistivity variation trend of SSSW reinforced RPC caused by SSSW content and diameter is not subject to test method. In other words, the test method selection of electrical resistivity is determined by specimen dimension, loading method, working condition and test requirement

together.

3.4 Electrical polarization phenomenon of SSSW reinforced RPC

The electrical polarization process of SSSW reinforced RPC after natural curing for certain ages is investigated by using two-electrode-DC and four-electrode-DC method respectively, as shown in Table 1 and Table 2. As shown in Table 1, the electrical resistivity measured by using two-electrode-DC increases with time during measurement, and it becomes stable after a period of time with the current on. Table 2 shows that the electrical resistivity of W20 measured by using four-electrode-DC floats up and down because of the too small value. The polarization is obvious for specimens without SSSWs or with low content of SSSWs in diameter of 8 μm . This is because that the conductivity of these composites is mainly dominated by ionic conduction and double layer capacitance formed in C-S-H gel surface and the interface between SSSWs and cement matrix. As a result, the charging of the capacitors causes a linear increase in the resistivity [8]. The tendency of polarization decreases with the increase of SSSW content and diameter, and the W20 is already not affected by polarization. Since a conductor cannot support a significant electric field, polarization will be weakened [39], i.e. the lower the electrical resistivity, the less the polarization. The polarization change rule of SSSW reinforced RPC is consistent with that of electrical resistivity, and the experimental results of polarization are not affected by electrode layout.

The occurrence of percolation phenomenon can also be observed by the change of polarization. The results show that the polarization is not obvious when the SSSW

contents are 1.5% and 0.5% for W08 and W20 respectively, which represents the occurrence of percolation. This is the same as the results obtained from the change of electrical resistivity.

Table 1 Change of electric resistivity of SSSW reinforced RPC measured by using two-electrode-DC method with test time under polarization effect

Specimens	Ages (d)	Time (s)										
		0	50	100	150	200	250	300	350	400	450	500
W0 ($\times 10^4 \Omega \cdot \text{cm}$)	3	5.8	7.2	7.4	7.5	7.5	7.5	7.5	-	-	-	-
	7	7.9	9.1	9.2	9.3	9.3	9.3	9.3	-	-	-	-
	14	13.8	16.7	17.1	17.5	17.7	17.7	17.7	-	-	-	-
	21	18.2	19.9	20.2	20.4	20.5	20.5	20.5	-	-	-	-
	28	28.3	31.5	31.9	32.2	32.2	32.3	32.3	-	-	-	-
W0805 ($\times 10^4 \Omega \cdot \text{cm}$)	3	3.9	6.1	6.5	6.7	6.8	6.8	6.8	6.8	-	-	-
	7	4.4	8.4	8.8	8.9	9.0	9.0	9.1	9.0	-	-	-
	14	7.1	9.7	10.1	10.2	10.3	10.4	10.5	10.5	-	-	-
	21	17.6	21.6	22.2	22.4	22.6	22.7	22.8	22.8	-	-	-
	28	26.8	33.2	34.0	34.4	34.6	34.8	34.9	34.9	-	-	-
W0810 ($\times 10^4 \Omega \cdot \text{cm}$)	3	0.3	0.7	0.8	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0
	7	0.6	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3
	14	1.5	1.8	2.0	2.1	2.2	2.2	2.3	2.3	2.4	2.4	2.4
	21	11.7	15.5	16.9	17.8	18.5	19.0	19.4	19.7	20.0	20.2	20.4
	28	22.3	27.2	28.7	29.7	30.4	30.9	31.2	31.5	31.7	31.9	32.1
W0815 ($\times 10^2 \Omega \cdot \text{cm}$)	3	5.5	5.6	5.7	5.7	5.7	5.8	5.8	5.8	5.8	5.8	-
	7	6.2	6.3	6.3	6.3	6.3	6.3	6.4	6.4	6.4	6.4	-
	14	6.0	6.4	6.4	6.4	6.4	6.5	6.5	6.5	6.5	6.5	-
	21	93.9	96.9	97.8	98.3	98.8	99.1	99.3	99.5	99.7	99.8	-
	28	63.7	77.2	77.8	78.1	78.3	78.3	78.3	78.3	78.3	78.3	-
W2005 ($\times 10^2 \Omega \cdot \text{cm}$)	3	2.3	2.6	2.6	2.6	2.6	2.6	-	-	-	-	-
	7	2.6	2.6	2.6	2.6	2.6	2.6	-	-	-	-	-
	14	2.5	2.5	2.5	2.5	2.5	2.5	-	-	-	-	-
	21	8.4	8.4	8.4	8.4	8.4	8.4	-	-	-	-	-
	28	6.6	6.7	6.7	6.7	6.7	6.7	-	-	-	-	-
W2010 ($\Omega \cdot \text{cm}$)	3	19.8	19.6	18.8	19.2	19.6	19.7	19.7	-	-	-	-
	7	19.6	19.6	19.6	19.6	19.6	19.6	19.6	-	-	-	-
	14	18.0	18.0	18.0	18.0	18.0	18.0	18.0	-	-	-	-
	21	50.0	50.1	50.1	50.1	50.1	50.2	50.2	-	-	-	-
	28	48.4	48.5	48.5	48.5	48.5	48.5	48.5	-	-	-	-
W2015 ($\Omega \cdot \text{cm}$)	3	18.3	18.3	18.2	18.1	18.3	18.3	18.3	-	-	-	-
	7	18.4	18.4	18.4	18.4	18.4	18.4	18.4	-	-	-	-
	14	17.4	17.4	17.4	17.4	17.4	17.4	17.4	-	-	-	-
	21	21.9	21.9	21.9	21.9	21.9	21.9	21.9	-	-	-	-
	28	21.6	21.6	21.6	21.6	21.6	21.6	21.6	-	-	-	-

