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Advances in multifunctional cementitious composites with conductive carbon nanomaterials for smart infrastructure

Wengui Li [a,*], Wenkui Dong [a,*], Yipu Guo [a], Kejin Wang [b], Surendra P. Shah [c,d]

[a] School of Civil and Environmental Engineering, University of Technology Sydney, NSW, 2007, Australia
[b] Department of Civil, Construction and Environmental Engineering, Iowa State University, IA, 50011, USA
[c] Center for Advanced Construction Materials, The University of Texas at Arlington, TX, 76019, USA
[d] Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL 60208, USA

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ABSTRACT

Conductive carbon nanomaterials have been extensively developed for smart cementitious composites to gain multifunctionalities (e.g. self-sensing, self-healing, self-heating, and electromagnetic interference shielding). This paper critically reviewed dispersion and percolation of 0 dimension (0D), 1 dimension (1D) and 2 dimensions (2D) carbon materials used in cementitious composites and their effects on the electrical and piezoresistive performances. The different dispersion methods summarized are from mechanical dispersion, ultrasonic and high shearing, chemical modification, mineral additives, to carbon materials at multiple dimensions and hybrid dispersion methods. The electrical resistivity and piezoresistivity of cementitious composites with single carbon material or hybrid carbon materials are comprehensively analysed and compared in terms of efficiency and self-sensing mechanism. Furthermore, the existing theoretical modelling studies have been reviewed, indicating that many factors related to the electrical and piezoresistive behaviours, such as water content and nanocomposite agglomeration, have not been considered yet. Although some previous studies demonstrated the potential of applying conductive cementitious composites for self-sensing or heating pavements, further explorations still should be conducted on sustainable and economical manufacturing. Subsequently, the challenges and perspectives of the self-sensing stability, data acquisition system and sensor configuration are proposed with potential solutions for future smart infrastructure.

1. Introduction

Electrically conductive cementitious composites have been widely investigated due to their special functionalities, such as the properties of self-sensing, self-healing, self-heating, and electromagnetic shielding, etc. In particular, the self-sensing property of cementitious composites originates from the piezoresistivity, which is also interpreted as the relationship between the electrical conductivity (resistivity) and the applied stress (strain). Generally, the electrical resistivity of conventional cementitious composites is too high to be captured through the ordinary digital multimeter. To reduce the electrical resistivity of cementitious composites, conductive fillers in various sizes from micro to nano scales have been employed to modify the cementitious composites, including the metallic materials of steel fibres, nickel powders, iron powders as well as the carbon materials of carbon black (CB), carbon fibre (CF), carbon nanofiber (CNF), carbon nanotube (CNT), graphene nanoplate (GNP) and graphite plate (GP), etc. [1,2]. Moreover, recycled metallic wastes and conductive rubber products were also considered as sustainable conductive fillers of conductive cementitious composites [3,4]. Their effects of conductive fillers on the electrical conductivity and self-sensing properties of cementitious composites are complex because of their different shapes, sizes, aspect ratios, electrical conductivity, piezoresistivity, and dispersion difficulties in the cement matrix. To have a better understanding of the complexity, this paper provides a comprehensive review of the electrical and piezoresistive properties of cementitious composites with commonly used carbon materials.

1.1. Carbon materials in cementitious system

Cementitious composites modified by carbon materials have been widely explored on their physical, mechanical, electrical and

* Corresponding authors. School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia.
E-mail addresses: wengui.li@uts.edu.au (W. Li), wenkui.dong@student.uts.edu.au (W. Dong).

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multifunctional properties. Table 1 lists the commonly used carbon materials applied in cementitious composites, ranging from 0 dimension (0D) (CB), 1 dimension (1D) (CF, CNF and CNT) to 2 dimension (2D) (GP and GNP). The dimensions of the carbon materials are determined by their shapes: 0D for spherical particles, 1D for fibres and 2D for plates. Many studies have demonstrated that 1D and 2D carbon materials perform better than 0D CB in the aspect of improving the mechanical properties of cementitious composites. For example, cementitious composites with 1D fibrous fillers generally have much ductility and mechanical properties. The discrepancy is mainly due to the enhanced bond between carbon fillers and cement matrix, as well as the crack bridging effect [5]. As for 2D carbon materials, very few studies have been conducted to compare their reinforcing effect to the 1D carbon materials in cementitious composites. The previous research reported that the identical concentration of 0.05% graphene oxide (GO) could significantly increase the compressive and flexural strength of cement paste compared to the counterparts reinforced with CNT [6]. It has been demonstrated that 2D carbon materials possess a high potential to improve the mechanical strengths of cementitious composites. However, in terms of the electrical conductivity, for a given dosage, 0D CB has difficulties in forming conductive passages by complete connection with each other because of their spherical properties, while the 1D fibrous carbon materials can more efficiently generate conductive networks in cementitious composites [7]. In the principle of increasing conductive passages and points, fibrous fillers with a high aspect ratio ranging from hundreds to thousands have been incorporated in the composites also filled with 0D CB. For the electrically conductive fibres, continual conductive passages and contact points were created through the linkages among conductors [8,9]. For the nonconductive fibres such as polypropylene fibres, the directional distribution of CB particles deposited on the fibres enhanced the establishment of conductive passages [10]. As the listed general range of sizes of carbon materials in Table 1, different types of 1D carbon materials possess multiple lengths and diameters. The 1D fibrous carbon materials at nanoscale with a higher aspect ratio can more effectively improve the electrical and mechanical properties of cementitious composites.

1.2. Multifunctionality

The electrical properties of cementitious composites with carbon materials have large application foreground in the multifunctional construction structures and materials, including but not limited to the self-heating and self-healing properties [11,12], crack and corrosion detection [13], temperature and humidity observation, electromagnetic interference (EMI) shielding [14] and the piezoresistivity-based stress/strain monitoring [15]. The self-heating property originates from the Joule effect that electric energy of power supplied conductive cementitious composites transfers into heat energy to increase the temperature. Because of increased temperature, the self-healing properties of cementitious composites can be strongly improved especially for the conductive asphalt concrete [16]. Since the inner crack and corrosion can alter the electrical resistivity of cementitious composites, crack and corrosion detection can be achieved in the case of previous calibration and adjustment [17]. Similarly, the temperature and humidity alterations of cementitious composites can be detected by the electrical resistivity changes, and then the results of environmental temperature and humidity changes can be assessed [18]. Reflection and absorption losses of an electromagnetic wave are two main reasons responsible for the EMI shielding. For conductive cementitious composites with carbon materials, the better electrical conductivity can assure the rise in shielding effectiveness. In addition, the increase of thickness of cementitious composites is also beneficial to the shielding effectiveness. As for the crucial feature of piezoresistivity-based stress/strain monitoring, the piezoresistivity implied the correlation between electrical resistivity changes of cementitious composites and the imposed stress or deformation. Normally the value known as gauge factor, which is also represented by the fractional changes of resistivity under unit strain, is proposed to evaluate the sensing efficiency or piezoresistive sensitivity of conductive cementitious composites.

1.3. Current research status

The research of electrical and piezoresistive properties of cementitious composites with carbon materials has attracted increasing attentions. Fig. 1 shows the number of studies on the effects of carbon materials on the electrical resistivity and piezoresistivity of cementitious composites based on the Scopus-indexed sources by 2021. It can be found that 1D CNT is the most popular carbon-based filler in cementitious composites. Generally, the number of choosing 1D carbon materials (CNT, CF and CNF) as conductive fillers in cementitious composites is larger than 2D carbon materials (GNP and GP) and far beyond the 0D CB. The reason might be due to the strongly improved electrical and

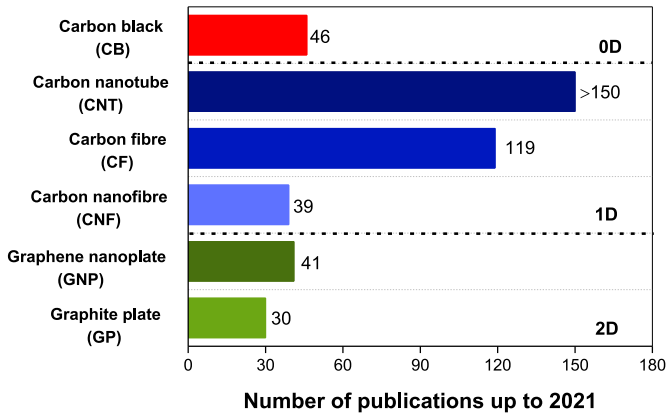
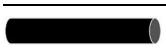


Fig. 1. Number of publications on electrical and piezoresistive properties of carbon materials reinforced cementitious composites by 2021 (based on Scopus database).

Table 1
Structural, physical and electrical properties of 0D, 1D, and 2D carbon materials.

Dimension	Type	Shape	Diameter/thickness	Length/width	Electrical resistivity (Ω·cm)	References
0D	Carbon black (CB)		20–100 nm	–	<0.22	Dai et al. [65]
1D	Carbon fibre (CF)		~10 μm	~5 mm	$\sim 3 \times 10^{-3}$	Chiou et al. [175]
	Carbon nanofiber (CNF)		60–200 nm	~80 μm	$\sim 1 \times 10^{-3}$	Chung [80]
	Carbon nanotube (CNT)		Inner: 5–10 nm Outer: 20–40 nm	10–30 μm	$\sim 1 \times 10^{-5}$	Ebbesen et al. [176]
2D	Graphene nanoplate (GNP)		<4 nm	<10 μm	$\sim 1 \times 10^{-3}$	Sedaghat et al. [177]
	Graphite plate (GP)		>100 nm	<178 μm	$\sim 1 \times 10^{-3}$	Wei et al. [178]

mechanical properties and durability of cementitious composites with 1D and 2D carbon materials [19]. Moreover, the late appearance of 1D CNT and 2D GNP and the excellent application potential of these materials into cementitious composites might be another reason. According to the above statistics, Fig. 2 shows the percentages of studies published by different countries. The US and China almost accounted for half of all studies, and the rest countries occupied the other half. Although a wide range of investigations has been done on the electrical resistivity and piezoresistivity of cementitious composites, multiple results, effectiveness, and even contradictions emerge in the studies. This review has systematically summarized and compared the electrical and piezoresistive properties of cementitious composites incorporating carbon materials of various dimensions, for researchers to better understand the utilization of carbon materials in cementitious composites.

2. Dispersion of carbon materials

Carbon nanomaterials have a high specific surface area and high surface energy, and tend to attract each other and form agglomerations. Since these carbonic agglomerations have weak cohesion and poor resistance to external forces, it has been proposed that many defect sites appear in cementitious composites and greatly limit the physical, mechanical and durable properties [20]. Although some investigators have proposed a solution by directly synthesising CNT onto cement particles to avoid the dispersion of carbon nanoparticles in cementitious composites [21,22], for most of studies, different methods including ultrasonic dispersion, chemical and mineral additives for surface modification are the preferred approaches, to uniformly disperse the carbon nanomaterials in cementitious composites. Furthermore, hybrid methods incorporating at least two of the above dispersion methods were proposed to arrange the dispersion problem of carbon materials efficiently. Since mechanical mixing such as hand or electromagnetic stirring often appears on the above treatments, it is mentioned together with the specific dispersion method.

2.1. Ultrasonic dispersion

The ultrasonic duration and energy are critical factors to influence the dispersion efficiency of carbon materials. Chaipanich et al. [23] firstly mixed the CNTs with a proportion of water under 10 min ultrasonic dispersion and then mixed the solution with cement materials, followed by the residual water adding into the mixer once the blends formed. They observed denser microstructures and improved mechanical properties of cementitious composites. Nochaiya et al. [24] dispersed the CNTs in mixing water for 5 min sonication, and obtained similar CNTs/cement composites with improved mechanical properties. Different from the previous ultrasonic duration, sonication time up to 2 h was investigated by Du et al. [25]. In Fig. 3, the sedimentation of black precipitates gradually increased from the well-dispersed GNPs suspension over time. The increase of sonication time reduced the sedimentation rate indicating the better dispersion of GNPs suspension. However, they did not test the structural integrity of GNPs and the mechanical properties of the cementitious composites. Similarly, the effect of sonication time from 2 to 5 h on the electrical conductivity of CNTs/polyaniline composites was investigated [26]. The longer duration increased the structure toughness but decreased the electrical conductivity, because of the conversion of conductive state. It could be seen that the sonication time mainly depended on the matrix/base of the carbon materials. The nanoparticle tends to disperse more easily in the water rather than a polymer-based matrix. Moreover, for the cement matrix, the differences in the ultrasonic duration might relate to the water to binder ratios, since it was concluded by Kim et al. [27] that cement composites at low water to binder ratios benefited CNTs dispersion and improved piezoresistivity. Furthermore, the shapes and dosages of fillers also relate to the sonication time, given different ultrasonic durations based on the concentrations and aspect ratios of carbon fillers were carried out in studies [28]. In addition to the ultrasonic duration, the effect of ultrasonic energy on the dispersion of CNTs was studied by Zou et al. [29]. They found that the dispersion efficiency increased with the increase of ultrasonic energy until reaching a plateau. Similar results were obtained by Metaxa et al. [30], with the first increased and then decreased flexural strength for the cementitious composites prepared with increasing ultrasonic energy. These results indicate optimal ultrasonic energy to achieve the optimal mechanical properties of cementitious composites because the high energy might destroy the CNTs and deteriorate the reinforcement effect.

