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Piezoresistive behaviours of carbon black cement-based sensors with layer-distributed conductive rubber fibres

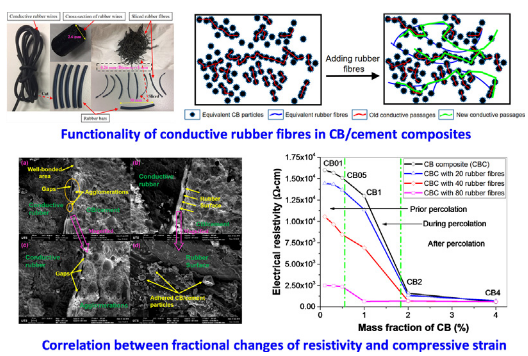
Wenkui Dong [a], Wengui Li [a,*], Luming Shen [b], Daichao Sheng [a]

[a] Center for Built Infrastructure Research, School of Civil & Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia
[b] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia

HIGHLIGHTS

- CB/cementitious composites with w/b ratios from 0.31 to 0.5 exhibit acceptable workability.
- The compressive strength of cementitious composites is sensitive to CB content.
- The electrical conductivity of CB/cementitious composites can be improved by conductive rubbers.
- Conductive rubber filled CB/cementitious composite is promising for structural health monitoring.

GRAPHICAL ABSTRACT



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ABSTRACT

Conductive rubber fibres filled carbon black (CB)/cementitious composites were developed to achieve the cement-based sensors with excellent piezoresistivity in this study. Ameliorations on the conductivity and piezoresistive sensitivity of CB filled composites were mainly explored with conductive rubber fibres embedded. Their compressive strengths were investigated to evaluate the practical application possibility. The results indicated that the composites with CB content <4.0 wt% possessed acceptable compressive strengths. In terms of conductivity and piezoresistivity, both conductivity and piezoresistivity of composites filled with 0.5 wt% CB increased with the rubber content, and their gauge factor raised to 91 when embedded with 80 rubber fibres (1.27 vol%). Moreover, phenomenon of "piezoresistive percolation" was observed by sharp fractional changes of resistivity for the composites filled with 1.0 wt% CB, where existed highest gauge factor reaching 482 when embedded with same rubber fibres. However, because of the excellent conductivity of 2.0 wt% CB filled composites, the gauge factor firstly increased but then slightly decreased around 100 with increase of rubber fibre content. Overall, conductive rubber fibres can significantly improve the piezoresistivity of CB/cementitious composites by the increased gauge factor.

1. Introduction

Cement-based materials are widely used in infrastructure construction for its low costs, excellent engineering properties and durability. However, the properties of electrical isolation restrict its further

* Corresponding author at: School of Civil & Environmental Engineering, University of Technology Sydney.
E-mail address: wengui.li@uts.edu.au (W. Li).

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development in the field of intelligent structures. Recently with more expectations on the intrinsic smart structures and buildings, many investigations have been conducted to pursue a higher electrical conductivity of cement-based composite, through which the structures could be provided with damage assessments [1], strain sensing [2–6], electromagnetic interference shielding [7–9], corrosion sensing [10,11], self-heating [12,13] and traffic monitoring abilities [14–16]. The process of significant resistivity reduction is called percolation, which means the minimum conductive fillers to generate the continual conductive passages and decrease resistivity [17,18]. Generally the electrical resistivity of cement-based materials is 10^6 to 10^9 $\Omega\cdot$cm, which could plunge to 10 to 10^5 $\Omega\cdot$cm with assistance of filled conductive particles or fibres [19,20]. On the other hand, it has been demonstrated that the conductive fibres reinforced cementitious composites possess a higher tensile and flexural strength and ductility due to the pull-out effect by fibres [21,22], and a superior compressive strength and compactness for conductive particles filled composites because of the filling effect [23,24]. For instance, Song *et al.* [25] observed that the 2.0% volume fraction of steel fibre reinforced concrete achieved a 98.3% improvement in splitting tensile strengths. Konsta-Gdoutos and Al-Dahawi et al. [26,27] tested the mechanical properties of carbon nanotubes (CNTs) reinforced cementitious composite and found a significant amelioration in compressive strength with only 0.048% and 0.55% CNTs by weight of binder, respectively.

Compared to the above-mentioned steel fibre or CNTs, conductive carbon black (CB) has a much cheaper price, but also possesses satisfied electrical conductivity and particle size. Generally, carbon black based polymer composites are mostly investigated to manufacture tyres or strain sensors [28–30]. However, previous studies have discovered that the conductive CB possessing excellent electrical conductivity could improve the conductivity of cement-based composite by a large margin, while slightly enhancing the mechanical properties of cement-based composite [31]. Li *et al.* [32] explored the compression strain sensing ability of carbon black filled cementitious composites and found its conductive percolation threshold being in the range of 12%–20% to the weight of cement, where the electrical resistivity decreased from 10^4 to 10^2 $\Omega\cdot$cm. However, for the same scope of resistivity reduction, the percolation threshold for CB/cement composite was only 0.7 wt%–2.5 wt% by Dai *et al.* [23], whose discrepancy from Li *et al.* [32] might be owing to their different dispersion efficiencies, particle sizes and specimens drying methods. It is also worth noting that the sensitivity of CB filled composite is always lower than that of the cement-based composite with CNT, CNF or any other frequently-used conductive particles or fibres, whose fractional changes of resistivity fluctuated in the range of 10–20% [32], and even lower to 3% [33], hence greatly limit the wider application of CB in the cement-based composites.

On the other hand, non-degradable rubber wastes cause severe environmental issues and deviate from the principles of sustainable community. Implementing rubber wastes into cement-based materials could relieve the above-mentioned ecological and economic stress, and bring specific advantages to the cement matrix such as better ductility, deformability and energy-absorption ability [34–36]. Conventional rubber wastes are isolated with high resistivity, until the emergence of special rubber products whose excellent electrical conductivity is essential to modern military, aviation and electronics industry. It has been found that the conductive rubber have capacity to improve the electrical conductivity of cementitious composites [37]. The conductive rubber products are manufactured through evenly dispersing small conductive particles, such as carbon black, aluminium powder or silver powder, into the polymeric matrix, hence decreasing the resistivity of rubber composite to only from 10^{-2} to 10^2 $\Omega\cdot$cm.

In this study, the conception of using above conductive rubber products on the CB/cement composites to explore its conductivity and piezoresistivity is proposed, as the CB filled cement-based composites exhibit poor sensitivity with less fractional changes of resistivity to strain. The carbon black/cement-based composites coupled with conductive rubber fibres and the superiorities by conductive rubber fibres on the conductivity and piezoresistivity of CB/rubber cementitious composites were experimentally investigated. Meanwhile, the mechanical and physical properties of the CB/rubber cement composites were also studied to explore the possibility of application for concrete infrastructures.

2. Experimental program

2.1. Raw materials

Conductive rubber wires filled with carbon black particles were collected from Jones Tech Co., Ltd., China, and its physical and mechanical properties are listed in Table 1. Previous studies demonstrated that the conductive fibres with higher aspect ratio have better performance than that with small aspect ratio or conductive particles in piezoresitivity of cement-based composites [38]. To obtain a more sensitive composite, those rubber wires were artificially cut into small rubber bars with 30 mm in length, then sliced into 8 rubber fibres per bar before coming into service. The original rubber wires have cross-section of 2.6 mm in diameter, and the sliced rubber fibres have the diameters from 0.26 to 1 mm. The specific procedure of conductive rubber fibres fabrication is displayed in Fig. 1. CB was purchased from the Xinxiang Deron Chemical Co., Ltd., China, and its physical and chemical properties are displayed in Table 2. General purpose cement provided by Independent Cement & Lime Pty. Ltd. and silica fume sourced from Concrete Waterproofing Manufacturing Pty. Ltd., Australia were used throughout the tests. High range water reducer produced by SIKA Australia Co., Ltd. was used to improve the dispersion of carbon black in composite, as well as to improve the felicitous workability.