Table 2 Change of electric resistivity of SSSW reinforced RPC measured by using four-electrode-DC method with test time under polarization effect

Specimens	Ages (d)	Time (s)										
		0	50	100	150	200	250	300	350	400	450	500
W0 ($\times 10^4 \Omega \cdot \text{cm}$)	3	3.9	5.0	5.1	5.2	5.2	5.2	6.2	5.2	5.2	5.1	5.1
	7	5.4	5.8	5.9	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
	14	5.6	7.7	8.5	9.0	9.5	9.9	10.2	10.4	10.7	10.9	11.1
	21	4.3	7.9	8.6	9.0	9.4	9.7	9.9	10.1	10.3	10.5	10.6

	28	10.3	13.4	14.5	15.5	16.4	17.1	17.8	18.3	18.9	19.3	19.6
W0805 ($\times 10^4 \Omega \cdot \text{cm}$)	3	5.8	5.8	5.9	5.9	6.0	6.0	6.0	6.0	6.1	6.1	6.2
	7	13.1	13.1	13.2	13.4	13.4	13.6	13.8	13.9	14.0	13.8	14.0
	14	11.1	11.2	11.3	11.4	11.6	11.6	11.6	11.6	11.5	11.7	11.8
	21	6.5	6.6	6.6	6.7	6.8	6.8	6.9	6.9	7.0	7.0	7.1
	28	5.7	5.9	6.1	6.2	6.4	6.5	6.5	6.6	6.7	6.8	6.8
W0810 ($\times 10^4 \Omega \cdot \text{cm}$)	3	0.16	0.20	0.22	0.23	0.23	0.24	0.24	0.24	0.24	-	-
	7	0.25	0.30	0.33	0.36	0.37	0.39	0.41	0.41	0.41	-	-
	14	0.23	0.23	0.23	0.26	0.24	0.26	0.26	0.26	0.24	-	-
	21	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	-	-
	28	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	-	-
W0815 ($\Omega \cdot \text{cm}$)	3	30.8	30.9	31.0	31.1	31.0	31.1	31.1	31.1	-	-	-
	7	30.8	34.9	22.7	28.1	21.4	32.2	31.4	32.2	-	-	-
	14	30.0	30.7	29.9	31.5	30.8	29.7	30.1	30.8	-	-	-
	21	30.0	30.6	30.0	28.7	29.4	27.7	30.2	30.5	-	-	-
	28	27.8	27.9	27.9	27.9	27.9	27.9	27.9	27.9	-	-	-
W2005 ($\Omega \cdot \text{cm}$)	3	68.0	69.2	69.2	69.2	69.2	69.2	-	-	-	-	-
	7	79.2	65.7	73.8	73.8	69.8	65.7	-	-	-	-	-
	14	73.6	70.9	68.9	67.6	79.0	76.3	-	-	-	-	-
	21	65.4	65.8	64.4	64.9	65.7	65.7	-	-	-	-	-
	28	41.1	41.0	41.1	41.1	41.1	41.1	-	-	-	-	-
W2010 ($\Omega \cdot \text{cm}$)	3	2.6	2.2	3.5	3.8	4.2	4.0	-	-	-	-	-
	7	4.3	4.2	4.2	4.1	4.2	4.2	-	-	-	-	-
	14	4.5	5.1	5.1	5.2	4.9	5.0	-	-	-	-	-
	21	2.8	2.7	3.1	3.2	3.6	3.5	-	-	-	-	-
	28	8.8	8.8	8.8	8.8	8.8	8.8	-	-	-	-	-
W2015 ($\Omega \cdot \text{cm}$)	3	6.9	7.1	7.1	7.1	7.1	7.1	-	-	-	-	-
	7	7.0	7.0	7.0	7.0	7.0	7.0	-	-	-	-	-
	14	7.0	7.1	7.0	7.0	7.1	7.0	-	-	-	-	-
	21	6.3	6.0	6.0	5.2	6.1	6.1	-	-	-	-	-
	28	4.6	4.6	4.6	4.6	4.6	4.6	-	-	-	-	-

