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RESEARCH PAPER

Mechanical and Conductive Properties of Smart Cementitious Composites with Conductive Rubber Crumbs

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Massive waste rubber products become very challenging because their disposal generates negative impacts on the ecological environments. The effect of conductive rubber crumbs replacing the fine aggregate on the physical, mechanical properties and electrical characteristics of cement composites were investigated in this study. The results show that the flowability of cement mortar increased when the rubber crumbs substitution rate lower than 10%, but decreased when the substitution rate higher than 10%. The compressive strengths of rubberized mortar were decreased with the increase of rubber crumbs. However, as the amount of rubber crumbs increased, less reduction on compressive strength was observed for the cement mortar at water-to-binder (W/B) ratio of 0.42, because of the better flowability. In terms of the electrical properties, both the near-surface resistivity and the volumetric resistivity of rubberized mortar were increased with the curing age because of the cement hydration. The near-surface resistivity of mortar was limitedly affected by conductive rubber crumbs, while the volumetric resistivity did gradually decrease with the increase of rubber content. The developed cement mortar containing recycled conductive rubber crumbs can be used for manufacturing self-sensing concrete.

1. Introduction

There is an increasing demand for uses of rubber in various industries and household because of its unique properties (e.g., high elasticity and durability). It has been reported that the world rubber production was 26.9 million tonnes in 2016, and it increased at an estimated rate of 2.8% annually. [1] Consequently, management of such massive waste rubber products becomes very challenging because their disposal generates large negative impacts on the ecological environments, public health, and economic efficiency. In Australia, 197,000 tonnes of waste tyres were produced in 2004, and it was predicted to increase at a rate of 2.0% annually. [2] It is even reported that approximately 51 million tyres are discarded in 2013 which shows increasing trend in recent years with population expansion. [3] Although great efforts have been made, over two third of these wastes are either treated by incineration or buried in landfills. These traditional methods cause severe emission of harmful gases into air and contaminate the soil by releasing toxic substances.

Recently, many researchers have developed multifunctional building materials using waste rubber products. One of the examples is to partially substitute aggregates with rubber crumbs in concrete. Such an application can be dated back to 1990s. Researchers found that the concrete having aggregates partially replaced by rubber crumbs with various particle sizes illustrated lower compressive and splitting tensile strengths but higher ductility. [4] Since then, many studies on the effects of rubber crumbs on concrete have mushroomed, ranging from the physical properties, mechanical properties, durability such as freeze-thaw resistance, abrasion resistance, carbonation, corrosion resistance etc. and special functions of sound and vibration absorption ability. [5]

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Physical properties of concrete are significantly affected by the addition of rubber crumbs. It has been proposed that the introduction of rubber crumbs as aggregates could introduce three times higher air content and much lower density than the conventional concrete, because of the decreased slump values and poor workability.[6] Due to the induced air bubbles during mixing, researchers also found higher water absorption for the rubberized concrete.[7, 8] However in other independent studies, rather than increasing the air content, gradually decreased air content in mortar was observed with the increase of tire rubber ashes.[9] The discrepancy might be due to different particle sizes of rubber crumbs. In terms of the workability, decreased slump values occurred for the cementitious composites with the addition of rubber crumbs.[6, 10] Even though, by means of improving the class consistency of aggregates, investigations still obtained the improved workability of rubberized concrete.[11, 12] Moreover, slight longer setting time and larger shrinkage of rubberized concrete was observed than the conventional concrete.[9, 12] To improve the bond between rubber crumbs and cement matrix, approaches such as addition of air detraining admixture or coating the surfaces of rubber crumbs by styrene-butadiene copolymer have been explored.[13]

Because of the low elastic modulus, rubber crumbs inside the cementitious composites normally led to lower compressive strength and modules. For instance, Li *et al*.[14] studied the concrete with low content of rubber crumbs and obtained their stress-strain curves. The results illustrated lower compressive strength, flexural strength and elastic modulus with the increase of rubber content. Not just rubber crumbs, Dong *et al*.[15] found the decreased compressive strength for the cementitious composites with increased content of rubber products, which was in the form of small rubber fibres. Nevertheless, Segre *et al*.[16] observed the higher flexural strength of cement paste filled with NaOH-treated rubber crumbs. Furthermore, Ganesan *et al*.[17] not only found higher flexural strength of rubberized concrete but achieved higher fatigue strength as well. Onuaguluchi[18] utilized the limestone powder as coatings on the surface of rubber crumbs to manufacture the rubberized cement mortar with additives of silica fume, and they achieved the composites with both enhanced interfacial microstructures, compressive and flexural strengths.

In the aspect of durability of cementitious composite containing rubber crumbs, previous studies found that the concrete filled with 5% and 10% rubber ashes was provided with better resistance to freeze-thaw cycles, as well as better anti penetration to chloride.[9, 19] Thomas *et al*.[20] concluded that the rubberized concrete possessed higher resistance to macro cell corrosion, acid attack and the aggressive environments. Furthermore, higher abrasion resistance was found by other researchers,[21-23] owing to the fact that rubber crumbs overstepped the smooth surface of concrete and worked like a

brush to decrease abrasion. Bravo and Brito[24] tested the carbonation penetration of rubberized concrete and found the progressively increased carbonation depth with the increased replacement ratio of natural aggregate by rubber crumbs. Moreover, they observed that the carbonation was more severe when coarse aggregates were replaced by rubber crumbs. Contrarily, probably contributed to various particle sizes of rubber crumbs, higher resistance to carbonation was detected for the rubberized concrete by Gupta *et al*.[21].

It had been discovered by investigators that the rubberized concrete exhibited the capacity to absorbed plastic energy and showed higher toughness.[4, 25-27] Moreover, higher deformability, damping properties, sound and vibration absorption ability were found for the rubberized cementitious composites. Najim and Hall 28 investigated the damping properties of crumb rubber modified concrete and obtained the composites with both enhanced damping ratio and damping coefficient. Gisbert *et al*.[29] found a better damping properties for the rubber modified cement mortar, and especially for the composites with smaller rubber particles sizes. Through analysing the stress-strain curves of cementitious composites with different contents of rubber fibres, Dong *et al*.[15] observed the larger loops generated with increase of stress cycles and magnitudes, and qualitatively concluded the better energy absorption and damping properties for the composites with more rubber fibres. In addition, by introducing the impedance tube method on the rubberized concrete, Corredor-Bedoya *et al*.[30] observed that the cement mortar with 15% rubber crumbs represented higher sound transmission losses, while composites with 25% rubber particles possessed higher sound absorption coefficient.