2.2. Rheology of CB filled composites

A simplified method to disperse CB was conducted under the cooperation of water and high range water reducer. However, the issues of super hydrophilic and water absorption characteristics of CB particles are often overlooked while experimentally studying the CB filled cement-based composites. Investigators have found that different mixing methods and contents of carbon-based conductors reinforced cementitious composites cause various fluidity of cement paste [39–41], and similarly, the use of CB greatly influence the workability of composite [33]. Hence in this test, the adjustment of water to binder (w/b) ratio and the content of water reducer are significant to achieve the composites with similar workability. Five groups of composites with different amounts of CB (0, 0.5 wt%, 1.0 wt%, 2.0 wt% and 4.0 wt %) were conducted with both 20% silica fume substitution ratio to cement, to increase the density of composites and piezoresistivity [3,42]. The content of water reducer in each group depended on the proportion of CB, by 0.8% to the weight of binder (containing cement and silica fume) for the composites without CB, 1.0% for the composites with 0.5 wt% or 1.0 wt% CB, and 1.2% for composites with 2.0 wt% and 4.0 wt% CB. Different w/b ratios for each group were carried out, followed by the measurement of penetration depth by the Vicat apparatus. The measurements were conducted after 3 h curing, and the penetration depths for CB filled composites varied with different water to binder ratios, as shown in Fig. 2.

For the composites with 0.5 wt% CB, 2.0 wt% CB and 4.0 wt% CB, the w/b ratios at 0.3, 0.35 and 0.45 respectively, could result in very poor workability of composite. These composites were labelled as "failed" because of the too low flow ability to stir, cast and shape during experiments. Contrarily, the red bars in Fig. 2 represent the excessive flow ability of the composites with large water to binder ratios, which even exceed the measurement range of Vicat apparatus (40 mm). In general, the penetration depths of green bar for composites with different contents of CB were very close compared to the red and blue bars. As a

Table 1
Physical and mechanical properties of conductive rubber fibres.

Rubber types	Conductive fillers	Density (g/cm^3)	Volume resistivity (Ω·cm)	Tensile strength (MPa)	Elongation (%)	Shore hardness	Ambient temperature (°C)
Conductive rubber	Carbon black	2.1 ± 0.25	0.1	1.5	230	70 ± 5	−55–160

consequence, different mix proportions were selected as shown in Table 3 based on the similar workability of CB filled composites. In Dai *et al.* [23], the water to binder ratios were from 0.27 to 0.38 to obtain satisfactory workability. The difference may come from the silica fume applied in this test.

2.3. Specimen preparation

As for the specimen preparation, firstly, add half of water into Hobart mixer, before the CB is added and mixed with the water for 3 min at the high rate. Then, prepare another half of water and mix with high range water reducer, which were gently poured into the mixer through the sides of inner wall and stirred at a low speed for another 3 min. In the first stirring, without water reducer, few air bubbles are created to ensure a maximal CB dispersion. In the second stirring, water and water reducer further increased the CB flowability in the container, and reduced the non-uniformity to improve the dispersion of CB.

After the preparation of CB solution, the cement and silica fume were added into the container and mixed for another 3 min, and then the composite was poured into the oil treated moulds (50 mm × 50 mm × 50 mm) at the 20 mm height and was vibrated. Then half of the conductive rubber fibres which are air-dried for a week beforehand were randomly placed in the composites. This was followed by adding composites to 30 mm height and arranging the left half rubber fibres. Afterwards, the mould was filled up to the top surface. Two copper meshes with thickness of 0.5 mm, width of 35 mm and length of 65 mm were symmetrically embedded into the cubic composites as electrodes with the average space of 30 mm before another vibration carrying out. For each type of specimen with various contents of CB and rubber fibres, three duplicated specimens were prepared to carry out the mechanical tests and two duplicated specimens for the piezoresistive tests. The specimens are placed in the standard curing chamber for 1 day, followed by being demolded and marked, then cured in the chamber with standard curing environments with the temperature at 25 ± 2 °C and humidity of 95% for another 27 days.

2.4. Measurement of electrical resistivity

Results demonstrate that the alternative current (AC) is better than the direct current (DC) for the resistance measurement by greatly eliminating the effects by polarization [43,44]. Therefore, function generator was connected into the series circuit of resistor (R) and cement specimen as power supply, and an oscilloscope was attached to measure the voltages of the resistor (R) and generator. During the process, the frequency of AC was fixed to 1 kHz and the voltage amplitude was 20 V. For every 2 min, the circuit was switched-off to measure the resistance of the resistor, and the stable resistance values showed no obvious heat generation throughout the process.

According to the above description on the circuit, the resistance of cementitious composites could be calculated by Equations as follows:

$$V_{input} = V_R + V_C \tag{1}$$

$$I = \frac{V_R}{R_R} \tag{2}$$

$$R_C = \frac{V_C}{I} = \frac{V_C}{\frac{V_R}{R_R}} = \frac{R_R V_C}{V_R} \tag{3}$$

where V_{input} denotes the input voltage by function generator, and V_R and V_C are the voltages of the resistor and specimen in Volt, respectively; I represents the current in circuit in Amp, and R_R and R_C are the resistance of the resistor and cement specimen in Ohm, respectively. Afterwards, the electrical resistivity was calculated based on Eq. (4), and the fractional changes of resistivity could be calculated by Eq. (5) as follows:

$$\rho_C = \frac{R_C S}{L} \tag{4}$$

$$FCR = \frac{\Delta\rho}{\rho_C} \times 100\% \approx \frac{\Delta R}{R_C} \times 100\% \tag{5}$$

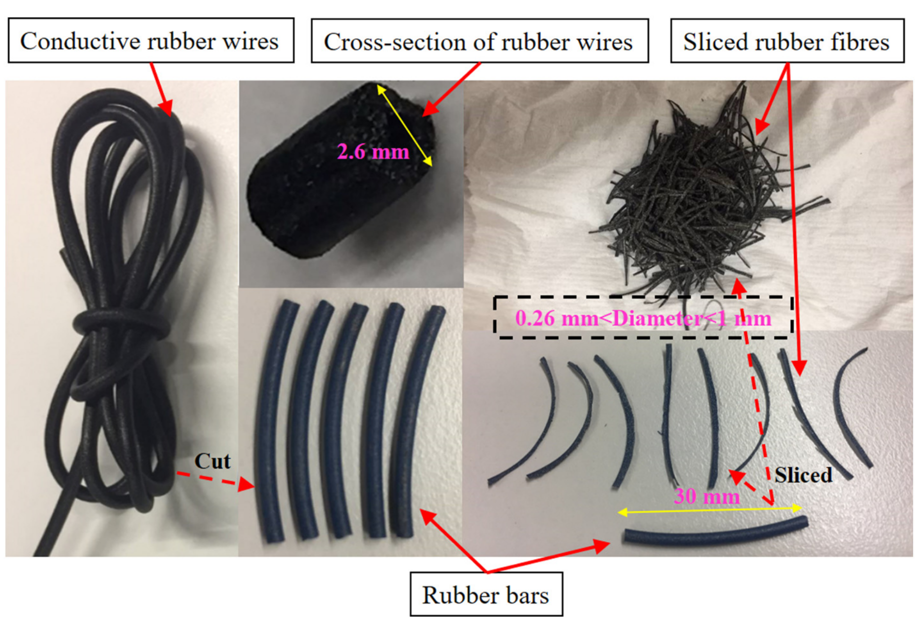


Fig. 1. Sliced conductive rubber fibres to make rubber fibres.

Table 2
Main physical and chemical properties of carbon black (CB).