2.2. Surface modification

The surface modification to improve the dispersion of carbon nanomaterials includes the application of surfactants in suspension and the surface coating of nanomaterials. Collins et al. [31] compared five different surfactants on the efficiency of CNTs dispersion in cement paste, and found that the polycarboxylate could strengthen the CNTs/cement composites with improved compressive strength. Chuah et al. [32] investigated the effect of polycarboxylate, air-entrainment and gum Arabic admixtures on the dispersion of GOs in cement composites. They observed the identical conclusion to Collins' results [31]

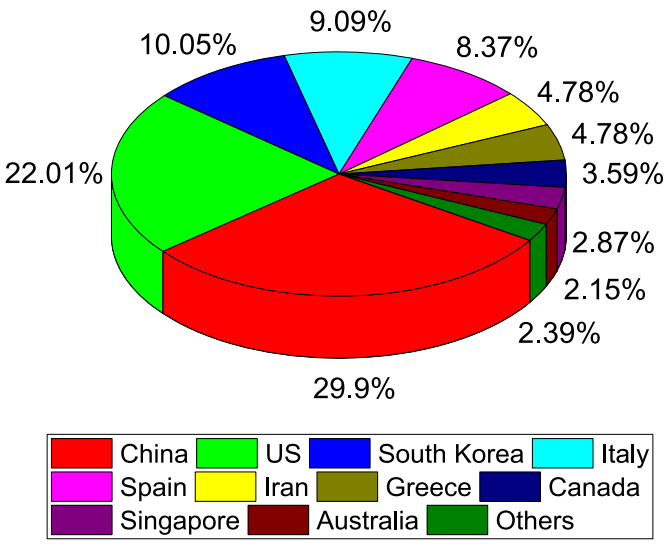


Fig. 2. Scopus-indexed publication statistics by different countries until 2021.

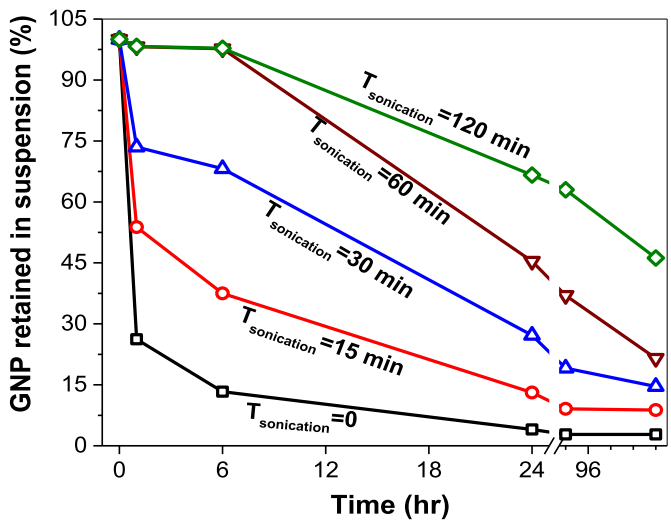


Fig. 3. Effect of ultrasonic duration on stability of GNP solution [25].

that the polycarboxylate was the most promising surfactant to disperse the carbon nanomaterials. Similarly, Luo et al. [33] compared another five surfactants on the CNTs dispersion in aqueous solutions. Not only was the CNTs solution with sodium dodecylbenzene sulfonate found with the largest delaminating time, but also the composites were observed with the best mechanical properties and electrical conductivity. By the UV spectroscopy observation, Deng et al. [34] compared four surfactants and drew the conclusion that the polyoxyethylene nonylphenylether at the concentration of 0.7 g/l exhibited the best dispersion efficiency. Among these surfactants, it was recommended that the ionic surfactants are more suitable for the CNTs/water-soluble solutions [35]. For the identical surfactant with various concentrations, Konsta-Gdoutos et al. [36] investigated their effects on the dispersion efficiency of CNTs. Given the CNTs agglomerates increased the viscosity under small shear strength, it has been found that the surfactant to CNTs weight ratio of 4.0 led to the suspension with the smallest viscosity and illustrated the best CNTs dispersion. Metaxa et al. [30] found that the surfactant to CNFs weight ratio could be 2.0 or 4.0. Generally, the surfactant can decrease the van der Waals forces, modify the hydrophobicity of carbon materials and enhance their dissolubility. However, although an effective surfactant can successfully disperse carbon nanomaterials, uneven distribution of fillers or poor bond among fillers to matrix might still be occurred in the cementitious composites [37].

Similar to the effect of surfactants, special treatment of previous surface decoration on the conductive fillers have been proposed for better uniform dispersion. By investigating the impact of polyacrylic acid polymers on CNTs surface functionalisation and the followed dispersion in water, Cwirzen et al. [38] observed acceptable workability and mechanical strengths of the CNTs/cement composites. As plotted in Fig. 4, it revealed the available ionic or covalent bonding between CNTs to polymers that prevent the re-agglomeration of CNTs suspension. However, for the CNTs coated by gum Arabic, it should be noted that lower cement hydration was observed for the CNTs/cement composites that hindered the final mechanical strengths. Li et al. [39] pre-treated the CNTs by a mixed solution of H_2SO_4 and HNO_3, and they found that the cementitious composites with treated CNTs were provided with both high mechanical properties and piezoresistivity than the counterparts with untreated CNTs. They proposed that the smoother surface of treated CNTs was more beneficial to electron movements and clung to the cement matrix. More like a mechanical modification, the modified CNFs after debulking process was proved more efficient to improve the mechanical performance of cementitious composites, implying the good dispersion of modified CNFs in the nanocomposites [30].

2.3. Mineral additives

Chung, Dong and Sanchez et al. [40–42] deemed that silica fume could improve the dispersion of CF, CB and CNFs and improve the mechanical, electrical and piezoresistive properties of cementitious composites, while they did not conduct more experiments on the specific influences by silica fume. Kim et al. [43] tested the CNTs cementitious composites with various contents of silica fume and achieved the composites with improved compressive strength and electrical conductivity. The number and size of CNTs agglomerations reduced because the silica fume intermixed with CNTs and broke the formation of agglomerations. The results showed the silica fume dosage of 10% by weight of cement exhibiting best performances. Similar results emerged for the silica fume incorporated CNTs cementitious composites for the application of EMI shielding [44]. In addition, it had been proposed that the silica fume was capable of dispersing the plate-like structures of carbon materials, such as GNPs and GOs. Li et al. [45] observed that the GOs could be covered with silica fume and thus have less tendency to get agglomerated. Bai et al. [46] concluded similar results on the GNPs cementitious composites with silica fume, and they proposed that the appropriate dosage of silica fume should be from 5% to 10% by the weight of cement. In general, the main reason for improved dispersion is because the silica fume particles insert into the conductive fillers to separate the agglomerates. On the other hand, not all mineral additives have the capacity to improve the dispersion of carbon nanoparticles. The effect of nanosilica on the dispersion and stability of CNTs aqueous solution relied on the CNTs concentration. For the small dosage of CNTs, the nanosilica nearly has no influence on the CNTs dispersion. However, in the case of high CNTs concentration, the dispersion and stability would be decreased with the addition of nanosilica [47]. Moreover, there exist mineral additives that can block the dispersion of carbon materials. According to the studies by Mendoza et al. [48], the presence of calcium hydroxide ($Ca(OH)_2$) in the cementitious composites could affect the dispersion of CNTs, since it hindered the electrostatic repulsion between CNTs and superplasticizer molecules, and resulted in the re-agglomeration. Similarly, mineral additives such as hydrated lime that can generate $Ca(OH)_2$ in cementitious composites might retard the dispersion of carbon materials.

2.4. Carbon materials in various dimensions

Investigations have revealed that carbon materials themselves possess the functionality to improve the dispersion efficiency of other carbon materials, especially for carbon materials with different dimensions. Öztürk et al. [49] applied the hybrid CF and CB in the self-sensing reinforced beams and obtained a lower electrical resistivity

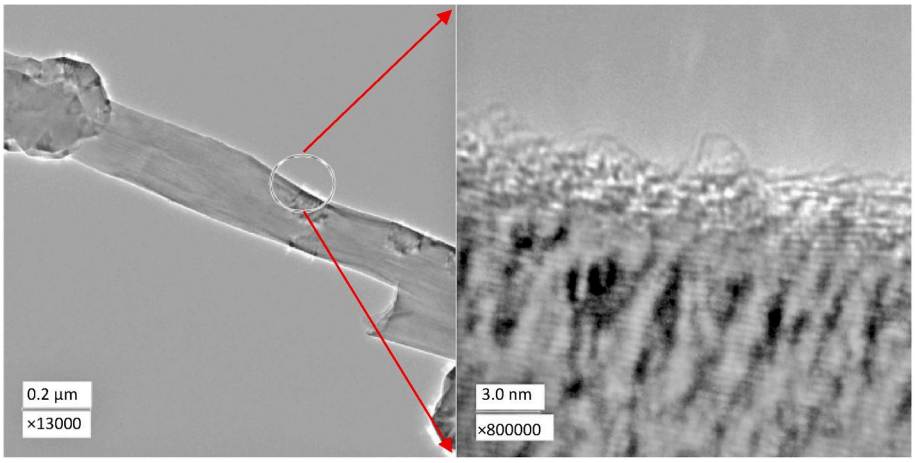


Fig. 4. Transmission electron microscope (TEM) images of CNT covered by polymers [38].

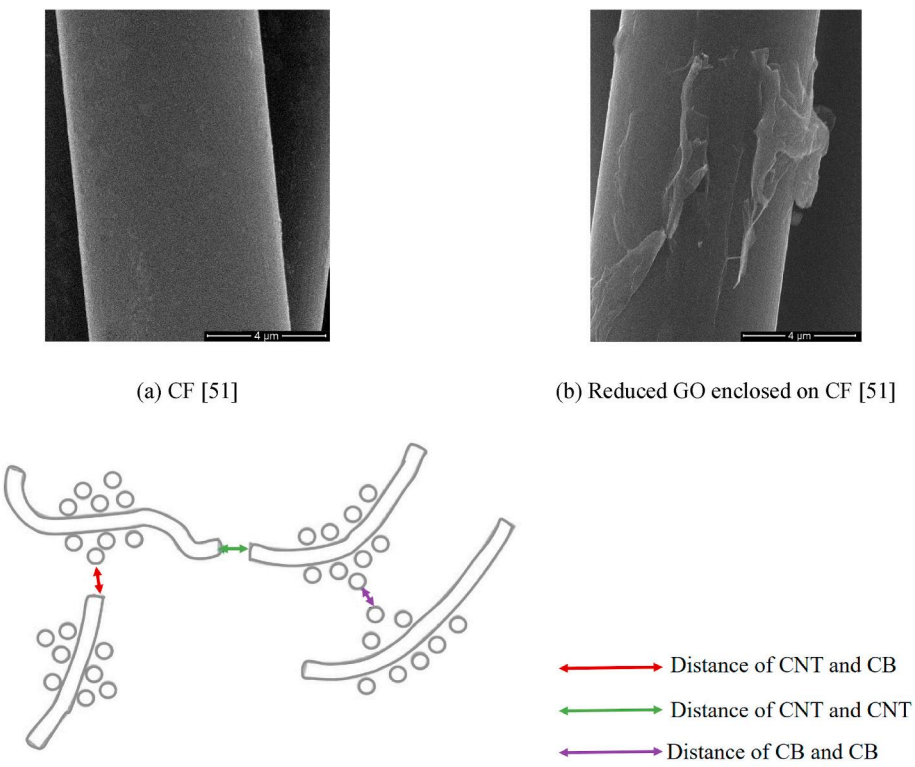
and higher deflection sensing capacity compare to the counterparts with single CF or CB. Lu et al. [50] employed GOs to assist the dispersion of CF and CNTs in the cementitious composites; the results of UV spectroscopy and improved mechanical properties indicated that the CF and CNTs were well dispersed with the existence of GOs. They attributed the phenomenon to the higher electrostatic repulsion of GO suspension than that of water. In the polymer matrix, Chen et al. [51] found that the EMI shielding of composites with reduced GO and CF exceeded the counterparts only with CF, and they observed that the reduced GO could help to disperse CF and build a more effective conductive network. It could be observed in Fig. 5(a) and (b) that the reduced GO was successfully immobilized on the surface of CF. Since the GNP has similar structures to reduced GO, studies concluded similar results on the cementitious composites with CF and GNP [52]. Apart from the 2D carbon materials, the 0D carbon black is also found beneficial for the dispersion of 1D carbon materials. Han and Zhang et al. [53,54] observed the grape bunch structures of CNTs and CB in the cementitious composites, and concluded that the addition of CB could improve the functionality of composites. As shown in Fig. 5(c), the addition of CB reduced the distance between fillers and increased the possibility of conductive passages generation. Moreover, studies have mentioned the usage of CB and CF in cementitious composites for conductivity development [55], which implied the application potential of the mixture of carbon materials at different dimensions.

2.5. Hybrid dispersion methods

Hybrid dispersion methods can more efficiently homogenize the carbonic nanoparticles in aqueous solutions and cement matrix. Table 2 lists different dispersion ways incorporating at least two of the aforementioned methods. Parveen et al. [56] proposed a novel dispersant of Pluronic F-127 incorporating 1 h ultrasonication to disperse CNT in cementitious composites, which expressed a significant enhancement on the mechanical strengths and modules. To reduce the sizes of agglomerations, Musso et al. [57] dispersed CNT suspension in acetone by means of an ultrasonic probe. Konsta-Gdoutos et al. [36] controlled the ultrasonic energy and surfactant concentration to disperse CNT and found that the application of ultrasonication was critical to obtain the well-dispersed CNT suspensions. Wang et al. [58] utilized the gum

Table 2
Hybrid dispersion methods of carbon materials in cementitious composites.