4 Electrical behavior of SSSW reinforced RPC under loading

4.1 Electrical behavior of SSSW reinforced RPC under cyclic compressive loading

The relationships between cyclic compressive stress/strain and the fractional change in electrical resistivity of SSSW reinforced RPC after natural curing for 28 days are established, as shown in Fig.6-Fig.11. The results indicate that the SSSW reinforced RPC has piezoresistive response under cyclic compressive loading within the elastic regime, and the characteristic of piezoresistive response varies with SSSW content and diameter although the maximum value of the fractional change in electrical resistivity can only achieve 1%. It can be seen from Fig.6 and Fig.7 that the

fractional change in electrical resistivity of W0805 and W0810 decreases upon loading and increases upon unloading, but the stability and reversibility of the piezoresistivity is poor. At the beginning of each cycle, the electrical resistivity is higher than the initial value never subjected to external force. This is because that some internal defects (e.g. native cracks, holes, gel peristalsis, etc.) are gradually reduced in cycles of compressive loading [7]. As shown in Fig.8, the fractional change in electrical resistivity of W0815 is only 0.3% upon loading and unloading. However, the change is stable and reversible. The electrical resistivity at the beginning of each circle is lower than the initial value never subjected to external force, which is different from W0805 and W0810. This results from the more and more lapping of SSSWs, due to gel viscous peristalsis under loading. Fig.9 shows that the characteristic of the fractional change in electrical resistivity of W2005 is similar to that of W0815. The experimental results also show that the W2005 has stable piezoresistive response although the fractional change in electrical resistivity is only 0.3% under cyclic loading. It can be seen from Fig.10 that there is a good repeatability of the fractional change in electrical resistivity for W2010, but the fractional change in electrical resistivity under cyclic loading is less than 0.1%. Fig.11 shows that there is no definite corresponding relationship between the fractional change in electrical resistivity and compressive stress/strain for W2015.

The fractional change in electrical resistivity of SSSW reinforced RPC decreases with the increase of SSSW content and diameter under cyclic compressive loading. The stability and reversibility of the piezoresistive response become better with the

increase of SSSW content in diameter of 8 μm . However, there is a reverse change trend with the increase of SSSW content in diameter of 20 μm . This is because that the contact status between SSSWs plays a critical role in the piezoresistive behavior of SSSW reinforced RPC. The stable piezoresistive response occurs only at appropriate SSSW content when the SSSWs are close to each other but cannot contact with each other such as W0815, W2005 and W2010. When the wire conductive network has been completely formed, the conductivity of the composites is mainly dominated by ohmic contact. Therefore, this kind of composites has no piezoresistivity such as W2015.

The strain sensitivity of SSSW reinforced RPC under cyclic compressive loading is shown in Table 3. It is interesting to note that the strain sensitivity of W20 is significantly lower than that of W08 at the same volume content, while the conductivity of W20 is better than that of W08. This represents that the dispersion of SSSWs in diameter of 20 μm is better than that of SSSWs in diameter of 8 μm . Table 3 also shows that the strain sensitivity of W08 is considerably larger than that of commercial metal strain gauge, which has gauge factor of 2.0-3.0. However, the research of Yu et al. [16] shows that the fractional change in electrical resistance of cement paste containing 0.1 wt.% CNTs can reach 11.4%, and the research of Azhari et al. [17] shows that gauge factor of cement paste (with silica fume) containing 15 vol.% carbon fiber or 15 vol.% carbon fiber and 1 vol.% multi-wall CNTs is approximately 445. But the matrix in the above references does not contain aggregate, and deform more obviously under cyclic compressive loading compared to RPC. The

experimental results also suggest that the conductive mechanism of SSSW reinforced RPC is different from that of carbon fiber reinforced cement-based materials [40]. There is no hole conduction in SSSW reinforced RPC, and the electron transport is relatively difficult due to the compact structure of RPC. As a result, only the adjacent SSSWs can make the composites have stable piezoresistivity.