Particle size (nm)	Resistivity (Ω·cm)	Pour density (g/l)	DBP* (ml/100 g)	Surface area (m^2/g)	pH	Ash content (%)
20	<0.43	0.375	280	254	7.5	<0.3

Note: DBP* means the dibutyl phthalate.

where ρ_C means the initial electrical resistivity of cementitious composite in Ω·cm; S the contact areas of the copper meshes to specimens in square centimetres (cm^2); L the distance between two copper meshes, unit: cm. FCR fractional changes of resistivity of cementitious composites; $\Delta\rho$ and ΔR are the resistivity and resistance changes of composites during compression tests, respectively. Eq. (5) depicts that the fractional changes of resistivity equals to the fractional changes of resistance, when the deformation of composites is very small compared to its size.

3. Results and discussions

3.1. Mechanical properties

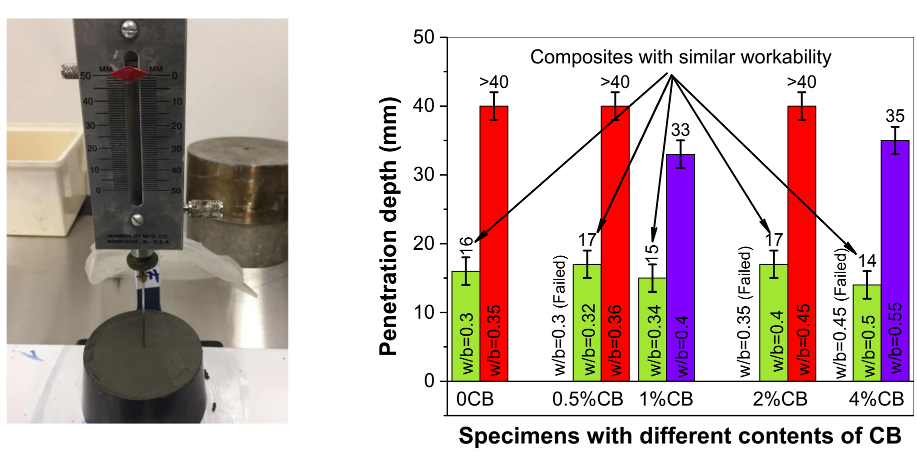
3.1.1. CB/cement composites

The composites filled with 0.1 wt% and 0.5 wt% CB were provided with excellent compressive strength of both higher than 50 MPa, and similar to the plain cement paste with 55 MPa. It can be considered that small amount of CB particles could fill up the micro pores in composite and improve the compressive strength, while negativities were also accompanied by larger w/b ratios. However, considerable strength decreases occurred when the CB content was larger than 1.0 wt% to the weight of binder, where the reduction rate reached 32.7%, 56.4% and 72.7%, respectively for the content of 1.0 wt%, 2.0 wt% and 4.0 wt% CB filled composites, with only 37 MPa, 24 MPa and 15 MPa remained, respectively. The reasons for their differences mainly came from the special physical characteristics of CB, which possessed excellent water absorption ability. Therefore, the CB particles had the capacity to absorb water content or attach on the cement surface when being mixed with cement mixture, which affected the cement hydration process. Fortunately this could be partially solved by adding more water according to the amount of CB in the composite, as shown in Table 3. On the other hand, CB particles with surface energy were extremely inclined to absorb together and form agglomerations and clusters, which showed no resistance to the loading forces compared to the harden hydration products.

3.1.2. CB/rubber fibres filled cement composites

The compressive strength of the conductive rubber fibres added CB/cement composite is shown in Fig. 3, with the rubber amount from 20 fibres (0.32 vol%), 40 fibres (0.64 vol%) to 80 fibres (1.27 vol%), and the CB content from 0.1 wt%, 0.5 wt%, 1.0 wt%, 2.0 wt% and 4.0 wt% to the weight of binder. Generally the compressive strength decreased with increase of rubber fibres for all the groups. For the composites with <1.0 wt% CB and 80 rubber fibres (1.27 vol%), the strength was still higher than 35 MPa, while the value decreased significantly to lower than 20 MPa when the CB content was more than 2.0 wt%, from which it could be deduced that the detriments caused on the compressive strength reduction by CB were more serious than its counterpart by rubber fibres. The strength reduction by the addition of CB may be attributed to poor cohesion between cement matrix and CB agglomerations. In addition, cement particles encircled by high surface energy of CB might block hydration and generate gaps and cracks. On the other hand, the reason for the degraded strength by rubber fibres comes from the lower strength and modulus of rubber itself, and most importantly, the weakened interfacial transition zones between rubber fibres and CB agglomerations and between rubber fibres and CB/cement matrix. Therefore, microstructures of the rubber/CB cementitious composites were characterized to identify the week regions in the boundaries of the three phases.

Fig. 4 illustrates the interfacial transition zones (ITZs) between rubber and CB agglomerations and between rubber surface and CB/cement matrix. The interfaces between rubber and CB agglomerations are displayed in Fig. 4(a) and (c), which shows loose boundaries of rubber fibres, gaps and CB/cement matrix. Obviously, the dense areas were more likely in the locations without CB agglomerations, and the small gaps out of poor cohesion tended to typically appear with CB agglomerations. In the magnified Fig. 4(c), obvious relationship between the gaps and agglomerations could be deduced since more than three gaps were created along with the agglomerations. In terms of the surface characteristic of rubber fibre in Fig. 4(b), continual gaps existed even in the well dispersed region and pronounced weak cohesion between rubber fibre and cement matrix. The cause of poor cohesion was probably due to the nature of materials, such as differences in dry shrinkage, or



(a) Vicat apparatus (b) Penetration depth

Fig. 2. Penetration depth of composites with different water to cement ratios.

Table 3
Mix design of CB/conductive rubber fibres filled cementitious composites.

Carbon black content (wt.* %)	Number of rubber fibres	Rubber content (vol.* %)	Cement	Silica fume	Tap water	Water reducer (wt%)
0	0	0	0.8*	0.2	0.3	0.8
0.1	0	0	0.8	0.2	0.31	0.8
	20	0.32	0.8	0.2	0.31	0.8
	40	0.64	0.8	0.2	0.31	0.8
	80	1.27	0.8	0.2	0.31	0.8
0.5	0	0	0.8	0.2	0.32	1.0
	20	0.32	0.8	0.2	0.32	1.0
	40	0.64	0.8	0.2	0.32	1.0
	80	1.27	0.8	0.2	0.32	1.0
1.0	0	0	0.8	0.2	0.34	1.0
	20	0.32	0.8	0.2	0.34	1.0
	40	0.64	0.8	0.2	0.34	1.0
	80	1.27	0.8	0.2	0.34	1.0
2.0	0	0	0.8	0.2	0.4	1.2
	20	0.32	0.8	0.2	0.4	1.2
	40	0.64	0.8	0.2	0.4	1.2
	80	1.27	0.8	0.2	0.4	1.2
4.0	0	0	0.8	0.2	0.5	1.2
	20	0.32	0.8	0.2	0.5	1.2
	40	0.64	0.8	0.2	0.5	1.2
	80	1.27	0.8	0.2	0.5	1.2

Note: wt.* means the mass fraction of carbon black to the sum of cement and silica fume (binder); vol. means the volume fraction of rubber fibres to one cubic specimen (50 mm × 50 mm × 50 mm); figures under the cement, silica fume, water and water reducer present their ratios to the weight of binder, for example, 0.8* under cement presents the cement to binder ratio of 0.8.

thermal expansion between rubber fibres and CB/cement matrix. Furthermore, the smooth surface of rubber might reduce the adhesion of CB/cement matrix, as shown in Fig. 4(d), with only small blocks of CB/cement adhered, rather than continual CB/cement hydration products.