Currently, very few systematic studies were proposed on the electrical properties of rubberized cementitious composites, because of the electrical insulation of commonly used rubber crumbs. Some studies found a higher electrical resistivity of rubberized concrete than the plain concrete, which even increased with the increase of rubber content.[31, 32] However, these conclusions are based on the application of non-conductive rubber crumbs. Once the cementitious composites modified with conductive rubber crumbs, the volume electrical conductivity of composites might be improved, which was partially demonstrated by authors when applied the rubber fibres into cementitious composites.[15, 33, 34] In this study, the electrical properties of cement mortar modified with various amounts (10-40% by weight of fine aggregate) of conductive rubber crumbs were investigated. Basic physical and mechanical properties of rubberized cementitious composites were involved to evaluate their application potentials. Afterwards, the electrical resistivity and microstructural properties of the rubberized composites are investigated. The related outcomes are expected to provide an insight into the utilization of conductive crumb rubber in the manufacture of

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piezoresistive cementitious composites such as self-sensing concrete, leading to the reduction of natural aggregate consumption and environmental footprints arising from the conductive rubber waste entering the landfills.

2. Experimental program
2.1 Raw materials
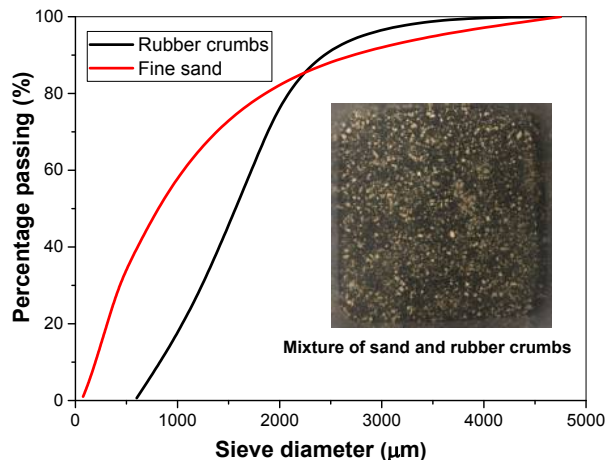
Fig. 1 Particle size distribution of fine sand and conductive rubber crumbs.

The binder used was a mixture of 90% (by weight) General purpose cement and 10% silica fume. There properties and main compositions are listed in Tables 1 and 2. Saturated surface dry sand possessing specific gravity of 2.0-3.2 g/cm^3 was used as fine aggregate. Its particle size ranged from 75 μm to 4.75 mm, and the gradation is shown in Fig. 1. Conductive rubber crumbs used were cut from larger rubber scraps into small particles, and their physical, mechanical and electrical properties are listed in Table 3. The conductive rubber crumbs had a volume resistivity as low as 0.1 Ω·cm, indicating excellent electrical conductivity. The particle sizes distribution of the conductive rubber crumbs is illustrated in Fig. 1.

2.2 Specimen preparation
Five groups of mixtures consisting of sand and different amounts of rubber crumbs were firstly prepared. The rubber crumbs were used to substitute sand at a rate of 0, 10, 20, 30 and 40% (by weight of sand). Three different water-to-binder (W/B) ratios, 0.4, 0.42 and 0.45, were investigated in this study. The detailed mix proportions of the rubber crumb modified cement mortar are listed in Table 4. To prepare a mortar mixture, water and superplasticizer of a designed mix was gently stirred in a Hobart mixer. Then, premixed cement-silica fume binder was added into the mixer and mixed for 1 min. Next, sand and rubber crumbs were placed into the cement paste and mixed for another 3 min.

To cast specimens, the freshly mixed mortar were placed into 50 cm ×50 cm ×50 cm metal moulds in 2 layers, and each layer was consolidated with vibration table for 1 min. Then, for one group, two copper meshes used as electrodes to measure the bulk resistivity of specimens, were vertically inserted into each of the mortar specimens, and they were 30 cm apart. Another group of the specimens were free from the embedded electrodes since the surface attached electrodes will be used. These specimens were then sealed with thin film and cured in

Table 1 Physical properties and main compositions of General purpose cement.

Appearance	Fineness Index (m^2/kg)	Initial setting time (hr)	Final setting time (hr)	Chloride (%)	Portland Clinker (%)	Gypsum (%)	Mineral addition (%)
Grey	370-430	1.5	3	0.01	85-94	5-7	Up to 7.5

Table 2 Chemical compositions and the physical properties of silica fume.

Silicon as SiO$_2$	Sodium as Na$_2$O	Potassium as K$_2$O	Available alkali	Chloride (Cl)	Sulphuric anhydride	Moisture content	Bulk density (kg/m^3)
89.6%	0.11%	0.23%	0.25%	0.16%	0.83%	1.5%	625

Table 3 Physical, mechanical and electrical properties of conductive rubber crumbs.

Conductive filler	Density (g/cm^3)	Volume resistivity (Ω·cm)	Tensile strength (MPa)	Elongation (%)	Shore hardness	Working temperature (°C)
Carbon black	2.1±0.25	0.1	1.5	230	70±5	-55~160

the chamber at the atmosphere of 95% relatively humidity and temperature of 25 °C. After 1 day curing, the specimens were demolded and placed in the same chamber to cure for additional 27 days. During curing, the electrical resistivity of the mortar specimens was recorded once every 3 days.

2.3 Experimental methods

2.3.1 Flowability

The flowability of the mortar mixtures was evaluated through the flow table test in accordance with ASTM C1437 (Standard Test Method for Flow of Hydraulic Cement Mortar), where the spread diameters of the tested mixture at 0 and 25 drops of the flow table were measured. For each spread, diameters were in three locations and the average value was chosen as the final flowability measurement.

2.3.2 Compression test

The compressive strengths of mortar specimens were tested using the compression machine of UH500 at the loading rate of 0.2 mm/min. For each mortar mix, three identical specimens were tested to determine the final strength at 28 days.

2.3.3 Microstructure characterization

The Zeiss EVO LS15 scanning electron microscope (SEM) was used to examine the morphology of the surfaces of saw-cut specimens, rubber crumb particles and the interfaces between rubber particles and cement matrix. The results are used to elucidate the mechanical and electrical properties of cement mortar in a microscale.

2.3.4 Electrical resistivity measurement

Currently two electrode configurations to measure the electrical resistivity of cement mortar have been proposed, ranging from the embedded electrodes to the surface attached electrodes.[35,36] However, very few researches systematically compared their differences and developments with curing age. Different from the embedded two copper meshes to measure the volumetric resistance of cement mortar, the two metal plates attaching on the top and bottom surfaces of modified cement mortar could determine the near-surface electrical resistance of composites.[37, 38] Since these two metal plates were regarded as electrodes, to ensure the well contact between the metal plates to mortar specimens, water saturated sponges were sandwiched in the middle of specimens to metal plates.[32] For these two electrodes configurations, direct current (DC) was applied to measure the electrical resistivity of modified cement mortar through a digital multimeter. Therefore, to obtain a stable resistance output, the measurement of resistance lasted at least 10 min for the elimination of polarization effect that might underestimate the finial electrical resistivity. In addition, since the electrical resistance of the composites will be greatly affected by the environmental factors,[39] the measurement is carried out in the environment of 25 °C temperature and 60% relative humidity from beginning to the end. Generally, the volumetric and near-surface electrical resistivity could be calculated according to the Eq. (1)[40] and Eq. (2):[38]

$$\rho_v = Rs/L \qquad (1)$$

$$\rho_s = RA/L \qquad (2)$$

Table 4 Mix proportions of rubberized cement mortar.