Table 3 Strain sensitivity of SSSW reinforced RPC under cyclic compressive loading

Specimens	Strain sensitivity	Standard deviation	Specimens	Strain sensitivity	Standard deviation
W0805	22.52	4.57	W2005	3.91	0.15
W0810	13.82	1.28	W2010	3.71	0.17
W0815	4.61	0.29	W2015	2.66	0.70

The cyclic compressive stress and fractional change in electrical resistivity of SSSW reinforced RPC have relatively poor quadratic correlation. This phenomenon can be attributed to the dense structure of RPC and the high bond strength between SSSWs and RPC matrix. Therefore, the contact resistance between SSSWs and cement matrix is less affected by the elastic loading.

4.2 Electrical behavior of SSSW reinforced RPC under failure loading

4.2.1 Electrical behavior of SSSW reinforced RPC under monotonic compressive loading

The fractional change in electrical resistivity of SSSW reinforced RPC after natural curing for 28 days under monotonic compressive loading is shown in Fig.12. It can be seen from Fig.12 that the fractional change in electrical resistivity first increases slowly and then rapidly with the increase of compressive stress/strain, and this can be attributed to the variation of conductive network and specimen deformation under loading.

Fig.12 (a) shows that the fractional change in electrical resistivity of W0 under

monotonic compressive loading can only reach 2.6%. This is because that the RPC matrix has low volume fraction of defects, and the dynamics of the defects has only minor effects on the electrical resistivity of RPC [19]. It can be seen from Fig.12 (b)-(g) that the fractional change in electrical resistivity corresponding to peak failure stress first increases and then decreases with the increase of SSSW content. The resistivity fractional changes of W0805 and W0810 under peak failure stress are 31.8% and 46.2%, while the changes of W2005 and W2010 are only 7.7% and 22.1%, respectively. However, the monotonic compressive stress/strain of W2005 and W2010 are greater than that of W0805 and W0810. The above phenomenon illustrates that the effect of strain and damage on resistivity change is less than that of inner SSSW dispersion, especially for SSSW reinforced RPC with low SSSW content. The specimen deformation is crucial to resistivity change until the SSSWs have formed conductive network. This can be used to explain the experimental results that the fractional change in electrical resistivity can reach up to 21.4% for W2015 while it is only 14.1% for W0815.

The strain sensitivity of SSSW reinforced RPC under monotonic compressive loading is shown in Table 4. It can be seen from Table 4 that the strain sensitivity has the same change trend with the fractional change in electrical resistivity, which is also closely related to the volume content and aspect ratio of SSSW. The strain sensitivity first increases and then decreases with the increase of wire volume content. The W0805 and W0810 have higher strain sensitivity than W2005 and W2010 respectively, while the strain sensitivity of W0815 is lower than that of W2015. The

former is based on the change of SSSW conductive network under loading, and the later can be attributed to deformation of specimens. The cluster of SSSW in diameter of 8 μm makes the effect of fiber reinforcement limited, while the SSSW in diameter of 20 μm can play good lateral restriction effect. The strain sensitivities are considerably larger than the gauge factor of commercial metal strain gauge. However, the test results are much less than the results of carbon fiber reinforced cement-based material, the fractional change in electrical resistance of which can reach up to 50% under 110KN monotonic compressive loading (the diameter of pressure surface is 50.8 mm) [17]. The gap is derived from the difference of matrix and conductive mechanism of carbon fiber and steel fiber.

Table 4 Strain sensitivity of SSSW reinforced RPC under monotonic compressive loading

Specimens	Strain sensitivity	Standard deviation	Specimens	Strain sensitivity	Standard deviation
W0805	62.8	4.14	W2005	17.9	0.92
W0810	94.9	1.20	W2010	42.7	0.78
W0815	29.7	6.29	W2015	42.0	2.90

The effect of monotonic compressive stress on resistance of SSSW reinforced RPC is also closely related SSSW content and diameter and it has the same change rule with strain sensitivity. Generally, the fiber with smaller diameter is easier to contact with each other in matrix at the same content and length, and the corresponding fractional change in electrical resistivity under loading is small. It is worth noting that the experimental results of W08 and W20 are contrary to the above general knowledge. This also represents that the dispersion of SSSWs in diameter of 20 μm is better than that in diameter of 8 μm in RPC. Therefore, the SSSW in diameter of 20 μm is more suitable to be used as conductive filler for RPC.

4.2.2 Electrical behavior of SSSW reinforced RPC under flexural loading

The electrical resistance of SSSW reinforced RPC after water and natural curing for 28 days is measured real-timely by using two-electrode-DC method under flexural loading. The relationships between the flexural-tensile stress/strain and fractional change in electrical resistivity are shown in Fig.13 and Fig.14.