3.2. Conductivity percolation of composites

3.2.1. CB/cement composites

The electrical resistivity of the CB/cement composites only filled with different contents of CB, generally decreased with the increase of CB, and the reduction tendency was significant within the percolation threshold, but became more obscure when beyond the percolation range. In this study, the percolation threshold of CB filled cement-based composite was in the ranges of 0.5 wt% to 2.0 wt%, and the initial percolation threshold was approximately 0.5 wt% to 1.0 wt% as shown in Fig. 5. This was very close to the results of Dai *et al.* [23], but with further improvements in narrowing down the percolation ranges.

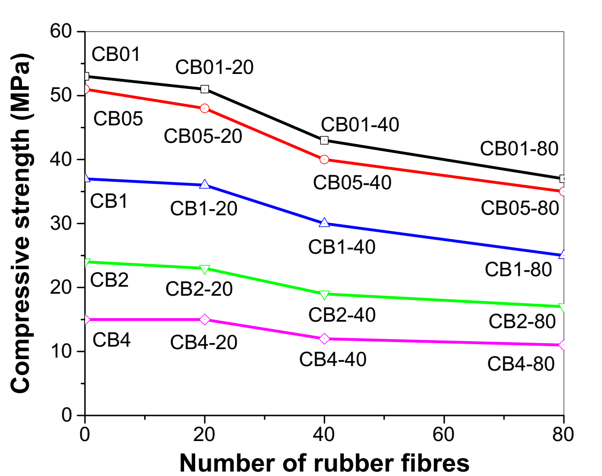


Fig. 3. Compressive strength of different contents of CB/rubber fibres cementitious composite.

3.2.2. CB/rubber filled cement composites

This section discusses the conductive rubber fibres mixed with the above-mentioned CB composites, to track the trace of percolation threshold of rubber/CB cementitious composites under the influence of conductive rubber fibres. The only CB filled composites, and the rubber/CB filled composites with 20 (0.32 vol%), 40 (0.64 vol%) and 80 (1.27 vol%) conductive rubber fibres were investigated and compared in accordance of their resistivity development, as displayed in Fig. 5. The composites with 20 rubber fibres (0.32 vol%) exhibited slightly lower resistivity than that without rubber fibres, and that tendency became more noticeable for the composite with 40 (0.64 vol%) conductive rubber fibres. The end of percolation worked as demarcation point, and two sections were created with one being before/in the process of percolation and another being at the stage after the percolation. In the first section, the electrical resistivity was sensitive to the amount of rubber fibres and an obvious reduction could be observed with the increase of rubber fibres. However, this reduction was gradually decreased and significantly narrowed after the percolation. For the composites with 4.0 wt% CB, the effect of conductive rubber fibres on electrical resistivity was nearly disappeared. Similar results were observed from the composites with 80 rubber fibres (1.27 vol%), the influence by conductive rubber fibres was negligible when the CB content exceeded 1.0 wt%.

In terms of the percolation threshold, the composites with only CB had initial percolation threshold from 0.5 wt% to 1.0 wt,%, which decreased with the increase of rubber fibres and dropped as low as 0.5 wt% for the same composite embedded by 80 rubber fibres (1.27 vol%). It indicates that the conductive rubber fibres could lower the threshold and make the composite easier to achieve percolation. This phenomenon could be explained by the schematic diagrams in Fig. 6. The conductive passages (red lines) might exist when the CB content was low with the majority of CBs being short and separated. Thus, the resistivity of composites was relatively high. Howbeit with the assistance of conductive rubber fibres (blue lines), the separated conductive paths gradually contacted with each other and linked to form continual conductive passages, which presented resistivity decrease. The more rubber fibres, the more connected conductive passages, and the lower resistivity the composites exhibited. Nevertheless, for the composites with CB content exceeding the percolation threshold, where conductive passages already formed and connected, limited impacts could be provided by the conductive rubber fibres, and that may be the reason for the negligible influences after percolation in the second section in Fig. 5.

On the other hand, apart from the aforementioned conductive mechanism along the fibres longitudinal direction, special conductive passages could be established through the rubber fibres from different layers. In the transversal surface of the CB/rubber filled composite, different kinds of conductive passages could be created by the two conductive phases' linkage of rubber fibres to the dispersed CB particles, rubber fibres to CB agglomerations or the interconnections between rubber fibres, CB particles and agglomerations themselves. Predictably, the vertical conductive paths could not only lower the volume resistivity, but somewhat improve the conductivity in the direction of rubber fibres. Overall, it was the electrical conductivity amelioration on both longitudinal and transversal directions by conductive rubber fibres that improve the conductivity and reduce the percolation of the CB/cement composites.

3.3. Piezoresistivity behaviours

With the consideration of the electrical conductivity amelioration by CB, and the previous mentioned significant negativities on compressive strength of the CB filled cementitious composites (approximately 15 MPa remained for 4.0 wt% CB), three groups of composites with CB contents of 0.5 wt%, 1.0 wt% and 2.0 wt%, and embedded with 0, 20

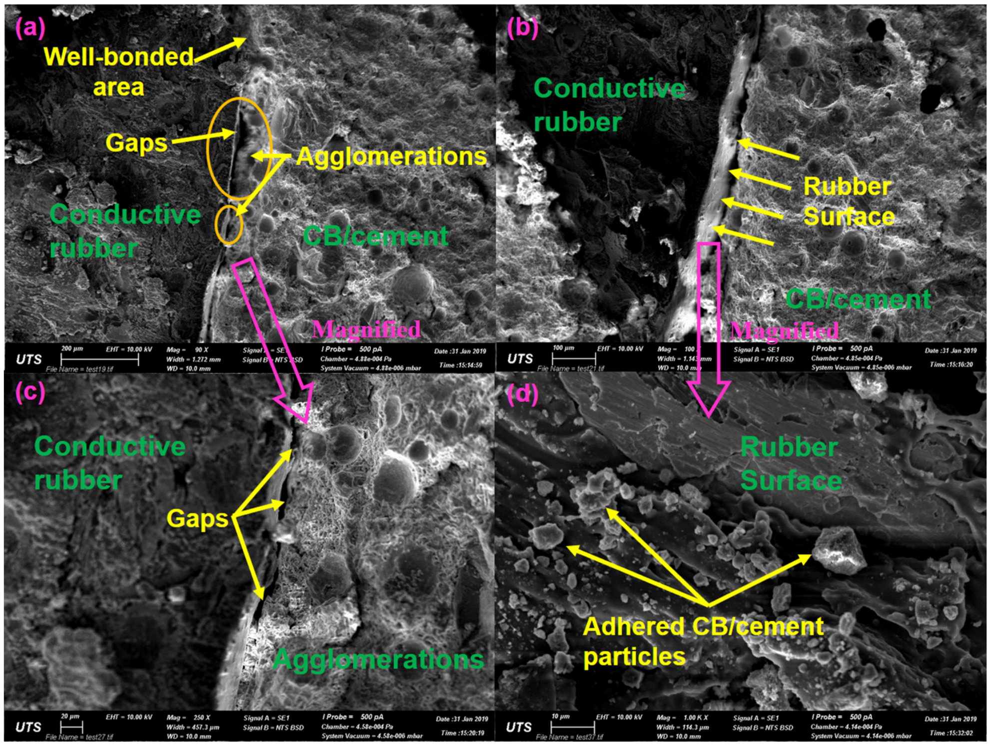


Fig. 4. Microstructures of the interfacial transition zone (ITZ) between rubber and CB/cement.

(0.32 vol%), 40 (0.64 vol%) and 80 (1.27 vol%) rubber fibres were chosen to study their piezoresistive dependence on the conductive rubber. In addition, previous studies found the types, contents, sizes, shapes and configurations of conductors in the cementitious composite and other influential factors such as environmental temperature and humidity, composite's rheology, curing and drying methods, and so on to achieve excellent piezoresistivity [45–53], but ignored the piezoresistive performance in different stages during resistivity reduction, namely prior to percolation, during percolation and after percolation, as shown in Fig. 5. Not only the chosen groups maintained satisfactory compressive strengths and ameliorated electrical conductivity, but also in different stages of before, during and after percolation, thus different piezoresistive characteristics of CB/cement composites before/after percolation threshold should be investigated.