Material types	Dispersion methods	Surfactant to carbon material ratio	Characterization	Refs.
CNT	Ultrasonication + Pluronic F-127	25–30	Microstructures Flexural strength	Parveen et al. [56]
CNT	Ultrasonication + superplasticizer + acetone	2.2	Microstructures	Musso et al. [57]
CNT	Ultrasonication + polymer	15–91	Microstructures Compressive strength	Cwirzen et al. [38]
CNT	Ultrasonication + surfactant	4.0	Rheology	Maria et al. [36]
CNT	Ultrasonication + surfactant (TNWDIS)	0.2	Microstructures Flexural strength Porosity	Xu et al. [61]
CNT	Ultrasonication + Gum Arabic	6.0	Porosity Microstructure Fracture energy	Wang et al. [58]
GNP	Ultrasonication + methylcellulose	7.0	UV spectroscopy Microstructure	Wang et al. [59]
CF	Ultrasonication + hydroxyethyl cellulose	0.75–3	Compressive, tensile and flexural strengths	Wang et al. [60]



(a) CF [51]

(b) Reduced GO enclosed on CF [51]

(c) Interaction of CB with CNT [190]

Fig. 5. Relative positions among mixed carbon materials with different dimensions.

Arabic to premix with CNTs solution, followed by 30 min ultrasonication and defoamer treatment to reduce the generated air bubbles. Subsequently, they combined the surfactant methylcellulose and ultrasonication to disperse the GNPs in cementitious composites [59]. With different mixing orders, Wang et al. [60] first premixed the CF with water and then added the hydroxyethyl cellulose for another stirring; the deformer was the last added to eliminate air bubbles. In both studies, they achieved denser microstructures and improved mechanical properties of cementitious composites. However, long-term sonication could raise the temperature of suspension and affect the dispersion of CNTs. To solve the problem, Xu et al. [61] applied a surfactant (TNWDIS) with aromatic ring and hydrophilic group to mix with CNT suspension, and then the ultrasonication was conducted six times with breaks. Similar to the studies which carried out the ultrasonication in ice/water bath [29], this method could avoid the increased temperature of suspension during sonication. As mentioned above, long-term ultrasonication might destroy the structural integrity and increase the temperature of suspensions, which strongly affect the mechanical properties of cementitious composites. The application of surfactant could overcome these disadvantages, but the dispersion efficiency was always limited, let alone the potential damages on the mechanical properties of cementitious composites [62]. As a consequence, the hybrid dispersion methods combining both surfactants and ultrasonication might be a better alternative to disperse carbon materials in cementitious composites.

3. Electrical and piezoresistive properties

The dispersion of nanomaterials in cementitious composites firmly relates to their electrical and piezoresistive properties. The cementitious composites are nonconductive materials with electrical resistivity reaching up to 10^9 Ω cm after hardening. The low electrical conductivity hindered the further application of cementitious composites in the field of smart infrastructures, such as the self-monitoring, self-heating and self-deicing pavements [63,64]. In particular, the self-monitoring characteristic of cementitious composites is based on the piezoresistive property, which means the applied stress/strain can be detected through the changes in the electrical resistivity. Once the relationship between the stress/strain and resistivity is determined and calibrated, the cementitious composites can automatically calculate the external forces or deformations by recording the electrical resistivity. To obtain resistivity alterations of cementitious composites, various carbon additives have been summarized to improve the electrical conductivity based on their dimensions, as shown in Table 3. The following section presents the current investigations on cementitious composites with conductive carbonic materials to improve the electrical conductivity and piezoresistive properties.

Table 3
Electrical resistivity and gauge factor for cementitious composites with different carbon materials.

Dimensionality	Type of carbon materials	Type of cement matrix	Dosage to binder (%)	Electrical resistivity (Ω·cm)	Gauge factor	Refs.
0D	CB	Cement paste	15.0 wt	–	55.3	Li et al. [70]
			20.0 wt		37.7	
			25.0 wt		51.9	
	CB	Mortar	6.5 wt	–	40–60	Monteiro et al. [72]
	CB	Mortar	7.0 wt	–	30	Monteiro et al. [67]
			10 wt		24	
	CB	Cement paste	0.5 wt	–	51	Dong et al. [69]
			1.0 wt		114	
			2.0 wt		105	
	CB	Cement paste	3.0 wt	–	330–1240	Dong et al. [121]
	CB	Mortar	~0.5 vol.	$\sim10^4$	–	Dai et al. [65]
			~1.0 vol.	$\sim10^3$		
			~4.0 vol.	$\sim10^2$		
1D	CF	Cement paste	2.6 vol.	–	16–33	Wen and Chung [179]
			5.1 vol.		41–58	
			7.2 vol.		23-34 (tensile)	
	CF	Cement paste	0.5 wt	–	700 (tensile)	Fu et al. [180]
	CF	Cement paste	0.1 wt	11713.63	–	Baeza et al. [181]
			0.3 wt	4546.30		
			0.5 wt	462.55		
	CF	Cement paste	0.5 vol.	–	90 (tensile)	Wen and Chung [152]
					350 (compress)	
	CNF	Concrete	1.0 vol.	20100	–	Gao et al. [182]
			1.5 vol.	10000		
			2.5 vol.	5400		
	CNF	Cement paste	2.0 wt	–	190	Baeza et al. [82]
	CNF	Cement paste	1.0 vol.	~5000000	–	Wang et al. [183]
			2.0 vol.	~1000000		
			4.0 vol.	~500		
	CNT	Cement paste	0.1 wt	~4200000	–	Maria et al. [184]
			0.3 wt	~5700000		
	CNT	Cement paste	0.1 wt	–	130	D'Alessandro et al. [185]
		Mortar			68	
		Concrete			23	
	CNT	Cement paste	2.0 wt	–	220	Materazzi et al. [186]
2D	GP	Cement paste	5.0 vol.	–	156	Sun et al. [105]
	GP	Mortar	1.2 vol.	–	0–30	Du et al. [104]
			2.4 vol.		100–1000	
			4.8 vol.		500–4000	
	GP	Mortar	5.0 wt	~2700000	–	Le et al. [94]
			10.0 wt	~400000		
			20.0 wt	~800		
	GNP	Concrete	0.43 vol.	55–202	–	Liu et al. [95]
			0.61 vol.	28–343		
	GNP	Concrete	6.4 wt	–	160.8	Liu et al. [187]

3.1. Single conductive filler

3.1.1. 0D carbon black

Carbon black (CB) has been widely used as conductive fillers in polymeric composites for the manufacturing of tires or electrical conductivity amelioration. However, it seems that the application of CB in cementitious composites is relatively unattractive because of the restricted physical and mechanical properties brought by CB particles. It has been reported that CB could reduce the compressive strength of cementitious composites with the increase of CB concentration [65], while studies also found that the small dosage of CB could increase the mechanical properties owing to the filling effect of CB nanoparticles [66]. However, the improved compressive strength of CB cementitious composites was still at a low level from 13 to 16 MPa, which is actually difficult to be applied in practical projects [67]. By investigating the hydration heat and crystal phases of cementitious composites with CB, the highest compressive strength reaching approximately 53 MPa was observed for the composites with 0.5 wt% CB. With increasing curing age, the positive effects of CB are diminished, and the compressive strength of CB cementitious composites is lower than that of plain cement mortar [68]. Another research also reported that monotonically decreased compressive strength of CB cementitious composites monotonically decreased with the increase of CB content [69]. This phenomenon might be due to the sphericity of the 0D CB, thus lack of cohesion and frictional resistance to the cement matrix. Also, the nanoscale CB possessing high surface energy could enclose the cement particles and entrap the water to affect the cement hydration and hardening process.

Fig. 6 compares the electrical resistivity of CB/cementitious composites by different studies. The electrical resistivity of cementitious composites decreased with the addition of CB. However, it seems that the resistivity reduction intensity has a solid relationship with the types and particle sizes of CB. Dai et al. [65] found the percolation threshold for CB cementitious composites ranging from 0.36 to 1.34 vol% (0.7–2.5 wt%), while a slightly lower CB content range of 0.5–2.0 wt% was achieved by Dong et al. [69] and much higher CB content range of 7.22–11.39 vol% was observed by Li et al. [70]. Based on their description of the raw materials, the particle sizes of CB in the above investigations were 33, 20 and 120 nm, respectively. It could be deduced that the CB nanoparticles with a smaller scale can more easily reach the percolation threshold. Moreover, the above studies showed a discrepancy in the specimen preparation by the usage of a dispersion agent or not. The well-dispersed CB nanoparticles in the cementitious composites can stimulate the formation of the conductive passage and enhance electrical conductivity.

For the self-sensing or piezoresistivity of cementitious composites doped with CB, the stable electrical output as a function of compressive stress/strain could be drawn, indicating that the CB cementitious composites are capable of sensing stress and strain for structural health monitoring (SHM). As shown in Fig. 7, the piezoresistive sensitivity, which is also called as gauge factor, was proposed in various investigations on the CB cementitious composites. The gauge factor ranging from 37.7 to 55.3 was obtained for the cementitious composites with 15.0–25 wt% CB by Li et al. [70]. Besides, they proposed a numerical model to evaluate the gauge factor under various strains, CB concentrations and temperatures [71]. Afterwards, the lowest piezoresistive sensitivity was found by Monteiro et al. [67] with the gauge factor ranging from 24 to 30 for the composites with 10 and 7.0 wt% CB. Given the CB nanoparticles had an identical particle size of 120 nm, the reduced gauge factor is considered owing to the introduction of fine aggregates, which might block the formation of conductive passages and weaken piezoresistivity. Later, they observed the slightly larger gauge factor from 40 to 60 for the CB cementitious composites when the CB concentration decreased to 6.5 wt% [72]. Because the aforementioned studies did not predisperse CB nanoparticles before manufacturing the composites, the piezoresistive sensitivity for the CB cementitious composites was obtained by Dong et al. [69] with the gauge factor ranging from 51 to 114, after the pre-treatment of CB dispersion by superplasticizer. Although super high gauge factor larger than 300 was developed in the study, the composites were not only with CB nanoparticles but also assisted by the macro conductive rubber fibres. It is noted that higher gauge factor was observed by Li et al. [73] who applied CB into fibres reinforced engineered cementitious composites (ECC). The results are similar to the previous investigation of using nonconductive polypropylene (PP) fibres to improve the stress sensing ability of CB cement-based sensors [10]. The better sensitivity is mainly due to the new formed conductive passages through the CB enclosed PP fibres. Based on the excellent piezoresistivity, the CB/cement-based sensor has been installed into the concrete beams for SHM application [74]. Therefore, the experimental results showed that the CB cementitious composites only possessed moderate piezoresistive sensitivity compared to the cementitious composites with other conductive fibres.

3.1.2. 1D carbon materials

Carbon fibre (CF), carbon nanofiber (CNF) and carbon nanotube (CNT) are the commonly used 1D conductive carbon materials in

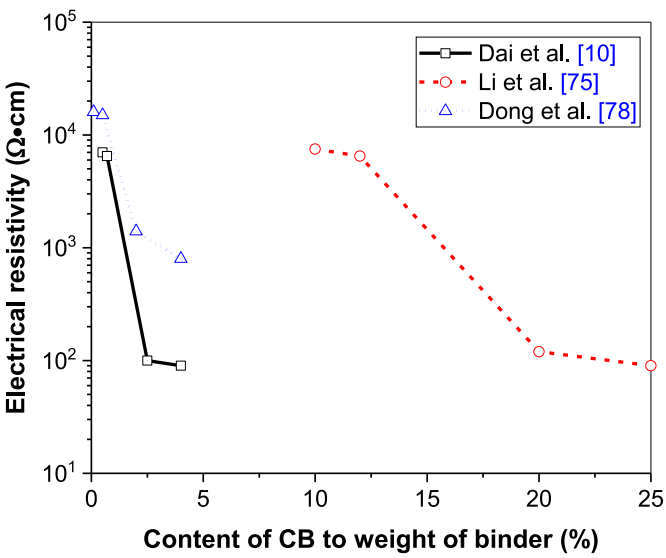


Fig. 6. Percolation threshold of cementitious composites with CB.

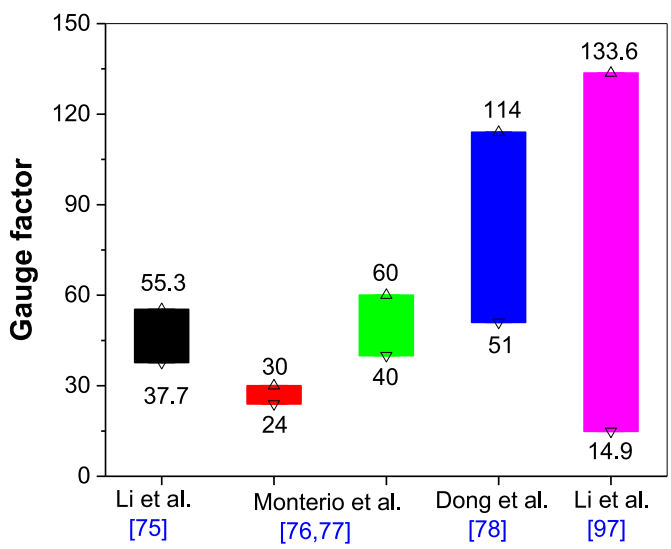


Fig. 7. Various gauge factors for the CB/cementitious composites under compression.

cementitious composites. Banthia et al. [75] firstly investigated the electrical resistivity of cementitious composites with CF by two embedded copper electrodes, and they found that the distance of electrodes and frequency of alternative current (AC) could affect the electrical resistivity of composites. The electrical conductivity brought by CF is also employed for the damage evaluation in the cementitious composites, where the irreversible resistivity during cyclic compression implied the created damages [76,77]. This is due to the inner induced micro-cracks and gaps destroyed the conductive passages and ruined the relationship between the electrical resistivity and the applied stress/-strain in the elastic regime. In addition, investigators applied the CF reinforced cementitious composites as stress/strain sensors to self-monitor the concrete structural health. Hundreds of times higher sensitivity (gauge factor) is observed for the CF cement-based sensors than the commercial strain gauge. Moreover, they found that the CF possesses additional benefits to improve the strength of cementitious composites, especially for the flexural and tensile strengths, given the excellent tensile strength of CF and the bridging effects in cementitious composites [78,79].