Fig.13 (a) and Fig.14 (a) show that the fractional change in electrical resistivity of W0 fluctuates between -2% and 2%, and the resistivity shows an instant rise when the flexural-tensile stress reach its peak. This indicates that the W0 has no piezoresistivity and its electrical behavior is free from curing condition. It can be seen from Fig.13 (b)-(d) that the electrical resistivity change rate of W08 after water curing for 28 days decreases with the increase of SSSW content, and the fractional change values under peak failure stress are 1.0%, 1.24% and 0.54% respectively. Fig.13 (e)-(g) show that the electrical resistivity change rate of W20 increases with the increase of SSSW content, and the fractional change values under peak failure stress are -0.14%, 0.68% and 1.43% respectively. Under flexural loading, the bottom part of specimens is tensioned, and the SSSWs 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 SSSWs 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 SSSW reinforced RPC under flexural loading presents offset phenomenon [41]. The offset phenomenon is particularly evident for W0815 and W2005 due to the adjacent SSSWs. When the wires are sporadically distributed in RPC matrix (such as W0805 and W0810) or the SSSWs have formed

extensive conductive network (such as W2010 and W2015), the increasing distance between SSSWs at the bottom part of specimens dominates the fractional change in electrical resistivity. This can be used to explain why the fractional change values of these specimens are larger than 0.5%.

It can be seen from Fig.14 (b)-(d) that the electrical resistivity change rate of W08 after natural curing for 28 days has the same trend with that of composites after water curing for 28 days. However, the fractional change values of W08 increase with the increase of SSSW content. This can be attributed to the pull-out of SSSWs at the bottom part of specimens under flexural loading, based on micro cracks generated by natural curing and the SSSW dispersion status in W08. Fig.14 (e)-(g) show that the electrical resistivity change rate of W20 decreases with the increase of SSSW content, and the change values under peak failure stress are less than 0.2%. The W2015 even has negative fractional change in electrical resistivity. This is completely different from that of composites after water curing for 28 days. It is because that the SSSWs have formed completely conductive network in W20 specimens and the micro cracks generated by natural curing make the insert of SSSW easier at the top part of W20 specimens. Therefore, the offset effect is obvious. This phenomenon is the same as the research of Azhari [42], because that the upper half of the specimen's cross section is compressed and the lower half undergoes tension when the specimen is subjected to flexure.

The strain sensitivity of SSSW reinforced RPC under flexure after water and natural curing for 28 days is shown in Table 5. Table 5 shows that the strain sensitivity

of specimens after water curing for 28 days under flexure has the same trend with that of specimens under monotonic compressive loading. This is because that the pull-out effect is more and more obvious with the content increase of SSSW in diameter of 20 μm , and the cluster of SSSW in diameter of 8 μm at high content hampers the presentation of fiber bridging. However, the strain sensitivity of specimens after natural curing for 28 days has no evident change-regular because of the existence of shrinkage crack. The W08 has higher strain sensitivity than W20, and the strain sensitivity of SSSW reinforced RPC under flexure is always larger than the gauge factor of commercial metal strain gauge.

Table 5 Strain sensitivity of SSSW reinforced RPC under flexural loading

Specimens (water curing)	Strain sensitivity	Standard deviation	Specimens (natural curing)	Strain sensitivity	Standard deviation
W0805	27.8	5.04	W0805	21.4	0.39
W0810	36.9	2.30	W0810	21.5	3.06
W0815	12.6	2.63	W0815	43.6	8.03
W2005	3.73	0.26	W2005	5.0	0.71
W2010	13.0	1.27	W2010	3.5	0.36
W2015	19.5	0.64	W2015	5.5	0.39

Based on above analysis, the fractional change in electrical resistivity of SSSW reinforced RPC under flexural loading is small, and is easily affected by curing condition. However, the incorporation of SSSWs makes the fractional change in electrical resistivity of SSSW reinforced RPC correspond to the combined effect of compression and tension under flexure. Therefore, strain, stress (or external force), crack and damage of SSSW reinforced RPC can be monitored through measuring the electrical resistivity of the composites.