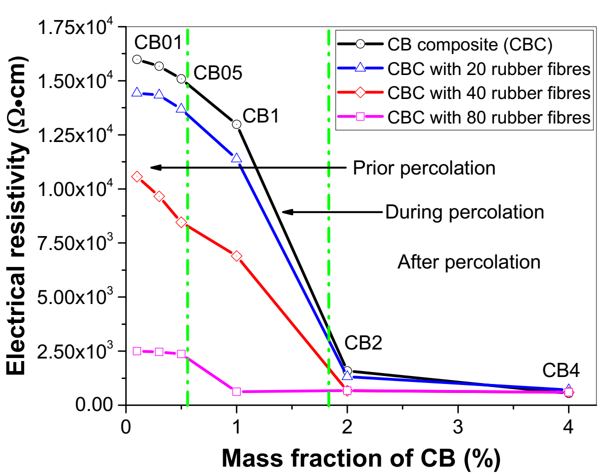


Fig. 5. Resistivity as a function of different contents of CB composites with various amounts of rubber fibres.

3.3.1. Composites with 0.5 wt% CB

Fig. 7 illustrates the fractional changes of resistivity for the composites filled with 0.5 wt% CB and embedded by different amount of conductive rubber fibres. The selection of approximately 2000 με as the ultimate strain is to ensure that the composites at the elastic stages, which outputs a more stable strain to determine the fractional changes of resistivity and gauge factor. Among them, positive correlation between fractional changes of resistivity and strain could be observed. Moreover, since the loading process was stress-controlled compression, it could be observed that the composites with larger rubber content reached the preset strain quickly because of the lower stiffness and elastic modules induced by conductive rubbers.

For the composites without rubber, more stable outputs of fractional changes of resistivity were observed, with the ultimate changes reaching 10.6%. The gentle resistivity increase at the beginning was owing to the polarization of composites, which could be negligible compared with the resistivity reduction caused by the compressive strain. For the composites with 20 rubber fibres (0.32 vol%) embedded, whose fractional changes of resistivity were fluctuated with compressive strain, was provided with slightly better piezoresistivity to 12.5%. Furthermore, when the rubber content increased to 40 (0.64 vol%) and 80 (1.27 vol%) fibres, the maximal fractional changes of resistivity rose to 15.0% and 20.1%, respectively, which were accompanied by more vulnerable fractional changes of resistivity, and both with sudden decreases. In general, there were two main reasons responsible for the resistivity fluctuation, including cracks and pores inside specimens and the interference from the conductive rubber. The distinguish of these two factors for resistivity fluctuation could be carried out by means of compressive strain observation, which was often smooth and continual in the process of loading for the dense and compact composite, but followed by sudden changes if there were cracks and pores inside the composite. In terms of the effect by conductive rubber, the existing contacted nearby rubber fibres might be detached or the separated ones might be connected in the process of loading, which greatly affects the electrical resistivity of the composites.

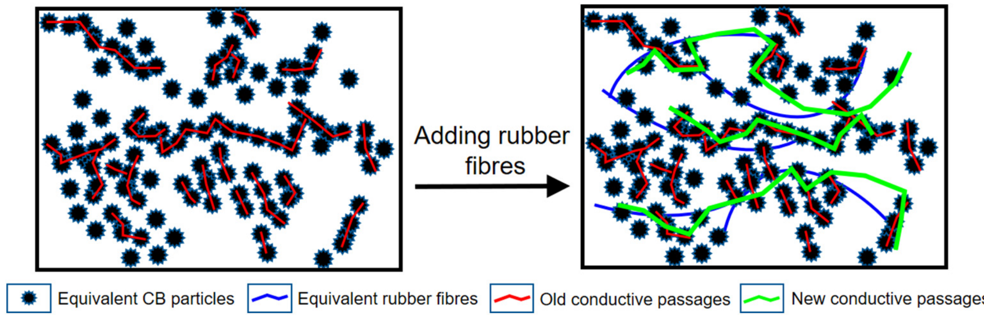
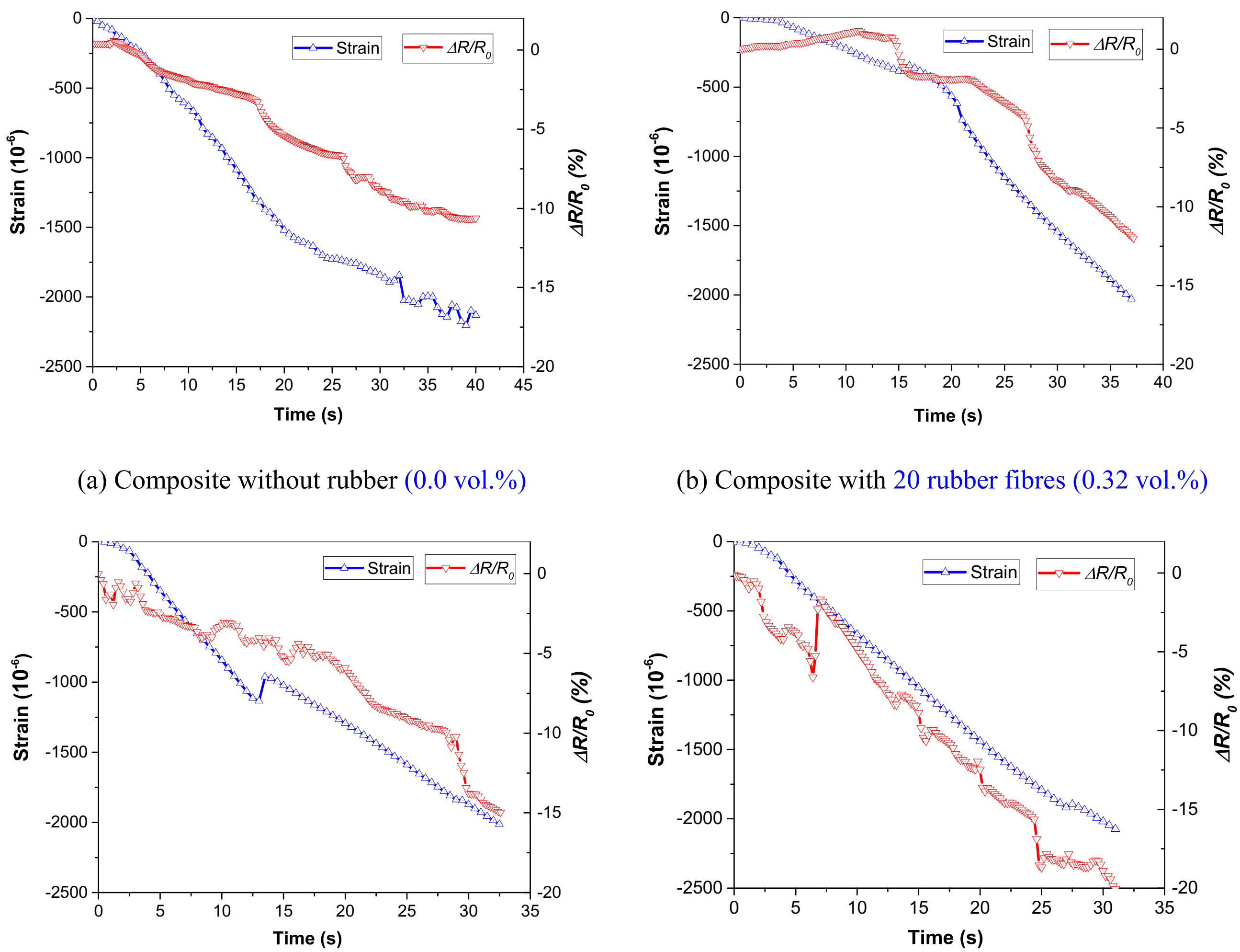


Fig. 6. Schematic diagram of the functionality of conductive rubber fibres on CB/cement composite.