In terms of CNF in cementitious composites, Chung [80] demonstrated that the CNF with a diameter of 100 nm was less effective to improve the electrical conductivity of cementitious composites, in comparison to the CF with 15 μm in diameter. The investigator attributed the phenomenon to the more substantial contact resistance between conductive fillers to the cement matrix in a specific area per unit volume because of the small sizes of CNF. However, different results were obtained for the CF and CNF reinforced concrete, in which better electrical conductivity was found for the concrete with CNF [81]. The discrepancy also occurred on the mechanical properties of CNF reinforced cementitious composites, since both significantly reduced and enhanced compressive strength of the composites were achieved [41, 81]. Because the CNF is easily self-agglomerated to form clusters, the worse electrical conductivity and reduced mechanical property is mainly due to the poor dispersion of CNF that causes micro defects in the cementitious composites. The improved mechanical strength is because of the CNF having the bridging effect to the cement matrix, as well as reducing the porosity in the composites. As for the piezoresistivity, the cement-based sensors with CNFs and CFs were attached to reinforced concrete beams for strain and damaging monitoring. The results showed a higher gauge factor of 191.8 for the CNF/cement-based sensor, while only 49.5 for the sensors with CF in the compression [82].

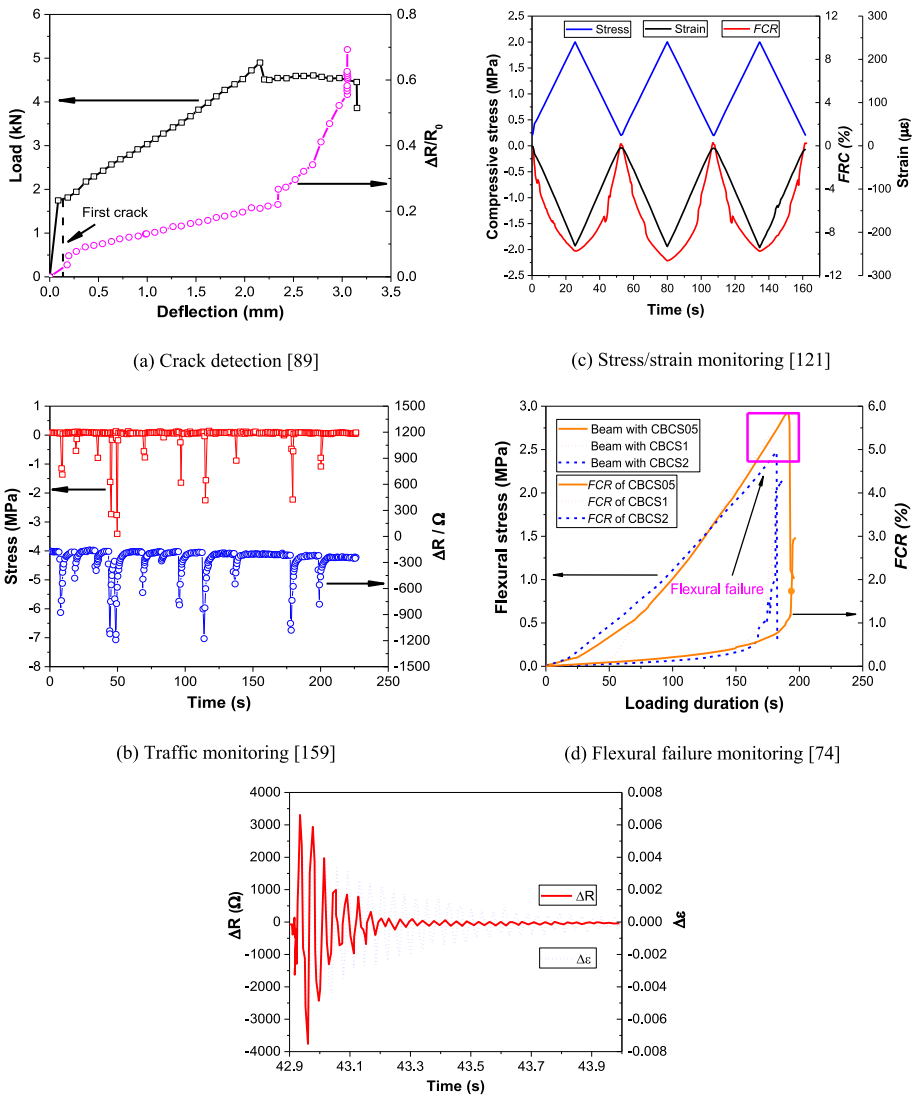
Compared to the CF and CNF, studies are more focused on the electrical and piezoresistive properties of cementitious composites reinforced with CNT [83]. By utilizing the electrical conductivity of CNT reinforced cementitious composites, Kim et al. [84] investigated their self-heating efficiency under the input voltages ranging from 3 to 20 V. In addition, Kim et al. [85] proposed that the chloride penetration into cementitious composites could be monitored, by the electrical conductivity alterations of embedded CNT/cement composites. They reported that the conductivity of composites was determined by the chloride ions movements and polarization effect. Based on the three impedance arcs/features in Nyquist plots, Wansom et al. [86] investigated the impedance spectroscopy of CNT/cementitious composites. They proposed that spectroscopy could distinguish the percolation from discontinuous CNT and characterize the agglomerations. Dong et al. [87] applied as-received CNT without pre-dispersion in cementitious materials and explored the effect of layer distributed CNT on the piezoresistivity.

Moreover, Ubertini et al. [88] utilized the embedded CNT cement-based sensors to measure the natural frequency of reinforced concrete beams. In terms of the piezoresistivity, Saafi [89] designed a wireless sensing network by CNT/cementitious composites and embedded those sensors into concrete beams for damage detection. It was observed that the mechanical behaviours could be reflected in the electrical resistivity of embedded composites. Han et al. [90] proposed a CNT concrete based traffic detection system and applied it into a roadway for the field test. It indicated that the collected signal could successfully detect the velocity of passing vehicles. Similarly, based on the embedded CNT/cement-based sensor, D'Alessandro et al. [91] found that the sensors were capable of detecting the static and dynamic strain and the natural frequency of concrete beams. They also needed for the calibration of cement-based sensors for commercial application. Fig. 8 presents the electrical resistivity changes of conductive cementitious composites in various situations. It revealed that the electrical signal and piezoresistivity could be an index to evaluate the cracks generation, traffic monitoring, stress/strain intensity, flexural failure of concrete beam and even the natural frequencies identification of structures through vibration.

3.1.3. 2D carbon materials

Cementitious composites with GNPs and GPs are gradually attracting more and more attention because of their electrical conductivity, plate-like structures, and relatively low prices. In addition to the excellent durability and mechanical properties brought to the cementitious composites, improvements on the electrical conductivity and piezoresistivity are still inspiring [92,93]. Le et al. [94] found that the electrical conductivity of high concentration GNP reinforced mortar was not only insensitive to moisture content but equivalent to the elastic compliance that made the damage self-sensing possible. Similarly, Liu et al. [95] investigated different failure patterns of GNP/cementitious composites under compression, and observed that the reaction of resistivity related to the damage evolution processes. Also, they suggested that the concentration of GNP should be higher than 6.4% by weight of cement to ensure satisfactory conductivity and piezoresistivity [96]. In addition to the CNT/cement-based sensors that have been applied for chloride penetration detection [85], the graphene/cement composite was proposed as well for the same purpose [97,98]. Because the electrical conductivity will be fluctuated by many factors such as temperature, humidity and carbonation, it is suggested that these influences should be eliminated before the practical application. Furthermore, investigators have studied the electrical conductivity of cementitious composites with GOs and found even higher resistivity compared to the plain composites [99]. However, Saafi et al. [100] investigated the electrical and piezoresistive behaviours of fly ash-based geopolymer with reduced GOs, and observed satisfactory conductivity and piezoresistivity. Generally, it can be deduced that the introduction of oxygen-containing groups on the graphene film decreases the electrical conductivity of GNP and deteriorates the conductivity improvement on the cementitious composites. The reduced GO regains the electrical conductivity that could be used for cement-based sensors manufacturing.

GP is one of the commonly used carbon materials because of its low cost and excellent electrical conductivity. The primary investigations on the electrical conductivity of asphalt concrete with GP showed that the percolation was approximately 10.9% by volume of asphalt and GP [101]. Yoo et al. [102] compared the self-sensing behaviours of the composites with graphite nanofibers and GNP, and they found that the cementitious composites with graphite nanofibers had better sensing capacity than those with GNP. Subsequently, the stress-sensing performances of GP/cement composite were studied by Fan et al. [103]. In comparison to the aforementioned GP asphalt concrete, a much higher percolation threshold of 20% by weight of cement was observed. Furthermore, by utilizing the graphite nanoplatelet (GiNP), the percolation was found between 2.4% and 3.6% by volume of composite for the GiNP-cement composites. As for the piezoresistivity, they observed the nonlinearity among fractional changes of resistivity to compressive strain, because of the poor cohesion between GP and cement matrix [104]. The discrepancy in the percolation threshold might be due to the different types of binders and the qualities of GP that affect the dispersion of GP in the matrix. For another application of GP/cement composites, Sun et al. [105] tested the piezoresistivity of GP/cement composite under static and dynamic loadings, and demonstrated the



(a) Crack detection [89]

(c) Stress/strain monitoring [121]

(b) Traffic monitoring [159]

(d) Flexural failure monitoring [74]

(e) Natural frequencies identification [88]

Fig. 8. Representative alterations of electrical resistivity of conductive cementitious composites during different applications.

excellent sensitivity and repeatability as a prototype sensor. Qin et al. [106] used conductive concrete with GP as a grounding device, to replace the traditionally grounding materials. Based on the Joule effect, Rao et al. [107] manufactured the deicing concrete pavements by the addition of GP. To reduce the EMI, the concrete with GP was proposed with additional shielding at 360 MHz, reaching 2.4 dB [108]. However, previous studies rarely mentioned the mechanical properties development of GP/cement composites. It was found that the cement paste with more than 6% GP possessed a lower compressive strength than that of plain cement paste [109]. Researchers even observed a 90% reduction in the compressive strength of concrete with GP when the GP content reached 15% to the weight of cement [110]. Generally, the drawbacks of GP in the mechanical properties of cementitious composites are mainly due to the thicker plates and the movable layers.

3.2. Hybrid conductive fillers

The mixed application of conductive fillers was observed with better performances on the electrical and piezoresistive properties of cementitious composites. The effect of hybrid usage of carbon materials among different dimensions on the electrical resistivity and piezoresistive sensitivity of cementitious composites is listed in Table 4. Ding et al. [111] tested the piezoresistive behaviours of the epoxy resin concrete with steel slag and GP. It seems that the addition of steel slag could help to form the conductive networks in the composites and benefit the piezoresistivity. Similarly, Yıldırım et al. [112] investigated the mechanical and shear damages self-sensing ability of chopped CF and CNT reinforced concrete, and found that the CF could significantly improve the flexural strengths and ductility of concrete. They found that the addition of CF could improve the sensing efficiency compared to the concrete beams only with CNT. By manufacturing the asphalt concrete with GP and CF, Liu and Wu [113] found that the specimens are more effective for compressive strain monitoring. Also, the combined use of GNP and CF in cementitious composites led to high conductivity and piezoresistivity [114]. On the other hand, the partial substitution of costly conductive fillers by cheap ones could dramatically reduce the engineering expenditure. Wu et al. [115] compared the electrical conductivity of the asphalt concrete with single CB, CF, GP and their hybrids, and they found that the CF is best to improve the conductivity, followed by GP and CB. Fortunately, the replacement of expensive CF by the low-cost CB and GP can reduce the engineering cost and maintain the similar electrical conductivity. In addition, although the electrical conductivity and piezoresistivity were not involved, the better EMI shielding for the cementitious composites with GOs deposited CF than

Table 4
Electrical resistivity and gauge factor of cementitious composite with different carbon materials.