5 AC impedance characteristic and intrinsic conductivity of SSSW reinforced RPC

5.1 EIS and equivalent circuit analysis of SSSW reinforced RPC

The EIS of SSSW reinforced RPC under different curing conditions can be drawn in Nyquist plot, as shown in Fig.15. The frequency in each plot decreases from left to right. It can be seen from Fig.15 that the location, time parameter and topological structure of EIS vary with SSSW content, diameter, and curing condition. The equivalent circuit, which is the most important and intuitive method for analyzing EIS, can connect EIS and electrode process kinetics model. The equivalent element (e.g. resistance, capacitance and inductance) and composite equivalent element (e.g. the series or parallel of resistance and capacitance), which have definite physical meaning, can be used to represent the various stages of EIS during the drawing process of equivalent circuit [43]. For example, the Nyquist plot of the parallel of resistance and capacitance is semicircle in the first quadrant or flattening semicircle because of the constant phase angle element carried by double layer capacitance in electrode interface, and an oblique line in the first quadrant represents the diffusion impedance caused by charge diffusion. Based on the theoretical analysis of equivalent element and EIS, the corresponding equivalent circuits of SSSW reinforced RPC are plotted in Fig.16.

Fig.15 (a) shows that the EIS of W0 consists of three parts, and the equivalent circuit of W0 is shown in Fig.16 (a). (1) The circular section can be represented by the parallel of resistance and capacitance element. The beginning of the EIS is marked as O, and it corresponds to pore solution resistance (R_s) in equivalent circuit. The value of R_s is an inverse function of porosity and pore solution concentration. The arc

diameter (OA section) in high frequency region contains the value of charge transfer resistance (R_{st}), which is closely related to the cement hydration product, water content, and ion concentration. The OA section of W0 after water curing for 28 days is smaller than that of W0 after natural curing for 28 days. This means that the charge transfer resistance is lowered due to high water content and ion concentration. Meanwhile, the OA section also involves the resistance caused by C-S-H gel surface capacitance, which is represented by C_d in Fig.16 (a). (2) The AB section represents that ion adsorption and desorption has been occurred in C-S-H gel surface in the process of voltage application, which is expressed as inductance (L) in equivalent circuit. (3) The BC section in low frequency region shows that the real part and imaginary part is linear dependence, and the slope is closely related to the inner connected pore structure of SSSW reinforced RPC. This electrochemical process is controlled by diffusion, and the corresponding impedance is called diffusion impedance (Z_w).

Fig.15 (b) shows that the EIS of W0805 is a classic Randles curve. The intersection point of the curve and x axis at the high frequency is marked as O, and it is determined by RPC matrix and SSSWs together. Therefore, the corresponding equivalent circuit is expressed as the parallel connection of pore solution resistance (R_s) and SSSW resistance (R_{sw}), as shown in Fig.16 (b). This is based on that a large part of matrix maybe bypassed by current flow due to SSSW incorporation. The OA section in Fig.15 (b) is controlled by the charge transfer resistance (R_{st}) and C-S-H gel surface capacitance (C_d) together. The AB section in Fig.15 (b) represents the

process of charge diffusion, which is irrelevant to SSSWs. This can be attributed to that the electric double layer forms at SSSW surface, and it make SSSW insulate under the excitation of low frequency AC voltage [44].

The linear part of EIS controlled by charge diffusion gradually disappears with the increase of SSSW content and diameter. This means that the SSSW has gradually become a leading element in the conductive pathway.

It can be seen from Fig.15 (c) that the EIS of W0810 appears as a dual tangent arc in Nyquist plot, which represents two time constants. The corresponding equivalent circuit is expressed as two series-parallel connections of resistance-capacitance cells, as shown in Fig.16 (c). One happens at the SSSW-matrix interface, and the other happens at the C-S-H gel surface. This indicates that the SSSWs behave insulating at low frequency and conducting at high frequency [45]. The resistance represented by the point of O at high frequency is make up of R_s and R_{sw} together. The lower frequency is required to collect the resistance produced by the C-S-H gel electric double layer capacitance and diffusion impedance for W0810 specimens after water curing for 28 days.

Fig.15 (d) and Fig.15 (e) show that the EIS of W0815 and W2005 has similar topological structure, and it is composed of two semicircles. The SSSWs and pore solution behave conducting in series-parallel way at high frequency. The corresponding equivalent circuit consists of R_{sw} , R_s and C_{sw} , as shown in Fig.16 (d), where C_{sw} represents the double layer capacitance at SSSW-matrix interface. The double layer capacitance of C-S-H gel surface and the charge transfer behave

conducting at low frequency, and their resistance can be represented by C_d and R_{st} respectively. Fig.16 (d) shows that the equivalent circuit has been dominated by SSSWs. This result illustrates that the percolation network has been formed when the contents of W08 and W20 are 1.5% and 0.5% respectively, in accordance with the test results of electrical resistivity.