Index	Cement	Silica fume	Fine sand	Conductive rubber crumb	Water	Superplasticizer (%)
M0*	0.9*	0.1	2	0	0.40 0.42 0.45	0.8
M10*	0.9	0.1	1.8	0.2	0.40 0.42 0.45	0.8
M20	0.9	0.1	1.6	0.4	0.40 0.42 0.45	0.8
M30	0.9	0.1	1.4	0.6	0.40 0.42 0.45	0.8
M40	0.9	0.1	1.2	0.8	0.40 0.42 0.45	0.8

Note: M0 and M10 present the modified mortar without rubber crumbs and with 10% rubber substitution rate to fine aggregate; figures under the cement, silica fume, fine sand, rubber crumbs, water and water reducer represent their ratios to the weight of binder, e.g. 0.9* under cement presents the cement to binder ratio of 0.9.

where ρ_v the volumetric electrical resistivity; ρ_s the near-surface electrical resistivity; R the measured electrical resistance in ohm; s the cross-sectional area of the specimen to copper meshes in square meter; L the distance between two electrodes in meter; A the cross-sectional area of the specimens in square meter.

3. Results and discussion

3.1 Flowability

The flowability of rubber modified cement mortars was normalized, and it is expressed as a ratio of the measured diameter to the diameter of the cement mortar without rubber crumbs at the W/B ratio of 0.4. The flowability of plain cement mortar and rubberized cement mortar with various rubber contents and W/B ratios is shown in Fig. 2. Generally, it was observed that the flowability of modified cement mortar increased with the increase of W/B ratio. However, it seems that the rubber crumbs did not always decrease the flowability of cement mortar, due to the slightly increased flowability for the composites with 10% rubber substitution rate. Afterwards, with the increase of rubber crumbs substitution rate, gradually decreased flowability was observed for all composites at various W/B ratios.
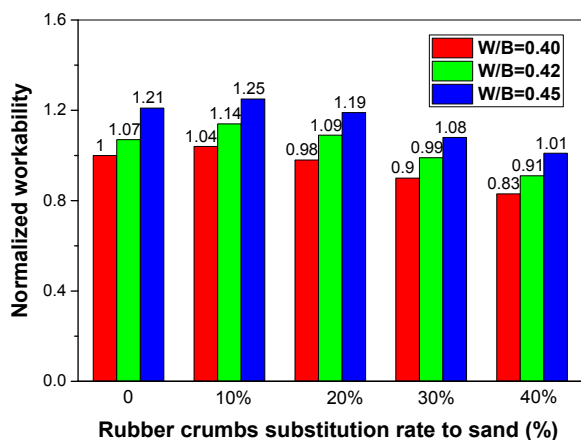

Fig. 2 Flowability of conductive rubber crumbs modified cement mortar with different W/B ratios and rubber contents.
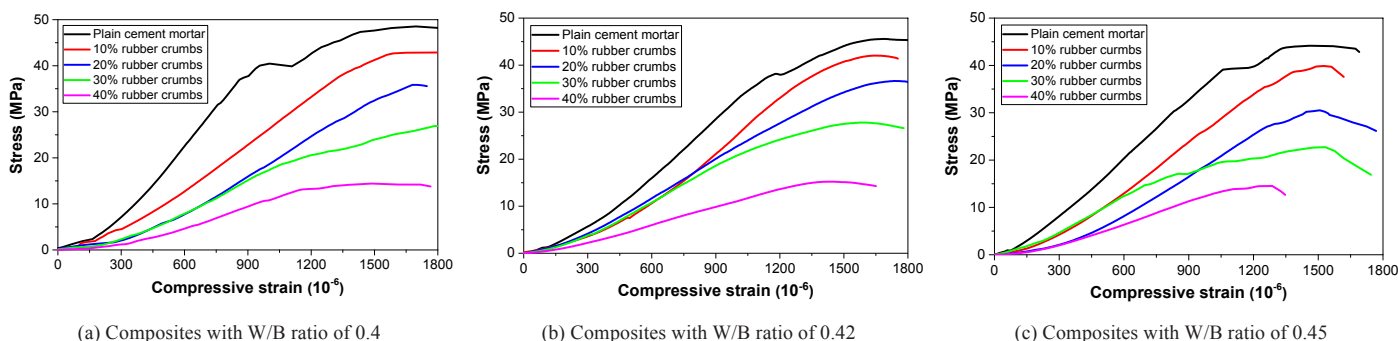
There are several reasons for the firstly improved workability followed by the decreased flowability with the increasing rubber substitutions. It has been found that the hydrophobic rubber crumbs have poor water absorption ability compared to the fine aggregate, so that the cement particles have more opportunities to be lubricated by the water molecule and that is why the mixtures performed higher flowability.[41] Even through, based on the proposal by Holmes and Güneyisi,[42, 43] the rubber crumbs added have possibility to increase the inter-particle friction between rubber crumbs and other mix components such as aggregate, which contributes to the decreased workability for the rubber crumbs modified cement mortar. In addition, the poor particle grading of rubber crumbs as illustrated in Fig. 1, also contributed to the poor flowability.[44] In this study, when the rubber content was low (10%), the superiorities of the hydrophobic rubber crumbs played the major role on the improved workability. Howbeit, the effect gradually weakened as the increased rubber crumbs induced inter-particle friction increasing and led to the worse flowability. Moreover, because the density of rubber crumbs was lower than that of fine aggregate, the higher volume of rubber crumbs might another reason for the worse flowability.

3.2 Mechanical properties

Fig. 3 shows the stress-strain curves of different contents of rubber crumbs filled cement mortar at W/B ratios of 0.4, 0.42 and 0.45. Generally it could be observed that the composites with higher rubber content possessed larger compressive strain under the same stress magnitude, demonstrating the improved deformability for the composites filled with rubber crumbs. However, clear reduction on the compressive stress could also be observed with the increase of rubber crumbs, just as mentioned in many other literatures.[45, 46] Simply based on the physical properties of rubber crumbs in Table 1, it could be deduced that the high elongation of rubber crumbs was responsible for the better deformability and lower ultimate strength for the rubberized cement mortar.

(a) Composites with W/B ratio of 0.4   (b) Composites with W/B ratio of 0.42   (c) Composites with W/B ratio of 0.45

Fig. 3 Compressive stress-strain curves of rubberized cement mortar at different W/B ratios.