Dimensionality	Dosage to binder (%)	Type of cement matrix	Electrical resistivity (Ω·cm)	Gauge factor	Refs.
0D and 1D	0.5 wt. CF + 0.5 wt. CB	Cement paste	604 791	13–17 ~332	Wen and Chung [188]
	1.0 wt. CF	Concrete	–	25.6	Ding et al. [55]
	1.0 wt. CF			13.5	
	0.8 wt. CF + 0.2 wt. CB				
	0.5 vol. CF + 1.0 wt. CB	Cement paste	~5000000 ~900	–	Chen et al. [189]
	0.5 vol. CF + 2.0 wt. CB				
	0.96 vol. CNT +1.44 vol. CB	Cement mortar	–	625–727	Han et al. [190]
1D and 1D	15 vol. CF	Cement paste	–	445	Azhari et al. [191]
	15.0 vol. CF + 1.0 vol. CNT			422	
	1.0 vol. CNT	Cement paste	–	167	Lee et al. [192]
	0.5 vol. CNT +0.1 vol. CF			160	
	1.0 wt. CB + 1.5 wt. CNT +0.2 wt. CF	Cement paste	10050 237	–	Hong et al. [193]
	1.0 wt. CB + 1.5 wt. CNT +0.4 wt. CF				
1D and 2D	1.0 wt. CF	Concrete	~1120	–	Chen et al. [194]
	0.7 wt. CF + 2.5 wt. GP		~990		
	0.5 wt. CF + 5.0 wt. GP		~970		
	4.0 wt. GNP +0.66 wt. CF	Cement mortar	–	295	Belli et al. [114]
0D, 1D and 2D	12.7 vol. GP	Concrete	140000	–	Wu et al. [115]
	7.3 vol. GP + 3.6 vol. CF		~1200		
	7.3 vol. CB + 3.6 vol. CF		~1400		

those only with CF indicated that the hybrid utilization of conductive carbon materials was an effective alternative [116].

3.3. Mechanism of conductivity

The electrical conductivity of the cementitious composite depends on whether or not conductive passages create throughout the specimen. With the increase of fillers, the electrical percolation threshold was proposed to present the beginning of the formation of conductive passages, where the electrical conductivity sharply increased within a small change in the concentration of fillers. In other words, the percolation threshold illustrates the smallest dosage ranges of conductive fillers that significantly increase the electrical conductivity of cementitious composites. Before the formation of continual conductive passages, various connecting states of conductive fillers represent different conductivity of cementitious composites. Fig. 9 shows the relative position of conductive rubber crumbs (CRC) in the cementitious composites with the raised content of fillers. With a small dosage, the conductive fillers are completely separated by the cement matrix and the composites show a high electrical resistivity. When the conductive fillers are at a moderate concentration, there exists the neighbouring state of fillers that partial conductive paths might be established due to the tunnelling conductivity. Once the content of conductive filler exceeds the percolation threshold, the complete contact among fillers can be observed, and hereafter the electrical conductivity of composites experienced a significant enhancement.

However, it is quite different for the 0D, 1D and 2D carbon materials to connect each other and form conductive passages, which makes their percolation threshold changeable in cementitious composites. As shown in Fig. 10(a)–10(c), the 1D carbon materials with a high aspect ratio perform better on declining the electrical resistivity of cementitious composites than those with 0D and 2D materials [117–119]. More electrical contact points tend to be established among 1D fibrous fillers rather than the 0D spherical fillers. Additional usage of 2D GiNP stimulates the formation of contact points, but the efficiency is relatively lower than that of 1D CNT under an identical volume fraction. The smaller sized nanoparticles perform better than the micro or macro-sized carbon materials in the cementitious composites. Still, the application of macro fibres can enhance the electrical conductivity of cementitious composites. As illustrated in Fig. 10(d) and (e), conductive CB nanoparticles are connected to form conductive passages. Hence, the cementitious composite is provided with moderate electrical conductivity and piezoresistivity. However, with the addition of macro PP fibres and conductive rubber fibres, new conductive passages are established by the connection of macro fibres and CB to fibres. Also, the directional distribution of CB nanoparticles on the surface of PP fibres enhances the formation of conductive passages, because the PP fibres possess a higher aspect ratio than that of CB. The appropriate concentration of macro fibres increases the contact points and the conductive passages in cementitious composites, which are beneficial to the conductivity and piezoresistivity [69]. Similarly, for the combined usage of CB and CNTs in cementitious composites, the CNTs elongate the conductive passages and enhances the electrical conductivity [120].

The conductive mechanism is slightly different for the cementitious composites with different water contents. Fig. 11(a) illustrates the contact characterization of CB nanoparticles with varying contents of water and their contacts to CNT in cementitious composites. Different from the electric conduction among CB and CNTs, the water films in their surface lead to the enhancement of ionic conduction. With the increase of water content from a totally dry to saturation state, the electric conduction is gradually weakened, whereas the ionic conduction is strengthened. The increased electrical resistance of cementitious composites implies that the ionic conduction possesses lower efficiency to increase the electrical conductivity of cementitious composites compared to electric conduction. In addition, it has been reported that there exists large contact resistance among conductive fillers which are enclosed with water film, as shown in Fig. 11(b). That is why the piezoresistivity of conductive cementitious composites is strongly affected by the water content. As for the interferences by temperature changes, although the electrical conductivity alters due to the changed thermal motion of electrons and ions, the piezoresistivity is found nearly consistent in the cementitious composites [121]. Another disturbance in the conductivity is originated from the aggregates in cementitious composites. Generally, the addition of aggregates not only play a dilution effect on the concentration of conductive fillers to affect the conductivity but retard the formations of conductive passages [122,123].

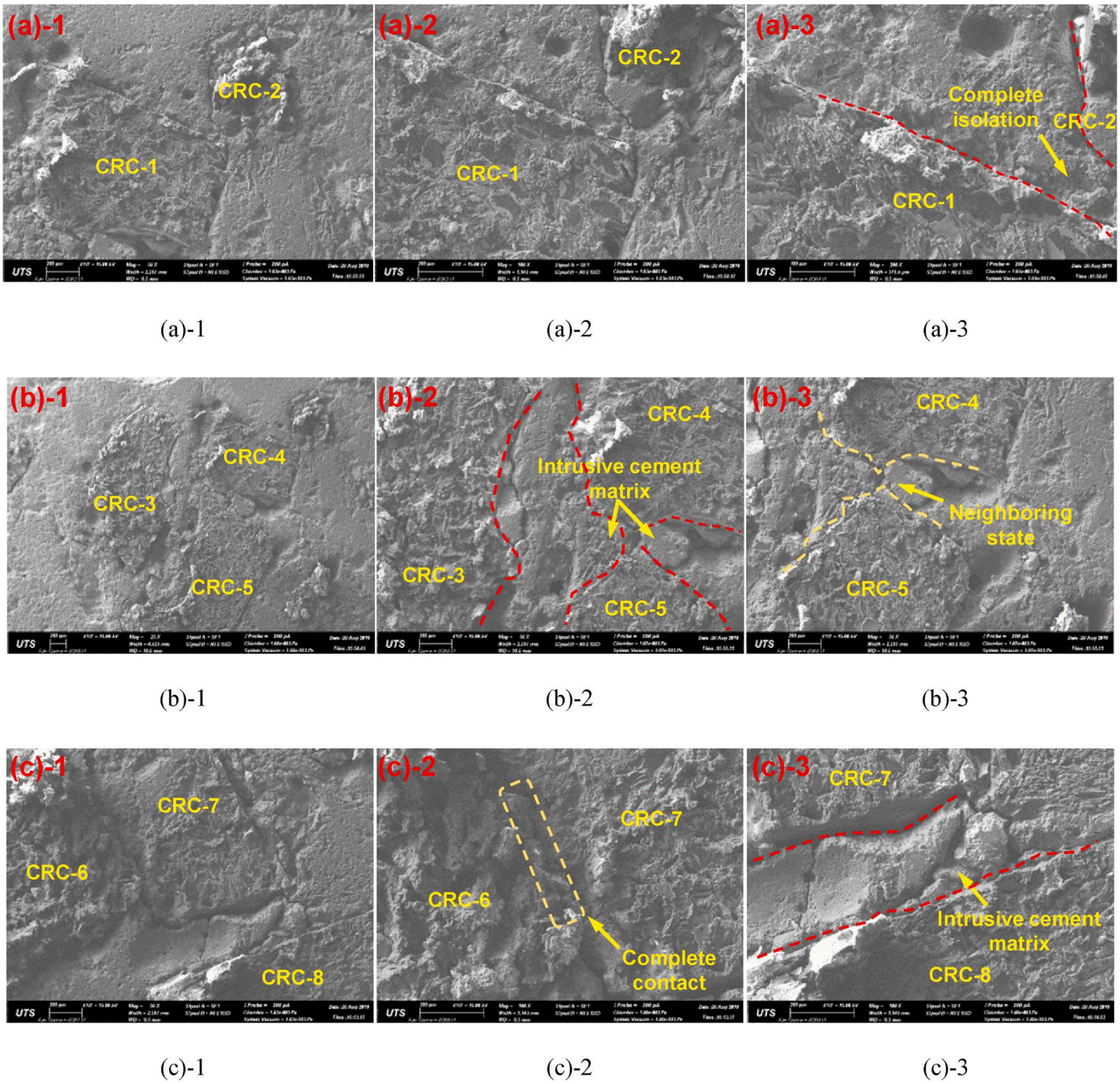


Fig. 9. Microstructural morphology of CRC filled cement mortar: (a) complete isolation; (b) neighbouring state; and (c) complete contact [195].

4. Theoretical modelling

4.1. Electrical conductivity

The numerical model proposed to estimate the electrical resistivity of plain cement paste was based on the effective medium and percolation theory [124]. It provided a method to evaluate the relative resistivity of cement paste and the C–S–H. In the case of the cementitious composites with the presence of conductive filler, Liu et al. [125] built a model regarding CF and fine sand to analyse the percolation behaviours of cementitious composites, the calculated percolation threshold in the ranges of 0.6–0.8 vol% was closed to the experimental result of 0.75 vol %. Xu et al. [126] derived the expression of electrical resistivity of CF/cementitious composites based on Ohm's law and tunnelling effect theory. The calculated resistivity alterations fitted well to the measured electrical resistivity for the composites with various contents of CF. Based on the 2D resistor mesh model and the fact that electrical resistivity of conductive concrete altered with presence of cracks, Downey et al. [127] found that the model could self-monitor the cracks generation inside the concrete. Azhari and Banthia [128] used a 3D percolation model to predict the percolation threshold of CF reinforced cementitious composites. They found that the breakage of CF would strongly affect the results, thus the effective length rather than the practical length of CF should be applied in the model. For the conductive nanomaterials, the agglomeration will significantly affect the electrical resistivity of composites. Therefore, to avoid the overestimation of the electrical conductivity by CNTs to cement matrix, Enrique et al. [129] considered the waviness of CNTs and the agglomerations in the micromechanics model. Bao et al. [130] improved the 3D percolation model by considering the effect of CNTs alignment on the electrical

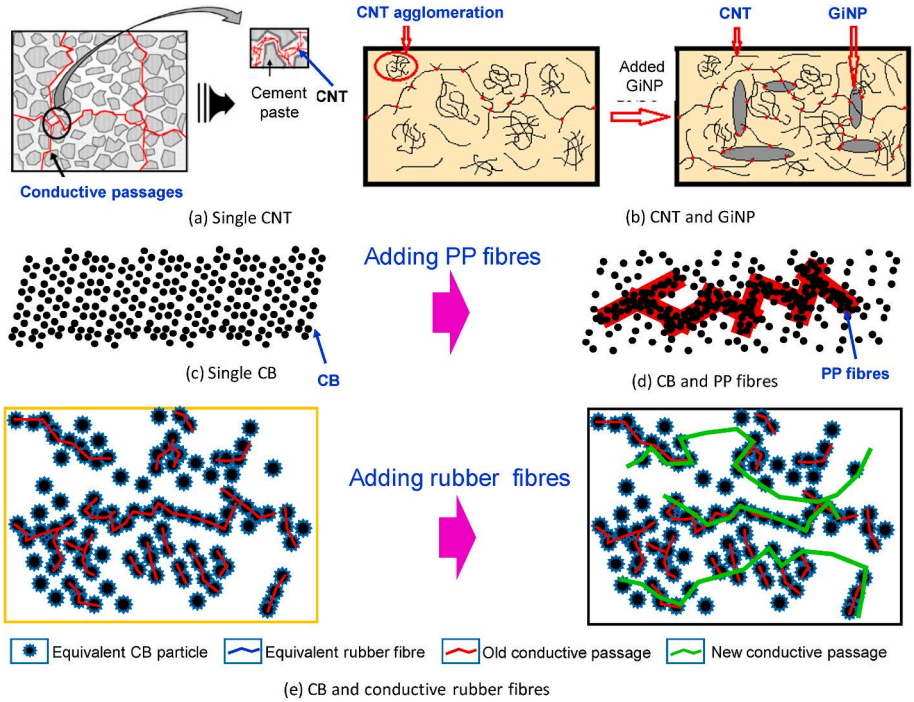


Fig. 10. Conductive mechanism of the cementitious composites with various conductive fillers.

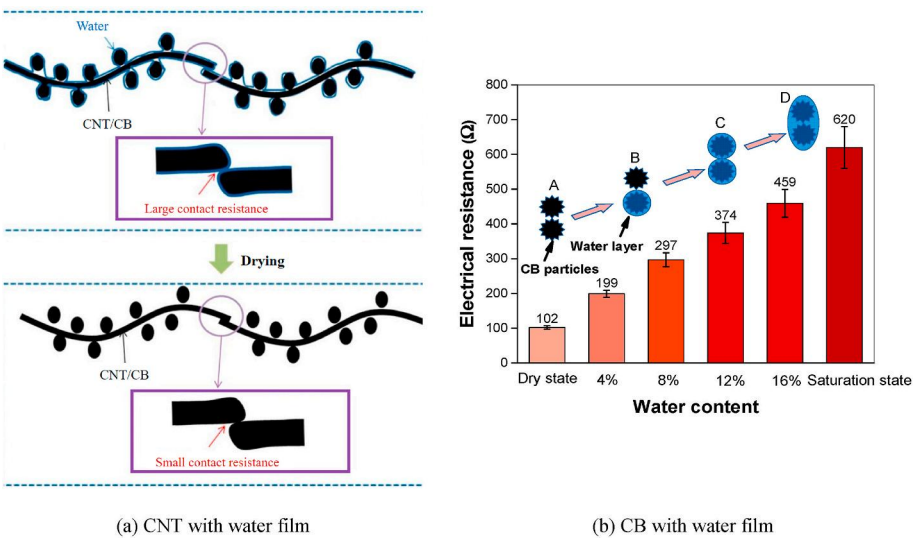


Fig. 11. Effect of water content on the electrical conductivity of cementitious composite [121,196].

conductivity and percolation. Furthermore, micromechanical models were used to examine the effects of moisture and CNT agglomeration on the electrical resistivity of cementitious composites [131].