Because of low impedance, the EIS test process of W2010 and W2015 is vulnerable to external and internal conduction connections. Therefore, the inductance appears in the fourth quadrant at high frequency, indicated by OA sections in Fig.15 (f) and Fig.15 (g). At low frequency, only a flattened semicircle (AB section) appears in the first quadrant. The depression angle of the semicircle can be attributed to a constant phase element, which is sensitive to the pore diameters of composites, especially in conductive fiber reinforced materials [46]. The equivalent circuits of W2010 and W2015 are shown in Fig.16 (e). It can be seen from Fig.16 (e) that the conductive pathway is composed of SSSWs entirely at high frequency. Meanwhile, the pathway involves a parallel connection of charge transfer resistance and double layer capacitance of C-S-H gel surface at low frequency.

Based on the above analysis, the conductive pathway of SSSW reinforced RPC can be divided into three categories. (1) When the SSSW content is below percolation threshold, the electrical transport behavior is dominated by cement matrix. The SSSWs are scattered in matrix and cannot contact with each other, so the electric conduction of the composite is limited. W0805 and W0810 are of this kind. (2) The SSSWs and cement matrix constitute a conductive pathway together with the increase

of SSSW content. Meanwhile, the double layer capacitance at SSSW-matrix interface and C-S-H gel surface also plays a certain role in electrical conduction. The conductive pathway of W0815 and W2005 falls into this category. (3) When the conductive network of SSSWs has been formed in composites, the electrical transport behavior is dominated by SSSWs. W2010 and W2015 belong in this category. The three categories show that the conductive mechanism of SSSW reinforced RPC mainly depends on the connection of SSSWs, which is different from that of carbon fiber reinforced cement-based materials [40].

5.2 Intrinsic conductivity analysis of SSSW reinforced RPC

The intrinsic conductivity of SSSW reinforced RPC is equal to the composite conductivity (σ) divided by the matrix conductivity (σ_m), as shown in Equation (1). Fixman equation relating the intrinsic conductivity to the aspect ratio (AR), or length divided by diameter of SSSW is shown as Equation (2) [45]:

$$\frac{\sigma}{\sigma_m} = \frac{R_m}{R} = 1 + [\sigma]_{\Delta} \Phi \quad (1)$$

$$[\sigma]_{\infty} = \frac{1}{3} \left(\frac{2(AR)^2}{[3\ln\{4(AR)\}-7]} + 4 \right) \quad (2)$$

where AR is aspect ratio of SSSW, Φ is volume content of SSSW, R_m is the composite resistivity, and R is matrix resistivity.

At the same SSSW content and aspect ratio, the deviation of the experimental results from the expected results calculated by Equation (2) can be used to quantify the dispersion of SSSWs. The calculated and experimental results of intrinsic conductivity are listed in Table 6. Table 6 shows that the intrinsic conductivity of SSSW reinforced RPC does meet the Equation (2). The experimental intrinsic

conductivity of W08 is much less than the calculated results, especially for specimens after natural curing for 28 days. However, the experimental result of W20 is higher than the calculated values, and it is also considerably greater than the experimental result of W08. This indicates that the SSSWs in diameter of 8 μm can not uniformly disperse in RPC, and they are easily clustered into bundle. On the contrary, the SSSWs in diameter of 20 μm have better dispersity, and the effective utilization ratio is improved correspondingly. Therefore, the SSSW in diameter of 20 μm is more suitable for improving the conductivity of RPC.

Table 6 The calculated and experimental intrinsic conductivity of SSSW reinforced RPC

Specimens	W0805	W0810	W0815	W2005	W2010	W2015
Experimental values (water curing)	17.5	61.0	218.3	343.4	2777.1	3701.0
Standard deviation	0.94	3.65	30.18	68.00	76.06	542.51
Experimental values (natural curing)	19.0	23.8	105.4	212.3	2708.0	4656.9
Standard deviation	1.92	1.01	6.55	86.00	266.21	397.13
Calculated values	281.8	562.5	843.3	53.7	106.5	159.3

6 Conclusions

Short-cut super-fine stainless wire (SSSW) with high aspect ratio has excellent mechanical behavior and is a promising conductive filler for developing multifunctional and smart concrete. It is especially suited for modifying reactive powder concrete (RPC) with homogenous and compact microstructure. In this study, the SSSW was introduced into RPC to produce conductive and piezoresistive composites. The electrical resistivity of SSSW reinforced RPC was investigated using different test methods. The electrical behavior of SSSW reinforced RPC under cyclic compressive loading, monotonic compressive loading and flexural loading was analyzed respectively, and the conductive mechanisms were revealed based on EIS and intrinsic conductivity analysis.