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The compressive strengths and elastic modulus of cement mortar with various rubber crumb substitution rates and different W/B ratios are plotted in Figs. 4 (a) and (b), respectively. For the composites at various W/B ratios, it seems that the compressive strength of composites decreased with the increase of rubber crumbs. Particularly, the highest compressive strength was 48.7 MPa for the plain cement mortar at W/B ratio of 0.4, and the lowest compressive strength was 14.4 MPa for the modified mortar filled with 40% rubber crumbs at the W/B ratio of 0.45. It could be seen that the compressive strength of composites filled ≥ 10% rubber crumbs reached the maximum when the W/B ratio at 0.42, rather than the normally considered W/B ratio of 0.4. Combining the phenomenon that the flowability started to decrease when the rubber crumb content higher than 10%, it could be deduced that the lower compressive strength of cement mortar at low W/B ratios of 0.4 was attributed to the more induced cracks and the decreased flowability by rubber crumbs. Moreover, the decreased flowability had possibility to

affect the uniformity of rubber crumbs in the composites and affect the compressive strength. Therefore, the composites at W/B ratio of 0.45 filled by 40% rubber crumbs had higher compressive strength than the counterpart at W/B ratio of 0.4. As for the elastic modulus, the plain cement mortar at W/B of 0.4 exhibited highest value of 29.5 GPa. The elastic modulus of rubberized cement mortar decreased with the increase of W/B ratio and the content of rubber crumbs. Similarly, the decreased elastic modulus of rubberized cement mortar was owing to the lower elastic modulus of conductive rubber crumbs and the induced cracks and the decreased flowability during casting.

3.3 Macro and micro morphology

Fig. 5 shows the cross-sectional morphology of rubberized cement mortar filled with different contents of rubber crumbs. Since rare discrepancies among composites at various W/B ratios, only the composites at the W/B ratio of 0.42 were chosen to illustrate their macro and micro morphology.
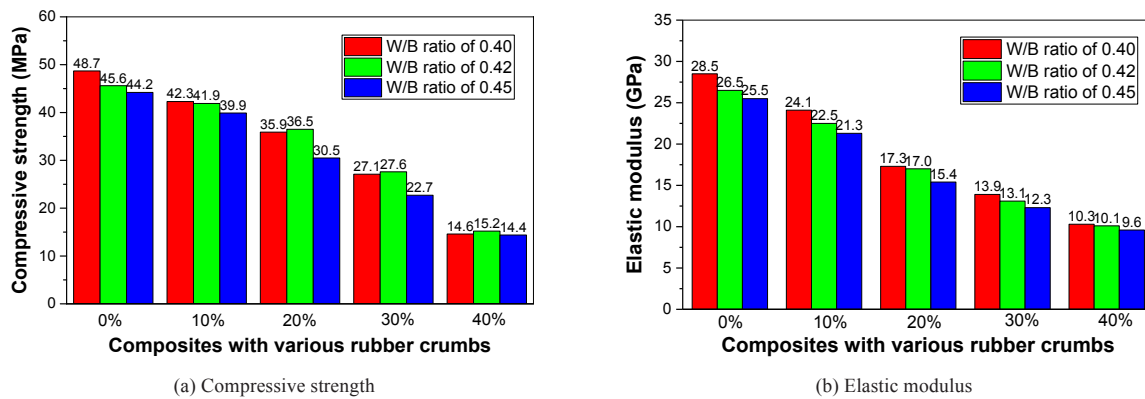

(a) Compressive strength   (b) Elastic modulus

Fig. 4 Compressive strengths and elastic modulus of rubberized cement mortar.

(a) Plain cement mortar   (b) 10% rubber crumbs   (c) 20% rubber crumbs

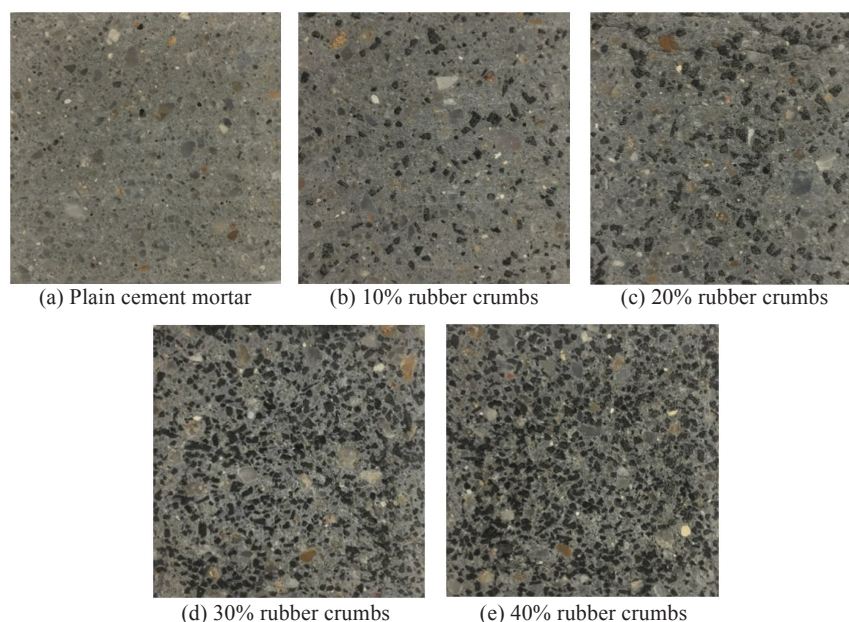(d) 30% rubber crumbs   (e) 40% rubber crumbs

Fig. 5 Cross-sectional morphology of rubberized cement mortar with different contents of conductive rubber crumbs.

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Generally, it could be seen that the rubber crumbs were evenly distributed in the cement matrix for all composites with various substitution rates. Due to these rubber crumbs had low strength and elastic modulus, the reduced compressive strength and elastic modulus were exactly sourced from the substitution of cement matrix and fine aggregate to the rubber crumbs. In terms of the rubber crumbs connection and the induced relationship to electrical conductivity of cement mortar, visible linkages between some rubber crumbs could be observed in these composites, especially for that filled with 40% rubber crumbs. Under the circumstances of more or less water content containing in the composites, it could be predicted that the composites filled with conductive rubber crumbs had capacity to improve the electrical conductivity.