4.2. Piezoresistive behaviour

Wen et al. [132] first attempted to model the piezoresistivity of CF reinforced cement paste, based on the pull-out effect between single fibre to cement matrix and the induced resistivity changes. Differently, based on the tunnel effect theory, Xiao et al. [71] simulated the CB nanoparticles as tunnel resistors and modelled their electrical resistivity changes under external strain, and acclaimed that the theoretical results fitted well with the experimental results. Even though the model calculated values agreed well with the experimental results, they did not take other conductors such as pre solutions or the effect of agglomerations into consideration. Furthermore, Zhang et al. [133] took into account the conductive networks created by single CNT and the CNT agglomerations, and found that the experimental measurements of piezoresistivity could be more accurately fitted. By considering the effect of CNT agglomerations, concentration and waviness, Enrique et al. [134] predicted the piezoresistivity of CNT reinforced self-sensing cementitious composites subjected to external strain based on the changes of volume fraction, fibres reorientation and tunnel resistance. The accuracy of the model was demonstrated by the comparison between experimental data to the calculated ones. Also, based on an equivalent lumped circuit where the piezoresistivity was modelled by the linear relationship between resistance and strain, they found the stimulated results could reproduce the superharmonic response of composites under harmonic mechanical loads [135,136]. Yang et al. [137] found that the interfacial debonding process in the

microstructure-guided electro-mechanical finite element model could successfully represent the electrical resistivity changes of cementitious composites, even though the reinforcements were metallic particles. García-Macías et al. [138] stimulated the piezoresistivity of CNT reinforced cementitious composites subjected to arbitrary strain states by the mixed micromechanics and finite element approach. The comparison with experimental data illustrated the effectiveness of electromechanical modelling.

5. Development of multifunctionalities for smart concrete

5.1. Self-heating behaviour

Based on the Joule effect, the electrically conductive cementitious composites under applied current would generate heat energy. The heat energy followed Eq. (1):

$$Q = I^2 Rt \tag{1}$$

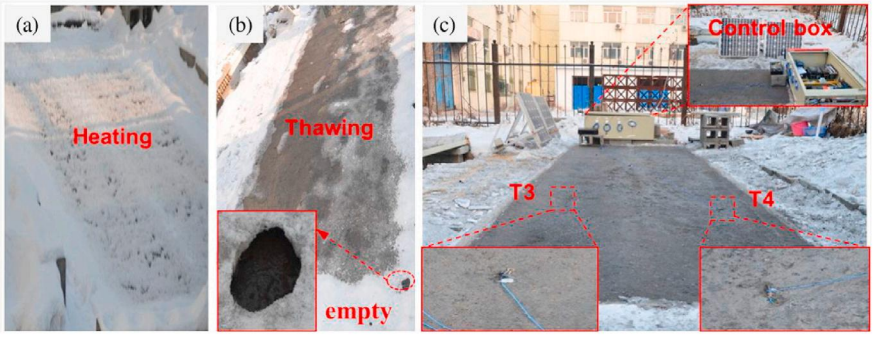
where Q is heat energy; I denotes the current generated through the composite; R corresponds to electrical resistivity, and t represents the power-on duration.

Wang et al. [139] manufactured the cement mortar with excellent conductivity, which could raise its temperature from room temperature to 90 °C within an hour under 8 V DC voltage. Sassani et al. [140] investigated the different amounts of CF on the electrical and self-heating properties of cementitious composites, and they recommended that the CF dosage was approximately 1.0 vol% to achieve the best heating performances. Chang et al. [141] embedded CNF paper as thermistor in concrete and found that the temperature of concrete increased to the values above the freezing point of water at the power input of 6 W. It implied that the concrete with CNF paper could be applied as self-heating construction materials, especially in the deicing pavements. Different from the experimental investigations, the self-heating properties of cementitious composites have been explored on the de-icing and snow melting properties of pavements. For example, the electrically conductive concrete with CF was applied in an airport to test the anti-icing properties [142]. Even though the more reduced conductivity of concrete was detected in the broad-scale application than that in the laboratory, the concrete generated 300–350 W/m^2 power density that was sufficient to melt the ice and snow, as depicted in Fig. 12(a). In addition, the concrete pavement with sandwiched conductive graphite-PET sheets also showed highly efficient snow melting [143]. Gomis et al. [144] proposed that the conductive cement paste could control the ice layers in pavements. Still, the cost was high because of the high-applied voltage. Therefore, the conductive cementitious composites should be further optimized to higher heating efficiency.

5.2. Self-healing properties

The traditional self-healing cementitious materials are normally originated from the addition of some minerals, polymers or bacteria, which will not be introduced in this paper. The self-healing property based on the electrical conductivity of cementitious composites is mostly limited to the asphalt concrete, given the increase of temperature benefits the capillary flow of bitumen and improves the crack recovery [145–147]. Liu et al. [148] found that the electromagnetic induction heating on the conductive porous asphalt concrete improved the self-healing efficiency of asphalt mastic. Jahanbakhsh et al. [149,150] applied CB into asphalt concrete to enhance its electromagnetic sensitivity. In addition to the improved mechanical properties, the induction heating of asphalt concrete found that the CB could strongly improve the heating efficiency and heal the asphalt concrete. However, different from the above results, Pamulapati et al. [151] compared the self-healing efficiency of asphalt concrete with/without conductive fillers, and found that the control asphalt concrete without conductors have better healing efficiency than those with conductors, even if they were not heated during induction. Hence, they concluded that another healing mechanism, rather than heat healing, was generated for the asphalt concrete.

(a) Self-heating concrete slab at an airport in the US [142]



(b) Snow-thawing process of concrete pavement [143]

Fig. 12. Practical application of self-heating concrete for pavement deicing.

5.3. Smart structural health monitoring

The conductive cementitious composites are widely investigated to substitute the conventional sensors of the foil strain gauge, optical fibre and piezo ceramic, etc., since the excellent monitoring efficiency and high durability. The self-monitoring is also called piezoresistivity which originates from the altered electrical resistivity of cementitious composites under external stress/strain. Studies mentioned above have partially illustrated the conductive cementitious composites with various carbon materials, while the effect of more conductive fillers such as steel fibre or nickel powder has not been reviewed on the piezoresistivity. For instance, Wen et al. [152] found that the cement paste with steel fibre had better piezoresistive sensitivity than that reinforced with CF, especially under tensile strain. This has been further elucidated that the cement mortar with steel fibre was provided with excellent sensitivity under tensile stress, with the gauge factor reaching up to 5195 [153]. Moreover, the steel fibre distribution inside the concrete could be detected based on the electrical resistivity measurement [154]. In terms of the nickel powder, Han et al. [155,156] explored the piezoresistivity of cementitious composites with nickel powder and found the gauge factor as high as 1336.5 and 1929.5. Furthermore, since the nickel powder could be directionally aligned in the magnetic field, the improved piezoresistivity could be observed for the cementitious composites because of the more generated conductive networks [157]. However, in comparison to steel fibre, it must be noted that nickel powder is one of the heavy metals that might cause diseases in humans and contaminate the environment.

In addition to the stress/strain monitoring, traffic information, weight, temperature and humidity self-monitoring of conductive cementitious composites have been investigated, as shown in Fig. 13. Shi et al. [158] found that the electrical resistance of concrete rollers with CF decreased with the increasing stress, but it was independent from the speed of the car tire. Therefore, the conductive concrete was able to monitor the traffic and weigh the vehicles in motion. In addition, to monitor the vehicle speed in motion, two separated sections of conductive concrete were embedded into the pavements. Then the average speed of the vehicle could be measured through the distance between two sections and the time interval [159]. Similarly, Zhang et al. [160] collected the electrical signal output of the conductive cementitious composites on field tests under a 10-tonne truck and a 6.8-tonne van, and they concluded that the conductive cement-based sensor was capable of monitoring the traffic flow and vehicle speed detection. As for the temperature and humidity monitoring, Dong and Xu et al. [121,161] found that the electrical resistivity of cementitious composites had a firm relationship to the environmental temperature and humidity. Once the connection was calibrated, the temperature and humidity could be measured through the changes of electrical resistivity. Moreover, Wang et al. [139] studied the electrical resistivity and electro-thermal properties of cement mortar with CF and found that they had a strong Seebeck effect. Hence, the conductive cement mortar could be an accurate temperature sensor.

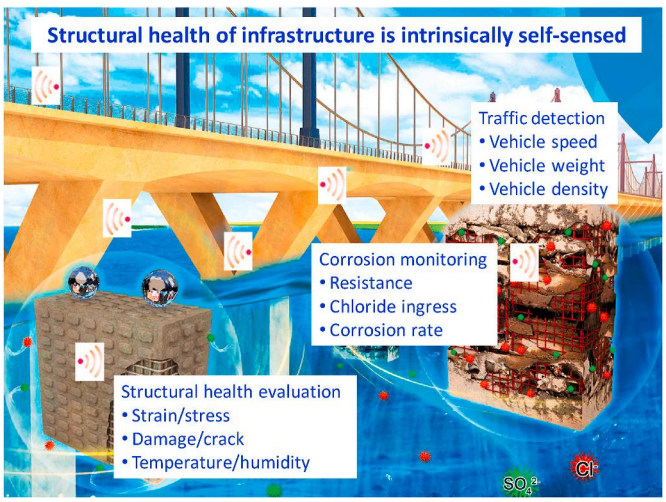


Fig. 13. Potential application of multifunctional self-sensing concrete for smart health monitoring of traffic, bridge and corrosion.

5.4. Electromagnetic interference shielding/absorbing properties

EMI (electromagnetic interference) shielding/absorbing is a critical technique to ensure the proper functioning of some electronics and devices. Moreover, long-term exposure to electromagnetic waves is harmful to human health by promoting the growth of tumour [162]. Cao et al. [163] compared the colloidal graphite as additives or coatings on the cement paste and found that the former was more effective in enhancing the EMI shielding, however, did not observe a significant reduction in the electrical resistivity. Moreover, Liu et al. [164] applied nano Fe_3O_4 into cementitious composites with CF, and they achieved the shielding effectiveness of 29.8 dB which was 34.4% higher than the counterparts only with CF. These results imply that the better conductivity of cementitious composites might improve the EMI shielding capacity, but the better shielding ability does not mean better conductivity. Although the EMI shielding ability does not require electrical conductivity, investigations have found that the cementitious composites with conductive fillers could be sharply increased on the EMI shielding compared to the plain counterparts [165,166]. Micheli et al. [167] investigated the EMI shielding performances of cementitious composites with 1% and 3% CNT and found the highest shielding effectiveness of 12 dB in the frequency of 2.6 GHz for the 3% CNT reinforced concrete. Similarly, higher shielding effectiveness of 28 dB was observed for the cementitious composites reinforced with CNT [168,169]. Different from the EMI shielding, the EMI absorbing represented that the EMI energy could be attenuated by transforming into other forms of energy. It has been reported that the addition of 2.5% CB significantly improved the loss factor of cementitious composites, and thus enhanced the EMI absorbing capacity by polarization [65].

6. Challenge and perspective

It should be mentioned that durability, thermal and mechanical properties of cementitious composites have been widely explored and the results are encouraging [170]. However, the electrical property of cementitious composites has been proved as one of the most promising characterizations for multifunctional cementitious composites. To extend the application of electrical property, further studies are needed on the effective control of the critical factors such as application environments, data monitoring system, dispersion, high production cost and health-related issues.

Variations in the temperature and humidity affect the electrical resistivity of cementitious composites; thus, the correlation to the targeted index could be affected. Taking piezoresistivity for example, it has been demonstrated that the temperature from −20 °C to 100 °C almost made no difference in the electrical resistivity changes under compression [121]. However, the temperature altered the initial resistivity before compression that might cause misunderstanding on the monitoring index, let alone the unknown performance of conductive cementitious composites in extreme environments outside the range of above temperatures. The piezoresistivity was also considerably fluctuated for the cementitious composites with different water contents from a completely dry state to a saturated state. Dong et al. [171] developed the hydrophobic cement-based sensors to eliminate the water interference. Some other studies attempted to use temperature and humidity compensation circuits to eliminate the effect of environmental factors [172], while the exact circuit configuration in conductive cementitious composites is very rare. Moreover, the durability and severability of

conductive cementitious composites under freeze-thaw cycles should be further investigated because the combined effects of temperature and humidity were applied on the cementitious composites.