Although the changes of resistivity unstably increased with strain, especially for the composites embedded with rubber fibres, similar increase patterns could be seen from both strain and fractional changes of resistivity for all the composites. To better understand their relationship and the gauge factor, Fig. 8 depicts the correlation between compressive strain and the fractional changes of resistivity for different rubber contents embedded composites, where specially established linear fitting formulas for the composites to show their gauge factors. It was observed that the fractional changes of resistivity to strain curves were almost straight lines for both composites, especially when eliminating the sudden resistivity changes caused by the pores/cracks. Hence, in consideration of the elastic loading regime during compression, it indicated that the CB/rubber cement-based composite possess acceptable performances to self-monitor its compressive strain. As shown in Fig. 8, the slopes of the fitting lines represented the gauge factors to evaluate the piezoresistive sensitivity of CB/rubber cementitious composite (the following figures are deviations). For the composites without rubber and the counterparts embedded with rubber fibres



(a) Composite without rubber (0.0 vol.%)

(b) Composite with 20 rubber fibres (0.32 vol.%)

(c) Composite with 40 rubber fibres (0.64 vol.%)

(d) Composite with 80 rubber fibres (1.27 vol.%)

Fig. 7. Fractional changes of resistivity for 0.5 wt% CB/cementitious composites.

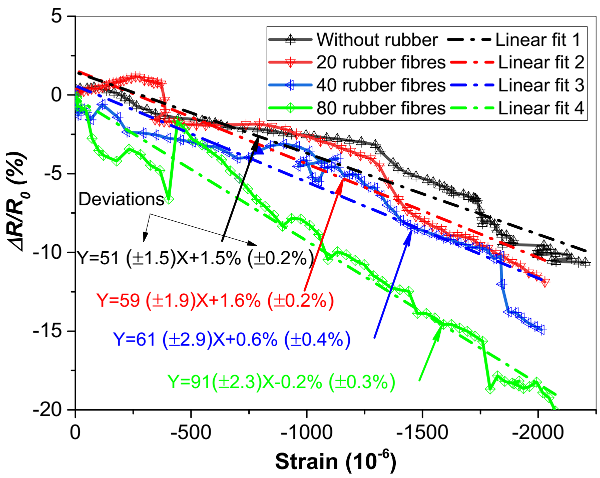


Fig. 8. Relationship between fractional changes of resistivity and compressive strain and their linear fittings for the 0.5% CB/cementitious composites.

contents from 20 (0.32 vol%), 40 (0.64 vol%) to 80 (1.27 vol%), their gauge factors were 51, 59, 61 and 91, respectively. In comparison to the composites only filled with CB, positive effects could be seen that the gauge factors of CB filled composites embedded with conductive rubber were significantly increased with the growth rate reaching 15.7%, 19.6% and 78.4%, with 20 (0.32 vol%), 40 (0.64 vol%) to 80 (1.27 vol%) rubber fibres, respectively.

To compare the results with other studies, Monteiro et al. [33] investigated the CB/cementitious composite and obtained the gauge factor of approximately 25 under 10 cycles of cyclic compressive loading. It was achieved higher gauge factor of 45 by using better CB dispersion technology of sonication [54]. Furthermore, Li *et al.* [32,55] obtained gauge factor of approximately 55 for CB composites, and their CB dispersion method was through water reducing agent and deformer rather than sonication. Generally, one reason for their gauge factors discrepancy probably is due to the different CB content, and the CB cementitious composite from Li *et al.* [32,55] seems to have better electrical conductivity and thus possesses a higher gauge factor. Another reason is the aggregates, which obviously decreased the gauge factors in Monteiro *et al.* [54]. In this study, the gauge factor of the cementitious composite only filled with 0.5 wt% CB was 51, similar to the other values. The instable outputs were possibly due to the lack of drying process, and the higher gauge factor might be due to the positive effects by silica fume. Overall, the gauge factor amelioration of the CB/cementitious composite was achieved by the embedded conductive rubber fibres, which increased to the value of 91 when the composite was embedded with 80 rubber fibres (1.27 vol%).

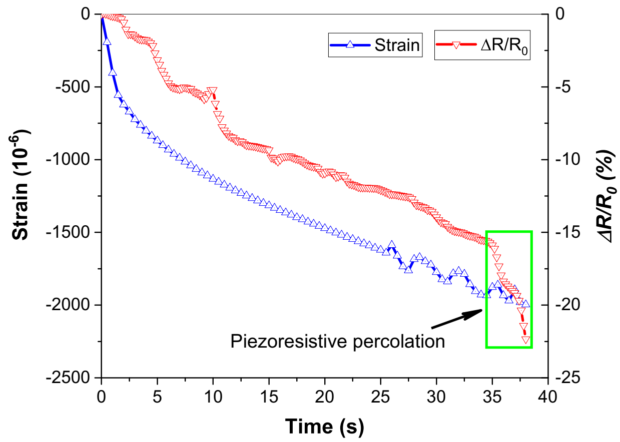
3.3.2. Composites with 1.0 wt% CB

Cementitious composites filled with 1.0 wt% CB were really close to reach the percolation threshold, where slight variations of conductive fillers might result in considerable resistivity changes as shown in Fig. 5. Similarly, it could be foreseen that there existed significant fractional changes of resistivity if the phenomenon of percolation took place simultaneously when the composite subjects to external loadings. Given the lack of description of piezoresistivity during electrical percolation, new definition on the word of “piezoresistive percolation” was proposed, to represent the sudden increase in fractional changes of resistivity or piezoresistivity and distinguish from the concept of generally used electrical percolation.

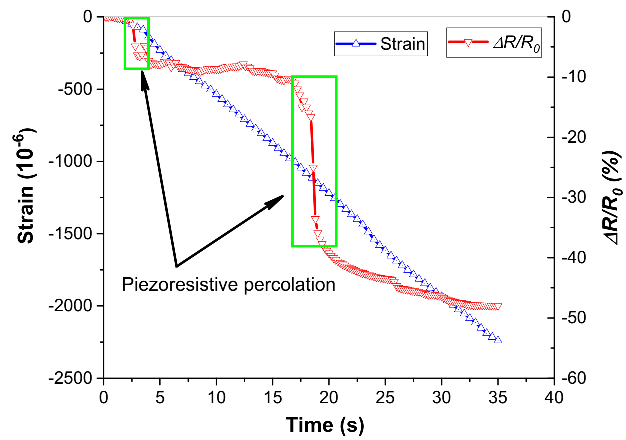
For the 1.0 wt% CB/cementitious composites without rubber fibres, higher fractional changes of resistivity were observed than that filled with 0.5 wt% CB, reaching approximately 22% as shown in Fig. 9(a). Furthermore, a rapid decrease of resistivity which was defined as piezoresistive percolation was emerged when the strain got close to the ultimate value. Considering that the content of 1.0 wt% CB were close to the percolation threshold of CB/cementitious composites, where small concentration changes of conductors could result in tremendous electrical signal fluctuation, the significant conductivity amelioration was very likely owing to the higher conductor's concentration in the composites under larger compressive strain, because of the compressed pores, cracks and the specimen itself. As for the same composites embedded with 20 rubber fibres (0.32 vol%), whose final fractional changes of resistivity reached nearly 49%, a small piezoresistive percolation occurred in the early compression stage in Fig. 9(b). It was considered that the sudden resistivity reduction was mainly originated from the rubber fibres, which might be connected with each other in a small proportion of composite, due to the fact that the compressive strain was small and the impacts from conductor's concentration could be neglected. Moreover, the conductive rubber fibres in the length of approximately 30 mm were nearly equal to the distance of two electrodes. Although these were flexible materials which can be curved or folded, the resistivity reduction caused by the rubber fibres was still faster than that by the compressive strain. Similarly, three piezoresistive percolations are illustrated for the 1.0 wt% CB filled composite with 40 rubber fibres (0.64 vol%) in Fig. 9(c), with the fractional changes of resistivity increasing to nearly 10% at the first piezoresistive percolation, approximately 40% at the second piezoresistive percolation, and slight higher than 80% at the last percolation. The first and second piezoresistive percolations were mainly due to the touch and connections between the rubber fibres, and the last piezoresistive percolation which led to a larger fractional changes of resistivity, was due to the combined actions of both rubber fibres and higher conductor's concentration under larger compressive strain. However, different from the other composites, a much severe piezoresistive percolation occurred for the composites with 80 rubber fibres (1.27 vol%), by the fractional changes of resistivity increasing from 10% to 100% in the middle stage of compression, then followed by a resistivity increase to the value of approximately 80%, as shown in Fig. 9(d). Even the composite with 80 rubber fibres (1.27 vol%) was provided with excellent conductivity, it can be seen that the significant resistivity reduction is because of the more connections between rubber fibres to form shortest conductive passages in the composite. Moreover, closer contact between the rubber fibres also resulted in a lower contact resistance and brought better conductivity. In terms of the reduced fractional changes of resistivity, one reason was related to the cracks which altered compressive strain values synchronously, and another one came from the dislocation and detach between rubber fibres, since the high compressive strain might destroy the already connected rubber fibres and increase the resistivity.