The microstructural morphology of rubberized cement mortar was investigated by SEM technology, especially in the boundaries between fine aggregate to cement matrix, conductive rubber crumb to cement matrix, conductive rubber crumb to conductive rubber crumb and the interfaces among fine aggregate, conductive rubber crumb and cement matrix. As shown in Fig. 6 (a), it could be found that the fine aggregate have a smooth boundary with cement matrix and exhibited good cohesion, indicating that the existence of conductive rubber crumbs will not greatly affect the bonds between fine aggregate to cement matrix. Fig. 6 (b) depicts the gaps in the interfacial transition zone between rubber crumbs and cement matrix, which was considered an unneglectable reason for the decreased mechanical properties. Moreover, once many rubber crumbs contact with each other, the negativities on the boundaries became more complicated and severe. As plotted in the Fig. 6 (c), the gaps propagated from one boundary between rubber crumbs and cement matrix, to another neighbouring boundary. It could be deduced that the linked gaps were more likely to generate in the mortar with higher content of rubber crumbs, and thus the connected gaps in the interfacial transition zones should also be responsible for the weakened compressive strength with the increase of rubber crumb substitution rate. In addition, the interfacial transition zone sandwiched in the boundaries of fine aggregate, conductive rubber crumb and cement matrix is displayed in Fig. 6 (d). Rather than the above-mentioned cracks, macro pores created in the interfacial transition zone (ITZ) of the three phrases. It means that the air bubbles are more easily introduced and located in the boundaries among three phrases, due to the rough surface of rubber crumbs and the air bubbles attraction by fine aggregates. [47] Furthermore, it has been reported that the micro pores might generate in the wall of macro pores and affect the mechanical properties of cementitious composites. [48] Overall, the macro and micro morphology demonstrated the potential conductivity improvements and mechanical properties reduction on the cement mortar by the conductive rubber crumbs.
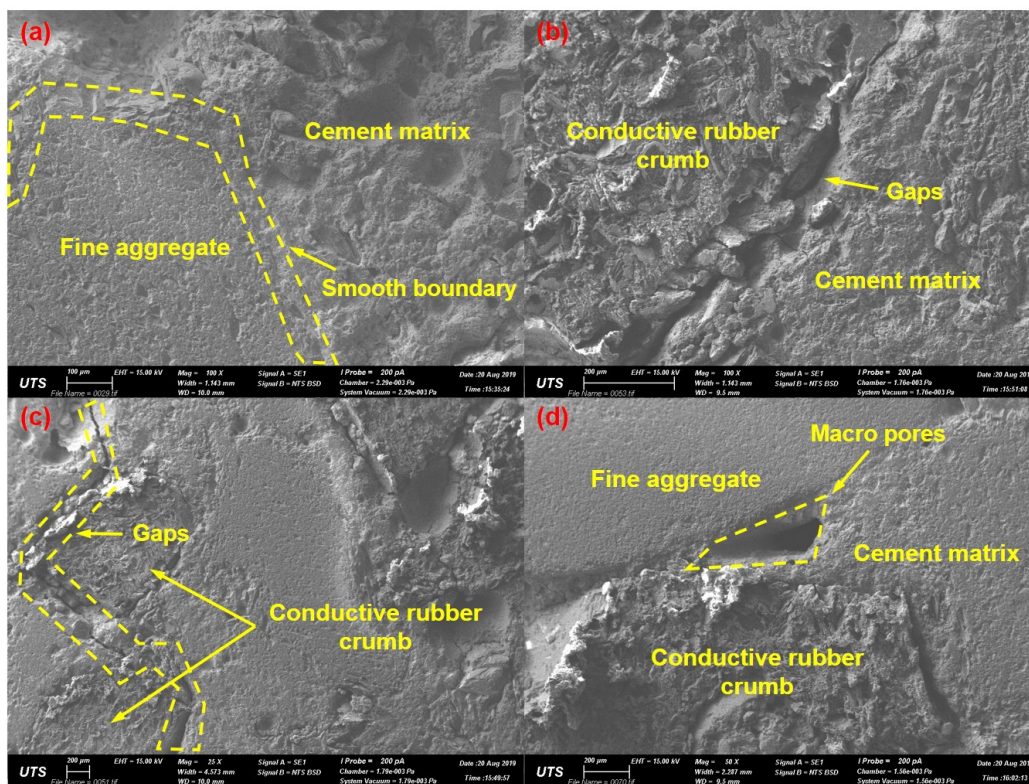

Fig. 6 Morphologies of the boundaries between (a) fine aggregate and cement matrix; (b) conductive rubber crumb and cement matrix; (c) conductive rubber crumb and conductive rubber crumb; and (d) fine aggregate, conductive rubber crumb and cement matrix.

3.4 Electrical resistivity
3.4.1 Near-surface electrical resistivity
Fig. 7 illustrates the near-surface electrical resistivity development of conductive rubber filled cement mortar with curing age at various W/B ratios of 0.4, 0.42 and 0.45. For all composites, it could be observed the electrical resistivity increasing with the increase of curing age. Since the composites were film sealed in the curing chamber that got rid of the offered humidity, the decreased electrical conductivity was due to the gradually eliminated moisture content in the surface of composites and the denser structures with cement hydration. Moreover, it could be seen that the composites experienced a much rapid increase of near-surface resistivity in the beginning of curing, especially before 7 days curing. Afterwards, the changes of near-surface resistivity slowed down with curing age. This shows a little discrepancy to the previous studies, where the volumetric resistivity of cement mortar significantly increased after 7 days curing. [15] The possible reason might be due to their different conductive mechanisms. The near-surface electrical resistivity measurement ignored the electrical resistance of inner part of composites, and the ions mainly passed though the surface or the superficial layer of composites. However, in the early curing age, the combined effect of faster hydration and the water evaporation in the surface of cement mortar made the water content lower than that of the inner regions, which is why the composites went through a faster increase of near-surface resistivity before 7 days curing.

As for the effect of different W/B ratios on the near-surface electrical resistivity, lower near-surface resistivity could be clearly observed in the early curing stage for the composites at higher W/B ratio of 0.42 and 0.45. Even though the increase tendency gradually slowed down with curing age, lower near-surface resistivity could still be observed for the composites at higher W/B ratios in the later curing stage. This is easy to understand because higher water content left on the surface or the superficial layer of composites. Also, because of the higher water content, faster cement hydration could be concluded by the higher reduction rate of electrical

conductivity in the early curing age. As a result, it seems that relatively higher resistivity increased for the composites at W/B ratios of 0.42 and 0.45, in comparison to the composites at W/B ratio of 0.4. Generally, it could be deduced that the influences of water content on the near-surface resistivity of cement mortar were very limited, since the resistivity values were similar and their developments were identical for all the composites.

In terms of the effect of conductive rubber crumbs on the near-surface resistivity of cement mortar, the rubberized mortar with rubber crumbs from 0 to 40% replacement ratio showed a very similar development with curing age. Generally, it could be observed that the composites with higher rubber substitution rates were provided with lower near-surface resistivity. As mentioned previously that the near-surface resistivity only covered the electrical properties of surface or superficial layers of cement mortar, the slightly decreased resistivity must originated from the improved conductivity of surfaces or superficial layers of composites. Therefore, the first reason might be due to the randomly dispersed conductive rubber crumbs in the composites, to increase the numbers of conductive passages and elongate them as well. Another reason probably sourced from the air pores induced by rubber crumbs, which were filled by conductive solutions in the superficial layers of composites to decrease the near-surface resistivity. However, it must be admitted that the conductive rubber crumbs were failed to greatly reduce the resistivity and could not improve the near-surface conductivity by orders of magnitude. One reason was that the majority of conductive rubber crumbs in the superficial layers were encapsulated by cement hydration products. In addition, the aforementioned rapid water losses in the surface or superficial layers of the composites greatly prohibited the conductive passages formation, leading to the rapid resistivity growth in the early curing ages.