Data collection system relates to the accuracy to evaluate the efficiency of multifunctional cementitious composites with capacities of self-sensing, self-heating, self-healing and EMI shielding. Currently, the methods to measure the electrical resistivity of cementitious composites are multiple from the two-point method to the four-point method by using direct current (DC) to alternative current (AC). The two-point method has similar effectiveness to the four-point method to evaluate the resistivity as long as the electrical resistivity of electrodes and conductive wires themselves could be neglected. For the dried cementitious composites where the polarization is not significant, an easier configuration of DC can be applied to measure the electrical resistivity. However, for the saturated composites or those with high water contents, the power supply of AC is highly recommended since the electrical signals under DC will take a long time to reach the electrostatic equilibrium in an electric field. In addition to the resistivity measurement methods, the layout of conductive cementitious composites and the data collection in the concrete structures should be paid more attention to sufficiently realize the functionality. For example, the conductive cementitious composites could be entirely used in the surface layer of self-deicing pavement, or it could only be needed in several key elements of concrete structures such as a tensile beam. Moreover, the exploration of cement-based sensors for defective area mapping could be carried out in future investigations.

Uniform dispersion of carbon materials in cementitious composites has a firm relationship to electrical conductivity. The field operation of carbon materials dispersion is not only complicated to the labour force, but also consuming additional energy for ultrasonication which increases both the project duration and expenditure. The commonly used carbon materials to improve the electrical conductivity of cementitious composites were high-priced such as the CNT or GNP. Hence, it dramatically increases the related cost based on the optimal mix proportion. Therefore, a better mix design of conductive cementitious composites should be explored by adopting less content of conductors, such as the utilization of electromagnetic fields or cheap fibres with a high aspect ratio [173]. Although rarely mentioned, according to the report from IARC of the World Health Organization, CNT has been regarded as a class 2B carcinogen, which might cause genetic disease to operators. Therefore, the sustainable alternative of conductive fillers such as recycled carbon fibre, recycled conductive rubber or recycled ceramics could be applied for conductive cementitious composites. Moreover, even for the same mixing proportion of functional cementitious materials, the deviation of electrical conductivity, piezoresistivity and other functions is high especially under the specific environments. Furthermore, because of the improved electrical conductivity and EMI shielding properties, the traditional non-destructive testing techniques for concrete structures might be influenced, which should be calibrated based on the altered electrical conductivity [174].

7. Conclusions

Conductive carbon materials from CB, CNT, CF, CNF, GNP, and GP have been used to improve the conductivity and piezoresistivity of cementitious composites. Based on the size and dimension, this paper systematically reviewed the cementitious composites with carbon materials on electrical characterization and piezoresistivity as well as self-heating, self-healing, and electromagnetic interference shielding for smart/functional cementitious composites. Some conclusions can be drawn as follows:

(1) Uniform dispersion of carbon materials in cementitious composites is critical to electrical and piezoresistive properties. Different dispersion methods such as ultrasonic dispersion, surface modification, mineral additives, and the mixture of carbon materials in various dimensions have been proposed. The hybrid usage of these techniques is carried out to achieve a better-dispersed suspension.
(2) The 0D CB are qualified additives to improve the electrical conductivity and piezoresistivity of cementitious composites. However, the conductivity promotion efficiency is lower than 1D and 2D carbon materials, since the spherical CB is more challenging to form conductive passages. It usually leads to the reduced fresh and mechanical properties of cementitious composites.
(3) The 1D CF, CNF, CNT and 2D GNP could significantly improve the electrical conductivity and piezoresistivity of cementitious composites as well as mechanical properties. The enhancement is either due to the bridging effect of fibres or the filling effect of carbon materials in the nanoscale. The 2D GP could improve the conductivity and piezoresistivity of cementitious composites, but at lower effectiveness, because the thicker plates and movable layers have cohesion problems to cement matrix.
(4) The modelling of electrical and piezoresistive properties of cementitious composites with carbon materials have been limitedly investigated. Many factors, such as types and contents of conductors, water content, temperature, agglomeration degree, microstructures, the frequency and intensity of input power, can affect the electrical conductivity and piezoresistivity. Current modelling includes only one or some of these factors, which sharply limits the field application of conductivity cementitious composites.
(5) Potential application of conductive cementitious composites has been summarized and discussed, ranging from self-heating and deicing pavements, self-healing asphalt concrete, self-sensing beams to the constructions with EMI shielding ability. More explorations should focus on the production and application of these products in terms of sustainability, low-cost, scale production and efficient installation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] D. Chung, Carbon materials for structural self-sensing, electromagnetic shielding and thermal interfacing, Carbon 50 (9) (2012) 3342–3353.
[2] W. Dong, W. Li, Z. Tao, K. Wang, Piezoresistive properties of cement-based sensors: review and perspective, Construct. Build. Mater. 203 (2019) 146–163.
[3] L. Wang, F. Aslani, Self-sensing performance of cementitious composites with functional fillers at macro, micro and nano scales, Constr. Build. Mater. 314 (2022), 125679.
[4] W. Dong, W. Li, K. Vessalas, K. Wang, Mechanical and conductive properties of smart cementitious composites with conductive rubber crumbs, ES Mater. Manuf. 7 (2020) 51–63.
[5] G. Li, P. Wang, X. Zhao, Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes, Carbon 43 (6) (2005) 1239–1245.
[6] Z. Lu, D. Hou, L. Meng, G. Sun, C. Lu, Z. Li, Mechanism of cement paste reinforced by graphene oxide/carbon nanotubes composites with enhanced mechanical properties, RSC Adv. 5 (122) (2015) 100598–100605.
[7] R. Howser, H. Dhonde, Y. Mo, Self-sensing of carbon nanofiber concrete columns subjected to reversed cyclic loading, Smart Mater. Struct. 20 (8) (2011), 085031.
[8] W. Dong, W. Li, K. Wang, Z. Luo, D. Sheng, Self-sensing capabilities of cement-based sensor with layer-distributed conductive rubber fibres, Sensor Actuator Phys. 301 (2020), 111763.

[9] W. Dong, W. Li, G. Long, Z. Tao, J. Li, K. Wang, Electrical resistivity and mechanical properties of cementitious composite incorporating conductive rubber fibres, Smart Mater. Struct. 28 (8) (2019), 085013.
[10] W. Dong, W. Li, K. Wang, Y. Guo, D. Sheng, S.P. Shah, Piezoresistivity enhancement of functional carbon black filled cement-based sensor using polypropylene fibre, Powder Technol. 373 (2020) 184–194.
[11] H. Yang, H. Cui, W. Tang, Z. Li, N. Han, F. Xing, A critical review on research progress of graphene/cement based composites, Compos. Appl. Sci. Manuf. 102 (2017) 273–296.
[12] O. Öztürk, G. Yıldırım, Ü.S. Keskin, H. Siad, M. Şahmaran, Nano-tailored multi-functional cementitious composites, Compos. B Eng. 182 (2020), 107670.
[13] H. Xiao, H. Li, J. Ou, Strain sensing properties of cement-based sensors embedded at various stress zones in a bending concrete beam, Sensor Actuator Phys. 167 (2) (2011) 581–587.
[14] D. Micheli, R. Pastore, A. Vricella, R.B. Morles, M. Marchetti, A. Delfini, F. Moglie, V.M. Primiani, Electromagnetic characterization and shielding effectiveness of concrete composite reinforced with carbon nanotubes in the mobile phones frequency band, Mater. Sci. Eng., B 188 (2014) 119–129.
[15] T. Schumacher, E.T. Thostenson, Development of structural carbon nanotube-based sensing composites for concrete structures, J. Intell. Mater. Syst. Struct. 25 (11) (2014) 1331–1339.
[16] Z. Wang, Q. Dai, X. Yang, Integrated computational-experimental approach for evaluating recovered fracture strength after induction healing of asphalt concrete beam samples, Construct. Build. Mater. 106 (2016) 700–710.
[17] M. Lim, H. Lee, I. Nam, H. Kim, Carbon nanotube/cement composites for crack monitoring of concrete structures, Compos. Struct. 180 (2017) 741–750.
[18] B. Lebental, W. Moujahid, C. Lee, J.L. Maurice, C. Cojocaru, Graphene-based resistive humidity sensor for in-situ monitoring of drying shrinkage and intrinsic permeability in concrete, in: NICOM 4: 4th International Symposium on Nanotechnology in Construction, 2012, p. 8. France.
[19] W. Dong, W. Li, X. Zhu, D. Sheng, S.P. Shah, Multifunctional cementitious composites with integrated self-sensing and hydrophobic capacities toward smart structural health monitoring, Cement Concr. Compos. 118 (2021), 103962.
[20] L.I. Nasibulina, I.V. Anoshkin, A.G. Nasibulin, A. Cwirzen, V. Penttala, E. I. Kauppinen, Effect of carbon nanotube aqueous dispersion quality on mechanical properties of cement composite, J. Nanomater. (2012), 169262, 2012.
[21] F. Ghaharpour, A. Bahari, M. Abbasi, A.A. Ashkarran, Parametric investigation of CNT deposition on cement by CVD process, Construct. Build. Mater. 113 (2016) 523–535.
[22] L.I. Nasibulina, I.V. Anoshkin, S.D. Shandakov, A.G. Nasibulin, A. Cwirzen, P. R. Mudimela, K. Habermehl-Cwirzen, J.E. Malm, T.S. Koltsova, Y. Tian, Direct synthesis of carbon nanofibers on cement particles, Transport. Res. Rec. 2142 (1) (2010) 96–101.
[23] A. Chaipanich, T. Nochaiya, W. Wongkeo, P. Torkittikul, Compressive strength and microstructure of carbon nanotubes–fly ash cement composites, Mater. Sci. Eng. A 527 (4–5) (2010) 1063–1067.
[24] T. Nochaiya, P. Tolkidtikul, P. Singjai, A. Chaipanich, Microstructure and Characterizations of Portland-carbon Nanotubes Pastes, Advanced Materials Research, Trans Tech Publ, 2008, pp. 549–552.
[25] H. Du, S. Dai Pang, Dispersion and stability of graphene nanoplatelet in water and its influence on cement composites, Construct. Build. Mater. 167 (2018) 403–413.
[26] S. Yun, J. Kim, Sonication time effect on MWNT/PANI-EB composite for hybrid electro-active paper actuator, Synth. Met. 157 (13–15) (2007) 523–528.
[27] H. Kim, I. Park, H.-K. Lee, Improved piezoresistive sensitivity and stability of CNT/cement mortar composites with low water-binder ratio, Compos. Struct. 116 (2014) 713–719.
[28] R.K.A. Al-Rub, A.I. Ashour, B.M. Tyson, On the aspect ratio effect of multi-walled carbon nanotube reinforcements on the mechanical properties of cementitious nanocomposites, Construct. Build. Mater. 35 (2012) 647–655.
[29] B. Zou, S.J. Chen, A.H. Korayem, F. Collins, C.M. Wang, W.H. Duan, Effect of ultrasonication energy on engineering properties of carbon nanotube reinforced cement pastes, Carbon 85 (2015) 212–220.
[30] Z.S. Metaxa, M.S. Konsta-Gdoutos, S.P. Shah, Carbon nanofiber cementitious composites: effect of debulking procedure on dispersion and reinforcing efficiency, Cement Concr. Compos. 36 (2013) 25–32.
[31] F. Collins, J. Lambert, W.H. Duan, The influences of admixtures on the dispersion, workability, and strength of carbon nanotube–OPC paste mixtures, Cement Concr. Compos. 34 (2) (2012) 201–207.
[32] S. Chuah, W. Li, S.J. Chen, J.G. Sanjayan, W.H. Duan, Investigation on dispersion of graphene oxide in cement composite using different surfactant treatments, Construct. Build. Mater. 161 (2018) 519–527.
[33] J. Luo, Z. Duan, H. Li, The influence of surfactants on the processing of multi-walled carbon nanotubes in reinforced cement matrix composites, Phys. Status Solidi 206 (12) (2009) 2783–2790.
[34] D. Shuang, W. Baomin, Study on dispersion of graphene nanoplates and rheological properties, early hydration of cement composites, Mater. Res. Express 6 (9) (2019), 095086.
[35] L. Vaisman, H.D. Wagner, G. Marom, The role of surfactants in dispersion of carbon nanotubes, Adv. Colloid Interface Sci. 128 (2006) 37–46.
[36] M.S. Konsta-Gdoutos, Z.S. Metaxa, S.P. Shah, Highly dispersed carbon nanotube reinforced cement based materials, Cement Concr. Res. 40 (7) (2010) 1052–1059.
[37] A. Yazdanbakhsh, Z. Grasley, B. Tyson, R.A. Al-Rub, Carbon nano filaments in cementitious materials: some issues on dispersion and interfacial bond, Spec. Publ. 267 (2009) 21–34.
[38] A. Cwirzen, K. Habermehl-Cwirzen, V. Penttala, Surface decoration of carbon nanotubes and mechanical properties of cement/carbon nanotube composites, Adv. Cement Res. 20 (2) (2008) 65–73.
[39] G.Y. Li, P.M. Wang, X. Zhao, Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites, Cement Concr. Compos. 29 (5) (2007) 377–382.
[40] D. Chung, Dispersion of short fibers in cement, J. Mater. Civ. Eng. 17 (4) (2005) 379–383.
[41] F. Sanchez, C. Ince, Microstructure and macroscopic properties of hybrid carbon nanofiber/silica fume cement composites, Compos. Sci. Technol. 69 (7–8) (2009) 1310–1318.
[42] W. Dong, W. Li, Y. Guo, X. He, D. Sheng, Effects of silica fume on physicochemical properties and piezoresistivity of intelligent carbon black-cementitious composites, Construct. Build. Mater. 259 (2020), 120399.
[43] H. Kim, I.W. Nam, H.-K. Lee, Enhanced effect of carbon nanotube on mechanical and electrical properties of cement composites by incorporation of silica fume, Compos. Struct. 107 (2014) 60–69.
[44] I.-W. Nam, H.-K. Kim, H.-K. Lee, Influence of silica fume additions on electromagnetic interference shielding effectiveness of multi-walled carbon nanotube/cement composites, Construct. Build. Mater. 30 (2012) 480–487.
[45] X. Li, A.H. Korayem, C. Li, Y. Liu, H. He, J.G. Sanjayan, W.H. Duan, Incorporation of graphene oxide and silica fume into cement paste: a study of dispersion and compressive strength, Construct. Build. Mater. 123 (2016) 327–335.
[46] S. Bai, L. Jiang, N. Xu, M. Jin, S. Jiang, Enhancement of mechanical and electrical properties of graphene/cement composite due to improved dispersion of graphene by addition of silica fume, Construct. Build. Mater. 164 (2018) 433–441.
[47] W. Li, W. Ji, F. Torabian Isfahani, Y. Wang, G. Li, Y. Liu, F. Xing, Nano-silica sol-gel and carbon nanotube coupling effect on the performance of cement-based materials, Nanomaterials 7 (7) (2017) 185.
[48] O. Mendoza, G. Sierra, J.I. Tobón, Influence of super plasticizer and Ca (OH) 2 on the stability of functionalized multi-walled carbon nanotubes dispersions for cement composites applications, Construct. Build. Mater. 47 (2013) 771–778.
[49] O. Öztürk, M. Koçer, A. Ünal, Multifunctional behavior of composite beams incorporating hybridized carbon-based materials under cyclic loadings, Eng. Struct. 250 (2022), 113429.
[50] Z. Lu, A. Hanif, G. Sun, R. Liang, P. Parthasarathy, Z. Li, Highly dispersed graphene oxide electrodeposited carbon fiber reinforced cement-based materials with enhanced mechanical properties, Cement Concr. Compos. 87 (2018) 220–228.
[51] J. Chen, J. Wu, H. Ge, D. Zhao, C. Liu, X. Hong, Reduced graphene oxide deposited carbon fiber reinforced polymer composites for electromagnetic interference shielding, Compos. Appl. Sci. Manuf. 82 (2016) 141–150.
[52] W. Qin, F. Vautard, L.T. Drzal, J. Yu, Mechanical and electrical properties of carbon fiber composites with incorporation of graphene nanoplatelets at the fiber–matrix interphase, Compos. B Eng. 69 (2015) 335–341.
[53] L. Zhang, B. Han, J. Ouyang, X. Yu, S. Sun, J. Ou, Multifunctionality of cement based composite with electrostatic self-assembled CNT/NCB composite filler, Arch. Civ. Mech. Eng. 17 (2) (2017) 354–364.
[54] L. Zhang, S. Ding, L. Li, S. Dong, D. Wang, X. Yu, B. Han, Effect of characteristics of assembly unit of CNT/NCB composite fillers on properties of smart cement-based materials, Compos. Appl. Sci. Manuf. 109 (2018) 303–320.
[55] Y. Ding, Z. Chen, Z. Han, Y. Zhang, F. Pacheco-Torgal, Nano-carbon black and carbon fiber as conductive materials for the diagnosing of the damage of concrete beam, Construct. Build. Mater. 43 (2013) 233–241.
[56] S. Parveen, S. Rana, R. Fangueiro, M.C. Paiva, Microstructure and mechanical properties of carbon nanotube reinforced cementitious composites developed using a novel dispersion technique, Cement Concr. Res. 73 (2015) 215–227.
[57] S. Musso, J.-M. Tulliani, G. Ferro, A. Tagliaferro, Influence of carbon nanotubes structure on the mechanical behavior of cement composites, Compos. Sci. Technol. 69 (11–12) (2009) 1985–1990.
[58] B. Wang, Y. Han, S. Liu, Effect of highly dispersed carbon nanotubes on the flexural toughness of cement-based composites, Construct. Build. Mater. 46 (2013) 8–12.
[59] B. Wang, R. Jiang, Z. Wu, Investigation of the mechanical properties and microstructure of graphene nanoplatelet-cement composite, Nanomaterials 6 (11) (2016) 200.
[60] C. Wang, K.-Z. Li, H.-J. Li, G.-S. Jiao, J. Lu, D.-S. Hou, Effect of carbon fiber dispersion on the mechanical properties of carbon fiber-reinforced cement-based composites, Mater. Sci. Eng. A 487 (1–2) (2008) 52–57.
[61] S. Xu, J. Liu, Q. Li, Mechanical properties and microstructure of multi-walled carbon nanotube-reinforced cement paste, Construct. Build. Mater. 76 (2015) 16–23.
[62] W. Dong, Y. Guo, Z. Sun, Z. Tao, W. Li, Development of piezoresistive cement-based sensor using recycled waste glass cullets coated with carbon nanotubes, J. Clean. Prod. 314 (2021), 127968.
[63] X. Yu, E. Kwon, A carbon nanotube/cement composite with piezoresistive properties, Smart Mater. Struct. 18 (5) (2009), 055010.
[64] S. Kashif Ur Rehman, Z. Ibrahim, S.A. Memon, M. Aunkor, T. Hossain, M. Faisal Javed, K. Mehmood, S.M.A. Shah, Influence of graphene nanosheets on rheology, microstructure, strength development and self-sensing properties of cement based composites, Sustainability 10 (3) (2018) 822.
[65] Y. Dai, M. Sun, C. Liu, Z. Li, Electromagnetic wave absorbing characteristics of carbon black cement-based composites, Cement Concr. Compos. 32 (7) (2010) 508–513.