Fig. 10 represents the fractional changes of the resistivity as a function of compressive strain for the 1.0 wt% CB filled composites with/without rubber. It indicates that the composite only filled with 1.0 wt % CB performed close linear relationship between fractional changes of resistivity and strain, while the composites embedded with rubber fibres had abrupt changes in the resistivity because of conductive rubber interference. As for the piezoresistive sensitivity, according to the linear fits, much higher gauge factors were observed, reaching the values of 114, 251, 375 and 482 for the composites without rubber, and the counterparts with 20 (0.32 vol%), 40 (0.64 vol%) and 80 (1.27 vol%) rubber fibres, respectively. In comparison to the usually dried cementitious composites filled with CB, which possess average gauge factor of 50 [32,33,54,55], the experimental results were at least twice of that value, and even improved by eight times for the composite with 80 rubber fibres (1.27 vol%). Moreover, compared with the commercial strain gauge, which has gauge factor of 2, the piezoresistive sensitivity was increased by hundreds of times.

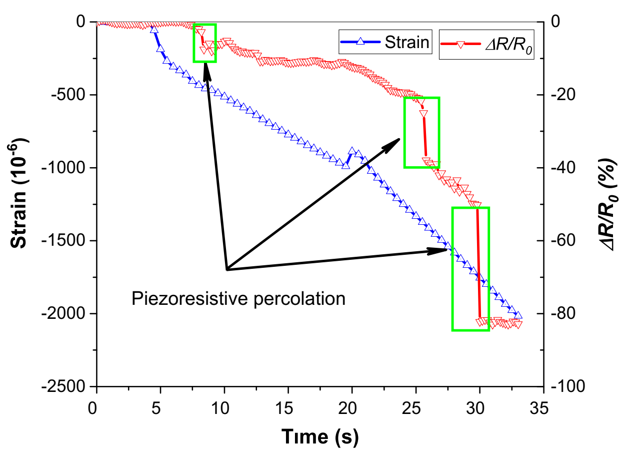
Different from the CB/cementitious composites in other studies, whose fractional changes of resistivity possessed approximate linear characteristics to strain, but instead were often provided with low



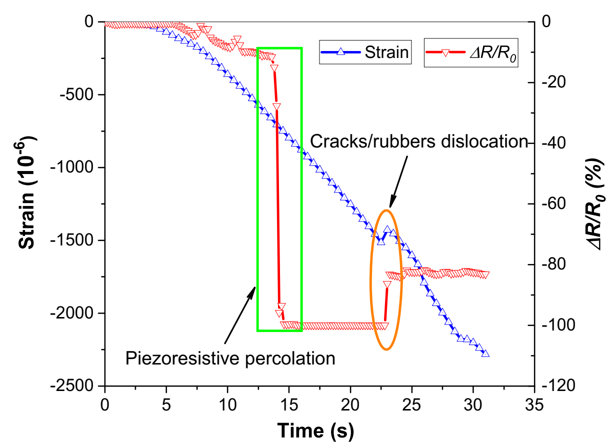
(a) Composite without rubber (0.0 vol.%)



(b) Composite with 20 rubber fibres (0.32 vol.%)



(c) Composite with 40 rubber fibres (0.64 vol.%)



(d) Composite with 80 rubber fibres (1.27 vol.%)

Fig. 9. Fractional changes of resistivity for 1.0 wt% CB/cementitious composites.

piezoresistive sensitivity [32,33]. Despite the poor linear relationship to the compressive strain due to the piezoresistive percolation, their gauge factors were greatly improved by several times for the composites with

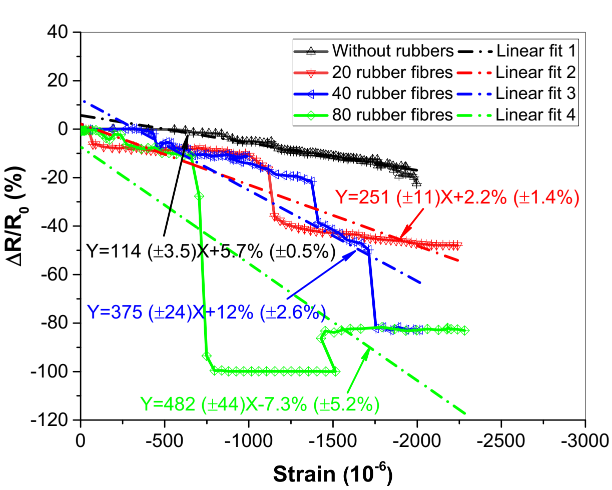
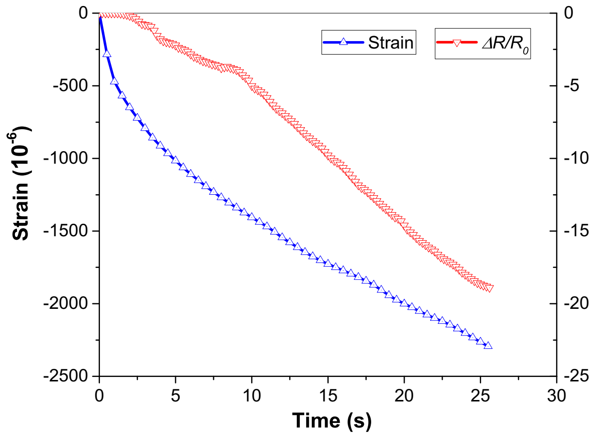


Fig. 10. Relationship between fractional changes of resistivity and compressive strain and their linear fittings for the 1.0 wt% CB filled composites.

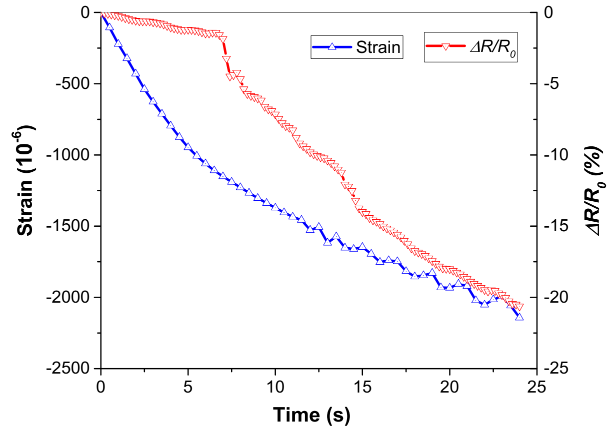
conductive rubber fibres. It means that the former sensor could obtain the exact values of strain/deformation by measuring the minor changes of resistivity, and the latter sensor with higher gauge factor out of piezoresistive percolation, had a capacity to acquire the ranges of strain/deformation values by a considerable resistivity changes. However, what is particularly worth mentioning is that the resistivity is various due to many factors, including ambient temperature and humidity, corrosions, input current and so on [20,56], which are common problems in real projects to confuse the sensor results. The larger gauge factor means the misunderstandings from the other factors could be negligible. Furthermore, because of the brittleness of cementitious materials, sometimes a rough value of strain/deformation could indicate the health condition of structures and elements, rather than a specific output.