3.4.2 Volumetric electrical resistivity
The volumetric resistivity of the conductive rubber crumbs modified cement mortar at different curing stages are displayed
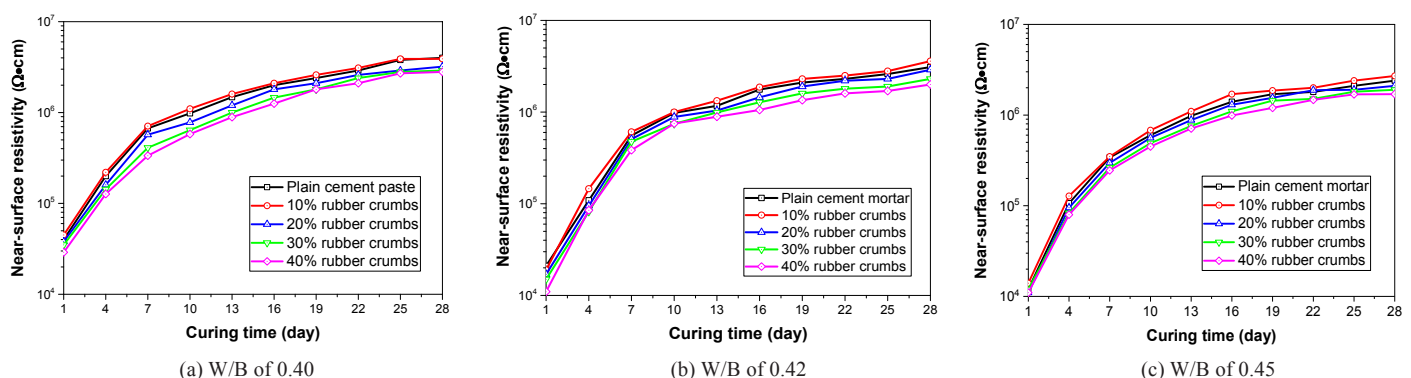

| (a) W/B of 0.40 | (b) W/B of 0.42 | (c) W/B of 0.45 |

Fig. 7 Near-surface electrical resistivity of rubberized cement mortar with curing ages at various W/B ratios.

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in Fig. 8, with the sub images Figs. 8 (a), (b) and (c) representing the composites at various W/B ratios of 0.4, 0.42 and 0.45, respectively. Similar to the development of near-surface electrical resistivity, the volumetric resistivity rose with curing age for all specimens no matter their rubber crumb substitution rates and W/B ratios. Also, it could be observed that the volumetric resistivity increased significantly in the early curing stage, while the growth rate gradually slowed down with the curing age in the late curing period. This is owing to the fast cement hydration in the beginning, which creates the nonconductive networks of cement hydration products. As for the plain cement mortar with various W/B ratios, the volumetric resistivity around 10^8 $\Omega \cdot$cm at W/B ratio of 0.4 was decreased by an order of magnitudes to 10^7 $\Omega \cdot$cm at the W/B ratio of 0.45 at curing age of 28 days. As previously mentioned that the specimens were film sealed without humidity supply, the conductivity amelioration was mainly due to the porosity solutions with free ions generating conductive passages. Hence, higher W/B ratios represented more pore solutions and more generated conductive paths, and led to the lower electrical resistivity. For the rubberized cement mortar with 10% rubber crumbs, it showed a very similar development of volumetric resistivity to the plain cement mortar. The results demonstrated the fact that the added rubber crumbs were relatively less which was completely enclosed by

nonconductive hydration products and fine aggregates. In addition to the closed volumetric resistivity to plain cement mortar, in the case of induced more air bubbles by the addition of rubber crumbs, slightly higher volumetric resistivity than that of plain cement mortar might be occurred, as shown in Fig. 8 (b).

For the composites with more rubber crumbs to sand substitution rate of 20%, dramatic resistivity reduction could be found in comparison to the counterparts without rubber and with 10% rubber crumbs in any curing stages. For the composites at the W/B ratio of 0.42, the resistivity was halved and as low as 1.0×10^7 $\Omega \cdot$cm after 28 days curing. It means that some of conductive crumbs were beginning to connect with each other and prolonged the conductive passages. However, since the electrical conductivity was still in the same order of magnitude, there was no continual and thorough conductive passages created between two electrodes. As for the composites with rubber crumbs substitution rates of 30% and 40%, lower electrical resistivity could be observed, because of the more connected rubber crumbs and the more created and prolonged conductive passages. The composites with 40% rubber crumbs showed the best conductivity at the W/B ratio of 0.45, which demonstrated that the conductive passages in the cement mortar were not created by the conductive rubber crumbs alone, but under the assistance of conductive pore solutions.
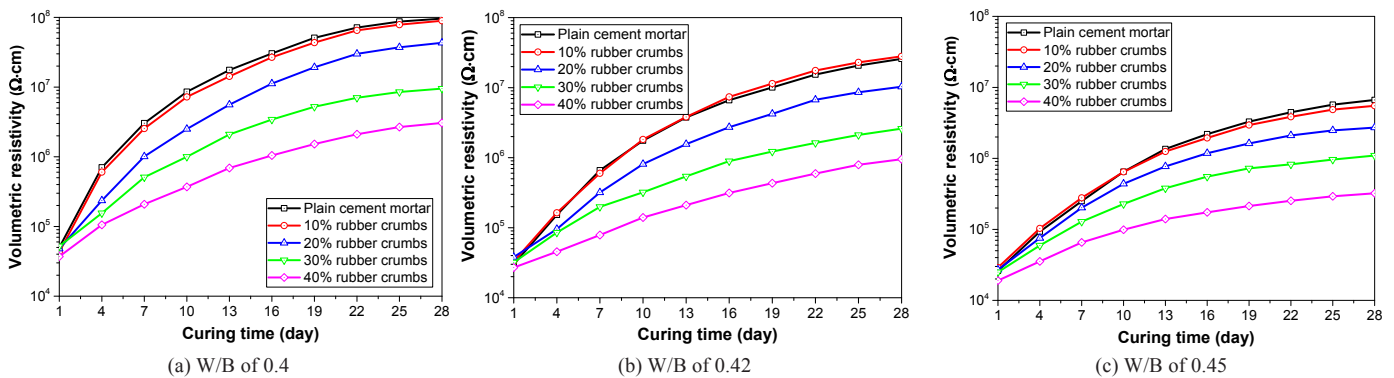