1) The effect of SSSW content and aspect ratio on the electrical resistivity of SSSW reinforced RPC is not subject to the test method, although the electrical resistivity values of composite with the same proportion have a little difference because of electrode layout, excitation voltage and curing condition. The electrical resistivity of SSSW reinforced RPC decreases with the increase of SSSW content and diameter, and only 0.5% SSSW in diameter of 20 μm can make the reduction of electrical resistivity reach up to four orders of magnitude. The polarization effect under DC voltage is not subject to electrode layout, and it weakens with the increase of SSSW content and diameter. The percolation has occurred when the contents of SSSW in diameter of 8 μm and 20 μm are 1.5% and 0.5%, respectively.

2) The piezoresistive response stability and reversibility of SSSW reinforced RPC under cyclic compressive loading increase with the content increase of SSSW in diameter of 8 μm , while there is almost no piezoresistivity when the content of SSSW in diameter of 20 μm is 1.5 vol.%. The fractional change in electrical resistivity first increases slowly and then rapidly with the increase of monotonic compressive stress/strain. The strain sensitivity of SSSW reinforced RPC can reach 22.5 and 94.9 under cyclic and monotonic compressive loading respectively. The fractional change in electrical resistivity under flexure first decreases and then increases due to the combined effect of compression and tension. The strain sensitivity of SSSW reinforced RPC under flexure can reach up to 43.6, and it is sensitive to natural curing because of the micro cracks caused by natural curing.

3) The conductive mechanism of SSSW reinforced RPC revealed by EIS is

closely related to the formation of SSSW conductive network, and the difference between calculated and experimental intrinsic conductivity demonstrates that the SSSW in diameter of 20 μm is more suitable to be used as conductive filler for RPC compared to SSSW in diameter of 8 μm

Thanks to the good compatibility between SSSWs and RPC, it is possible to obtain high performance and multifunctional/smart concrete with favorable conductivity and self-sensing capability. The firstly proposed SSSW reinforced RPC in this study will be the preferred material for special engineering area, such as airport pavement, military bunker engineering and nuclear fallout shelter. For further investigations, future experimental work may be directed towards exploring the electrothermal behavior and electromagnetic shielding effectiveness of SSSW reinforced RPC, and developing the sensing function to damage and crack propagation.

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Figures

(a) In diameter of 8 μm

(b) In diameter of 20 μm

Fig.1 Morphology of SSSWs

(a) Cyclic and monotonic compressive loading

(b) Flexural loading

Fig.2 The schematic of electrode layout and loading regime

(a) Water curing

(b) Natural curing

Fig.3 The electrical resistivity of SSSW reinforced RPC measured by using two-electrode-AC method

(a) W08, water curing

(b) W20, water curing

(c) W08, natural curing

(d) W20, natural curing

Fig.4 The electrical resistivity of SSSW reinforced RPC measured by using two-electrode-DC method

(a) W08

(b) W20

Fig.5 The electrical resistivity of SSSW reinforced RPC measured by using four-electrode-DC method

(a)

(b)

Fig.6 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W0805 under 7 times of cyclic compressive loading

(a)

(b)

Fig.7 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W0810 under 7 times of cyclic compressive loading

Fig.8 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W0815 under 7 times of cyclic compressive loading

Fig.9 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W2005 under 7 times of cyclic compressive loading

Fig.10 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W2010 under 7 times of cyclic compressive loading

(a)

(b)

Fig.11 Variation of the fractional change in electrical resistivity with stress (a) and strain (b) for W2015 under 7 times of cyclic compressive loading

(a) W0

(b) W0805

(c) W0810

(d) W0815

(e) W2005

(f) W2010

(g)W2015

Fig.12 The relationship between monotonic compressive strain, stress and fractional change in electrical resistivity of SSSW reinforced RPC

(a) W0

(b) W0805

(c) W0810

(d) W0815

(e) W2005

(f) W2010

(g)W2015

Fig.13 The relationships between flexural-tensile strain, stress and the fractional change in electrical resistivity of SSSW reinforced RPC (water curing)

(a) W0

(b) W0805

(c) W0810

(d) W0815

(e) W2005

(f) W2010

(g) W2015

Fig.14 The relationships between flexural-tensile strain, stress and the fractional change in electrical resistivity of SSSW reinforced RPC (natural curing)

(a) W0

(b) W0805

(c) W0810

(d) W0815

(e) W2005

(f) W2010

(g) W2015

Fig.15 EIS of SSSW reinforced RPC

(a) W0

(b) W0805

(c) W0810

(d) W0815/W2005

(e) W2010/W2015

Fig.16 The equivalent circuits of SSSW reinforced RPC

R_s -Pore solution resistance; R_{st} -Charge transfer resistance; L -Inductance; C_d -C-S-H gel surface capacitance; Z_w -Diffusion impedance; R_{sw} -SSSW resistance; C_{sw} -SSSW-matrix interface capacitance