3.3.3. Composites with 2.0 wt% CB

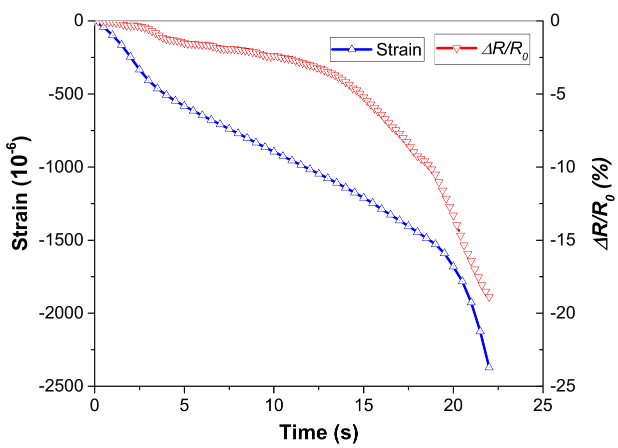
As illustrated in Fig. 11, the fractional changes of resistivity for the 2.0 wt% CB/cementitious composites showed smooth increase with the compressive strain when compared with the composites filled with 1.0 wt% CB. For all composites, the maximum fractional changes of resistivity reached approximately 20%. As shown in Fig. 5 the composites filled with 2.0 wt% CB were in the range of after percolation threshold, which possessed better electrical conductivity with a resistivity of several hundred Ω·cm. Hence, the conductivity amelioration by



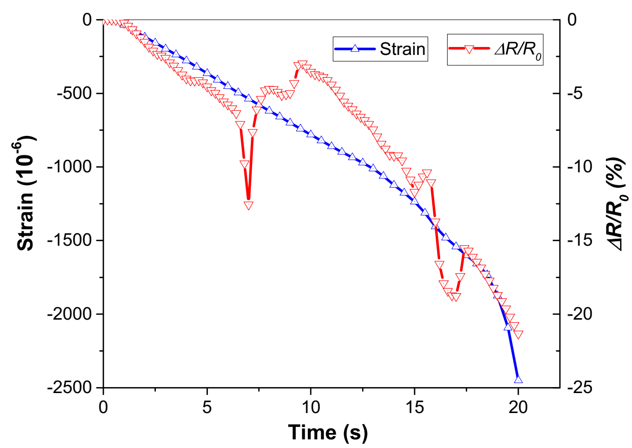
(a) Composite without rubber (0.0 vol.%)



(b) Composite with 20 rubber fibres (0.32 vol.%)



(c) Composite with 40 rubber fibres (0.64 vol.%)



(d) Composite with 80 rubber fibres (1.27 vol.%)

Fig. 11. Fractional changes of resistivity for 2.0 wt% CB/cementitious composites.

the conductive rubber was relatively small for more formed conductive passages by CB particles. In other words, when the composites were subjected to loadings, the contact between the rubber fibres could not greatly decrease the resistivity, thus the rubber interference on the fractional changes of resistivity was weakened, with only slight fluctuations for the composite with rubber content of 80 fibres (1.27 vol%).

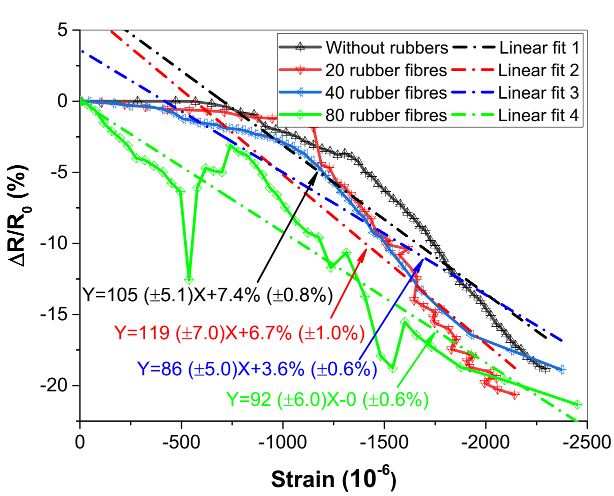


Fig. 12. Relationship between fractional changes of resistivity and compressive strain and their linear fittings for the 2.0 wt% CB/cementitious composites.

Fig. 12 illustrates the relationships between the fractional changes of the resistivity and the compressive strain of the 2.0 wt% CB/cementitious composite. Except for the composites embedded with 80 rubber fibres (1.27 vol%), all of the composites exhibited continual and nearly linear fractional changes of the resistivity with regard to the compressive strain. However, it seems that the gauge factors had no direct relationship to the rubber content, and the values reached 105, 119, 86 and 92 for the composites without rubber and with 20 (0.32 vol%), 40 (0.64 vol%) and 80 (1.27 vol%) rubber fibres, respectively. The reasons were explained previously, for the already formed conductive passages by CB rather than conductive rubber fibres. In addition, compared to similar studies focusing on CB particles, the improved sensitivity for the 2.0 wt% CB/composites was most likely caused by the effects of silica fume and the pore solutions in the composites which had never been dried [7,57]. Moreover, the composites without rubber or embedded with 20 rubber fibres (0.32 vol%) achieved the best gauge factors of 105 and 119, while it was decreased with the increasing number of rubbers. This might be due to the negativities caused by more content of conductive rubber fibres, which cause more cracks and gaps in the composites to decrease the gauge factors. Also, detach between connected rubber fibres reduced conductivity and damaged gauge factor as well.

4. Conclusions

Suitable water to binder (w/b) ratios for the similar workability of CB/cementitious composites was firstly investigated through probe penetration test in this study. Then the CB/cementitious composites embedded with different amount of conductive rubber fibres were explored, including their compressive strength, and the improved electrical conductivity and piezoresistivity. The main conclusions can be drawn up as follows:

(1) For composites filled with 0.1 wt%, 0.5 wt%, 1.0 wt%, 2.0 wt% and 4.0 wt% CB, the w/b ratios of 0.31, 0.32, 0.34, 0.4 and 0.5, respectively, could provide the composites with similar and excellent workability.
(2) The compressive strength of cementitious composites was more sensitive to the CB content, and decreased to approximately 15 MPa for the 4.0 wt% CB/composites. Contrarily, the composites with 80 rubber fibres (1.27 vol%), illustrated less negativities on compressive strength, especially for the composites with higher CB content.
(3) The electrical conductivity of the CB/cementitious composites was improved by the conductive rubber fibres. The more rubber fibres, the better conductivity is. The percolation threshold was clearly decreased for the 0.5–1.0 wt% CB/cementitious composites embedded with 80 rubber fibres (1.27 vol%).
(4) Conductive rubber had capacity to improve the gauge factor of 0.5 wt% CB/cementitious composites, by the growth rate of 78.4% compared to the results from other literatures; for 1.0 wt % CB/cementitious composites, the gauge factor significantly increased to hundreds of times higher than commercial strain gauge but with worse linearity to compressive strain, because of the phenomenon of piezoresistive percolation; Since the better conductivity for the composites with 2 wt% CB, conductive rubber rarely influenced its conductivity and piezoresistivity.
(5) The improved gauge factor indicated the great application potential for the application of CB/conductive rubber cement-based composites to monitor concrete structural health or pavement traffic conditions in low cost and high sensitivity.

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