Fig. 8 Relationship between volumetric resistivity of rubberized cement mortar and curing age with different W/B ratios.
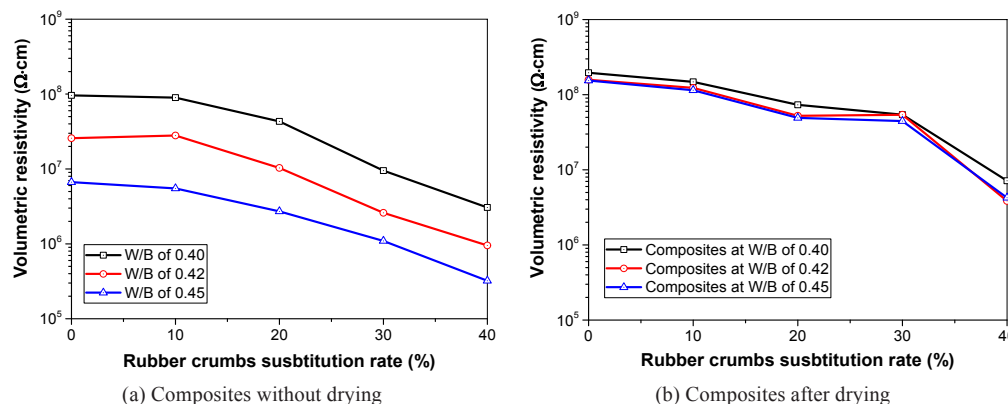

Fig. 9 Volumetric resistivity for the modified cement mortar with different rubber substitution rates under initial and dried states at 28-day curing.
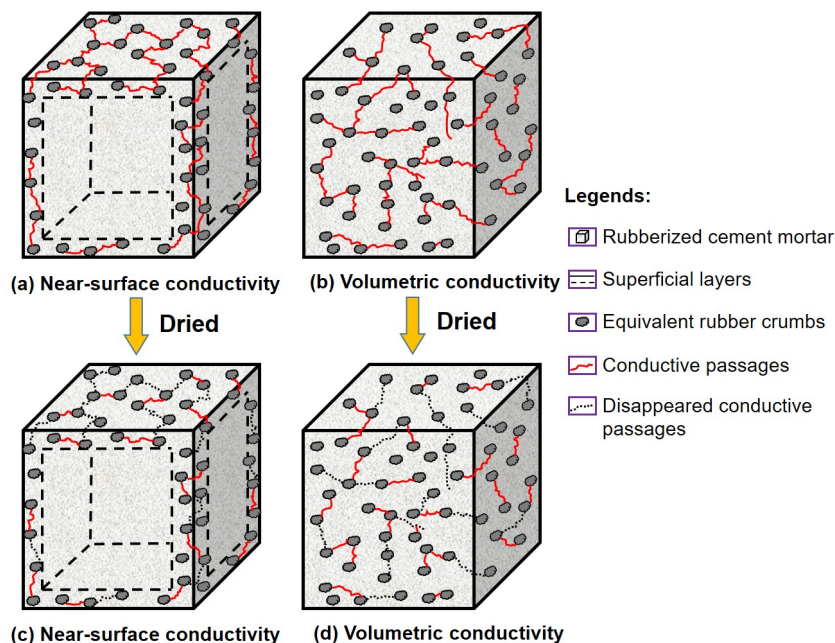
Overall, the results illustrate that the conductive rubber crumbs did have the capacity to ameliorate the electrical conductivity of cement mortar by partially substituting the fine aggregate.

To evaluate the effect of water content inside the rubberized composites on the volumetric resistivity, Fig. 9 represents the volumetric resistivity of conductive rubber crumbs modified cement mortar before and after being dried in the oven at the temperature of 50 °C for 3 days. For the composites at 28 days curing without drying, the volumetric resistivity firstly reduced very slowly or slightly increased (W/B ratio of 0.42) in Fig. 9 (a) when rubber crumbs substitution rate was 10%. The increase of volumetric resistivity might due to the air bubbles induced by the addition of rubber crumbs.[49, 50] Afterwards, the resistivity gradually decreased at a consistent rate among composites at different W/B ratios, and the reduction reached nearly one order of magnitude when the rubber crumbs substitution rate was 40%. Different from the commonly used nanomaterials reinforced cementitious composites, it could be seen that there never existed sudden and swift electrical resistivity reduction when the added rubber crumbs replacing fine aggregate increased from 10% to 40%. In terms of the dried composites in Fig. 9 (b), all the mortar showed an increase on the electrical resistivity and the discrepancy between composites at various W/B ratios greatly reduced after the drying treatment. It was clear that the resistivity reduction mainly originated from the decreased water content and pore solutions in the composites. Because the mortar with higher W/B ratio of 0.45 contained larger water content, the drying treatment could decrease water content to the utmost, and that was why the resistivity increase reached the maximum compared to the counterparts at lower W/B

ratios. Moreover, it could be observed that the mortar with 30% rubber crumbs substitution rate illustrated much faster resistivity reduction than that with 20% rubber crumbs substitution rate. This was due to the more air bubbles and pores by rubber crumbs in the mixture, which were filled with conductive solutions before drying and thus exhibited better conductivity. However, the pore solutions were considerably decreased after the samples were dried and displayed even higher resistivity than the mortar with smaller rubber content. Generally, it could be seen that the rubberized cement mortar after drying gently decreased with the increase of rubber crumbs, especially when the substitution rate reached 40%. Overall, the percolation never showed with the increase of rubber crumbs no matter for the mortar being dried or not. It considered that the phenomenon was related to the conductive mechanism of rubber crumbs in the cement mortar, which will be described particularly in the next section.

3.4.3 Conductive mechanism

Fig. 10 represents the effects of conductive rubber crumbs to ameliorate the electrical conductivity of modified cement mortar, incorporating the cross-sectional morphology of rubberized cement mortar on the macro and micro scales. In particular, two conductive mechanisms were proposed to describe the near-surface conductivity and volumetric conductivity in the sub images of Figs. 10 (a) and (b), respectively. Different from the initially existed conductive phrase of pore solutions, the added conductive rubber crumbs in the mortar could work as another solid electron and ions carrier and promote the free movements of conductive ions. Moreover, the introduction of rubber crumbs in the mixing

(a) Near-surface conductivity   **(b) Volumetric conductivity**

Dried   **Dried**

Legends:

▫ Rubberized cement mortar
▭ Superficial layers
◉ Equivalent rubber crumbs
⌁ Conductive passages
⋯ Disappeared conductive passages

(c) Near-surface conductivity   **(d) Volumetric conductivity**

Fig. 10 Schematic diagram of electrical conductive passages in rubberized cement mortar before and after drying treatments.

process could bring additional air bubbles and increase the porosity, which were normally filled with conductive solutions and elongate the conductive passages. Another characterization of rubberized cement mortar was due to the different thermal and physical properties between rubber crumbs and cement matrix. Hence, the micro cracks had higher possibility to emerge between two rubber crumbs. It means that the pore solutions filled cracks could be easily connected in the assistance of conductive rubber crumbs as shown in Figs. 10 (a) and (b), which directly leads to the electrical resistivity reduction. Generally, the more conductive rubber crumbs in the cement mortar, the more numbers of connected micro cracks and the longer conductive passages the composites possessed.

In addition, for the near-surface conductivity of rubberized cement mortar where two attached metal plates in the up/down surfaces worked as electrodes, based on the measured lower electrical resistivity, it could be deduced that the superficial layers of rubberized cement mortar had higher conductivity than the central regions of composites. Therefore, as shown in Fig. 10 (a), the movements of electrons or ions mainly concentrated on the surface or superficial layers of cement mortar. It must be pointed out that the conductive rubber crumbs were almost enclosed by the cement hydration products or fine aggregates, as a consequence, the conductive passages must went through the coated hydration products to connect with rubber crumbs, in order to create more conductive passages with stronger electron transition and ions movements. As for the volumetric conductivity in Fig. 10 (b), since the electrodes were inserted into the composites, the conductive passages were more likely created in the regions between two electrodes. Also, the higher volumetric resistivity of rubberized cement mortar illustrated that the less conductive passages formed during the closed circuit. In terms of the effect of water content, Figs. 10 (c) and (d) show the conductive passages development of rubberized cement mortar after drying treatment. On account of the increased resistivity, it could be deduced that the initial conductive passages disappeared owing to the decreased pore solutions after drying treatment. Different from the cementitious composites filled with conductive nanoparticles, whose electrical conductivity probably improved with the drying process due to the decreasing surrounded water content to reduce the contact resistance between nanoparticles,[51] the lost water content and disappeared conductive passages connecting nearby rubber crumbs caused the worse conductivity for the rubberized cement mortar. It can demonstrate that the enhanced conductivity of cementitious composites was not simply sourced from the connected rubber crumbs, but also with the assistance of conductive pore solutions.

In terms of the absence of percolation, previous studies have proposed that the electrical conductivity amelioration of cementitious composites by small conductive nanoparticles or nanofibers were sourced from the combined effects of flied emission, electron tunnelling and percolation theory, based on their contents and particle spacing in the cementitious composites.[52, 53] Generally, the percolation only occurred in the case of extensive particles connecting with each other to form continual passages, then the electrical resistivity of composites suddenly reduced by orders of magnitudes.[36] Since the rubber crumbs were mille-sized particles with much smaller specific surface area in comparison to nanoparticles, they were hardly to create connected conductive passages throughout the cement matrix between two electrodes. As plotted in Fig. 11, the composites filled with 20% and 40% rubber crumbs showed their real connection situation. For the composites filled by 20% rubber crumbs, a majority of the rubber crumbs were blocked by surrounded cement matrix and dispersed individually in Fig. 11 (a). Only a small amount of rubber crumbs connected with each other. The number of connected rubber crumbs increased with the increase of rubber crumb substitution rate in Fig. 11 (b), but still could not form the continual conductive passages. Nevertheless, due to the
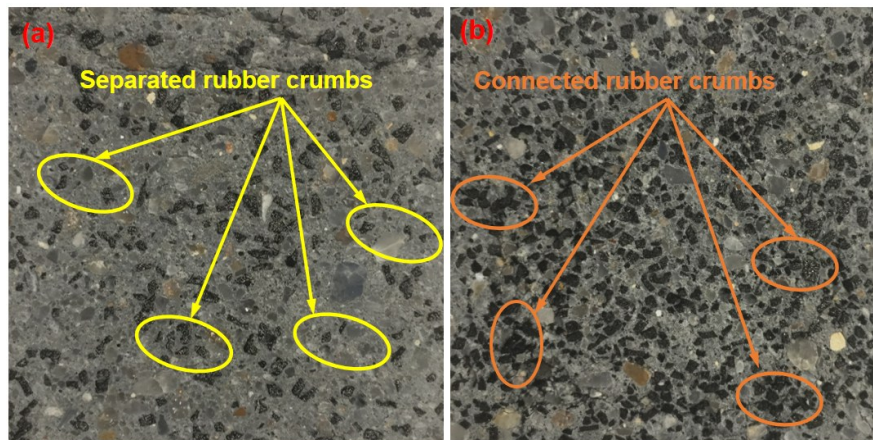
Fig. 11 Crumb connectivity of rubberized cement mortar with 20% and 40% conductive rubber replacing fine aggregate.

existence of pore solutions, the connected rubber crumbs could ameliorate the electrical conductivity of whole cement mortar. The conductive mechanism of rubberized cement mortar was similar to the cementitious composites filled with small amount of nanoparticles, where the conductive passages failed to establish. Therefore, it can deduce that the percolation would not happen under this circumstances and that was why there was no sudden resistivity reduction for the composites with various contents of rubber crumbs.

4. Conclusions

Properties of concrete are significantly affected by the addition of rubber crumbs. The effect of conductive rubber crumbs replacing the fine aggregate on the physical, mechanical properties and electrical characteristics of cement mortar were investigated in this study. The major conclusions can be drawn as follows:

(1) The flowability of composites containing conductive rubber crumbs was firstly increased then decreased with the increase of rubber crumb substitution rate for sand. Based on the current experiments, the critical value of rubber content was approximately 10%.

(2) For the plain mortar, the compressive strength was higher at a lower W/B ratio. However, for the modified mortar with rubber crumbs, the compressive strength was greatly decreased with increasing crumb content, especially for the mortar with a W/B of 0.4. For mortar filled with not less than 20% rubber crumbs, the highest strength was found in the specimen with a W/B of 0.42.

(3) The near-surface electrical resistivity of rubberized composites decreased with the increase of W/B ratios, but not dramatically decreased with the increase of rubber crumbs. It demonstrated that the conductive rubber crumbs can't greatly ameliorate the near-surface electrical conductivity of cement mortar.

(4) The volumetric electrical resistivity of rubberized cement mortar decreased with the increase of W/B ratios and rubber crumb substitution rates. Although the dried mortar expressed a resistivity increase, there still existed lower electrical resistivity for the mortar with higher rubber contents. It is concluded that the improved conductivity of rubberized cement mortar was sourced from the cooperation of water content and conductive rubber crumbs.

(5) The percolation never generated for the modified cement mortar filled with different conductive rubber crumbs from 10 to 40%, as a result of separately distributed rubber crumbs in the composites. It seems that the larger particle sizes of rubber crumbs compared to the commonly used conductive nanoparticles were responsible for this phenomenon.

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