[66] W. Dong, W. Li, L. Shen, S. Zhang, K. Vessalas, Integrated self-sensing and self-healing cementitious composite with microencapsulation of nano-carbon black and slaked lime, Mater. Lett. 282 (2021), 128834.
[67] A.O. Monteiro, P.B. Cachim, P.M. Costa, Self-sensing piezoresistive cement composite loaded with carbon black particles, Cement Concr. Compos. 81 (2017) 59–65.
[68] M.-G. Pârvan, G. Voicu, A.-I. Bădănoiu, Study of hydration and hardening processes of self-sensing cement-based materials with carbon black content, J. Therm. Anal. Calorim. 139 (2) (2020) 807–815.
[69] W. Dong, W. Li, L. Shen, D. Sheng, Piezoresistive behaviours of carbon black cement-based sensors with layer-distributed conductive rubber fibres, Mater. Des. 182 (2019), 108012.
[70] H. Li, H. Xiao, J. Ou, Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites, Cement Concr. Compos. 28 (9) (2006) 824–828.
[71] H. Xiao, H. Li, J. Ou, Modeling of piezoresistivity of carbon black filled cement-based composites under multi-axial strain, Sensor Actuator Phys. 160 (1–2) (2010) 87–93.
[72] A. Monteiro, A. Loredo, P. Costa, M. Oeser, P. Cachim, A pressure-sensitive carbon black cement composite for traffic monitoring, Construct. Build. Mater. 154 (2017) 1079–1086.
[73] M. Li, V. Lin, J. Lynch, V. Li, Multifunctional carbon black engineered cementitious composites for the protection of critical infrastructure, in: High Performance Fiber Reinforced Cement Composites 6, Springer, 2012, pp. 99–106.
[74] W. Dong, W. Li, Z. Luo, G. Long, K. Vessalas, D. Sheng, Structural response monitoring of concrete beam under flexural loading using smart carbon black/cement-based sensors, Smart Mater. Struct. 29 (6) (2020), 065001.
[75] N. Banthia, S. Djeridane, M. Pigeon, Electrical resistivity of carbon and steel micro-fiber reinforced cements, Cement Concr. Res. 22 (5) (1992) 804–814.
[76] D.-M. Bontea, D. Chung, G. Lee, Damage in carbon fiber-reinforced concrete, monitored by electrical resistance measurement, Cement Concr. Res. 30 (4) (2000) 651–659.
[77] B. Chen, J. Liu, Damage in carbon fiber-reinforced concrete, monitored by both electrical resistance measurement and acoustic emission analysis, Construct. Build. Mater. 22 (11) (2008) 2196–2201.
[78] R.K. Abu Al-Rub, B.M. Tyson, A. Yazdanbakhsh, Z. Grasley, Mechanical properties of nanocomposite cement incorporating surface-treated and untreated carbon nanotubes and carbon nanofibers, J. Nanomech. Micromech. 2 (1) (2012) 1–6.
[79] S. Wen, D. Chung, Effects of strain and damage on strain-sensing ability of carbon fiber cement, J. Mater. Civ. Eng. 18 (3) (2006) 355–360.
[80] D. Chung, Electrically conductive cement-based materials, Adv. Cement Res. 16 (4) (2004) 167–176.
[81] S. Erdem, S. Hanbay, M.A. Blankson, Self-sensing damage assessment and image-based surface crack quantification of carbon nanofibre reinforced concrete, Construct. Build. Mater. 134 (2017) 520–529.
[82] F.J. Baeza, O. Galao, E. Zornoza, P. Garcés, Multifunctional cement composites strain and damage sensors applied on reinforced concrete (RC) structural elements, Materials 6 (3) (2013) 841–855.
[83] W. Dong, W. Li, L. Shen, Z. Sun, D. Sheng, Piezoresistivity of smart carbon nanotubes (CNTs) reinforced cementitious composite under integrated cyclic compression and impact, Compos. Struct. 241 (2020), 112106.
[84] G. Kim, F. Naeem, H. Kim, H.-K. Lee, Heating and heat-dependent mechanical characteristics of CNT-embedded cementitious composites, Compos. Struct. 136 (2016) 162–170.
[85] H.-K. Kim, Chloride penetration monitoring in reinforced concrete structure using carbon nanotube/cement composite, Construct. Build. Mater. 96 (2015) 29–36.
[86] S. Wansom, N. Kidner, L. Woo, T.O. Mason, AC-impedance response of multi-walled carbon nanotube/cement composites, Cement Concr. Compos. 28 (6) (2006) 509–519.
[87] W. Dong, W. Li, Z. Luo, Y. Guo, K. Wang, Effect of layer-distributed carbon nanotube (CNT) on mechanical and piezoresistive performance of intelligent cement-based sensor, Nanotechnology 31 (50) (2020) 505503.
[88] F. Ubertini, A.L. Materazzi, A. D'Alessandro, S. Laflamme, Natural frequencies identification of a reinforced concrete beam using carbon nanotube cement-based sensors, Eng. Struct. 60 (2014) 265–275.
[89] M. Saafi, Wireless and embedded carbon nanotube networks for damage detection in concrete structures, Nanotechnology 20 (39) (2009) 395502.
[90] B. Han, K. Zhang, T. Burnham, E. Kwon, X. Yu, Integration and road tests of a self-sensing CNT concrete pavement system for traffic detection, Smart Mater. Struct. 22 (1) (2012), 015020.
[91] A. D'Alessandro, F. Ubertini, E. García-Macías, R. Castro-Triguero, A. Downey, S. Laflamme, A. Meoni, A.L. Materazzi, Static and dynamic strain monitoring of reinforced concrete components through embedded carbon nanotube cement-based sensors, Shock Vib. (2017), 2017.
[92] S.K.U. Rehman, Z. Ibrahim, M. Jameel, S.A. Memon, M.F. Javed, M. Aslam, K. Mehmood, S. Nazar, Assessment of rheological and piezoresistive properties of graphene based cement composites, Int. J. Concr. Struct. Mater. 12 (1) (2018) 64.
[93] D. Dimov, I. Amit, O. Gorrie, M.D. Barnes, N.J. Townsend, A.I. Neves, F. Withers, S. Russo, M.F. Craciun, Ultrahigh performance nanoengineered graphene–concrete composites for multifunctional applications, Adv. Funct. Mater. 28 (23) (2018), 1705183.
[94] J.-L. Le, H. Du, S. Dai Pang, Use of 2D Graphene Nanoplatelets (GNP) in cement composites for structural health evaluation, Compos. B Eng. 67 (2014) 555–563.
[95] Q. Liu, W. Wu, J. Xiao, Y. Tian, J. Chen, A. Singh, Correlation between damage evolution and resistivity reaction of concrete in-filled with graphene nanoplatelets, Construct. Build. Mater. 208 (2019) 482–491.
[96] Q. Liu, Q. Xu, Q. Yu, R. Gao, T. Tong, Experimental investigation on mechanical and piezoresistive properties of cementitious materials containing graphene and graphene oxide nanoplatelets, Construct. Build. Mater. 127 (2016) 565–576.
[97] M. Jin, L. Jiang, M. Lu, S. Bai, Monitoring chloride ion penetration in concrete structure based on the conductivity of graphene/cement composite, Construct. Build. Mater. 136 (2017) 394–404.
[98] W. Dong, W. Li, Y. Guo, F. Qu, K. Wang, D. Sheng, Piezoresistive performance of hydrophobic cement-based sensors under moisture and chloride-rich environments, Cement Concr. Compos. 126 (2022), 104379.
[99] X. Li, L. Wang, Y. Liu, W. Li, B. Dong, W.H. Duan, Dispersion of graphene oxide agglomerates in cement paste and its effects on electrical resistivity and flexural strength, Cement Concr. Compos. 92 (2018) 145–154.
[100] M. Saafi, L. Tang, J. Fung, M. Rahman, F. Sillars, J. Liggat, X. Zhou, Graphene/fly ash geopolymeric composites as self-sensing structural materials, Smart Mater. Struct. 23 (6) (2014), 065006.
[101] M. Liantong, W. Shaopeng, L. Xiaoming, C. Zheng, Percolation model of graphite-modified asphalt concrete, J. Wuhan Univ. Technol.-Materials Sci. Ed. 20 (1) (2005) 111–113.
[102] D.-Y. Yoo, I. You, S.-J. Lee, Electrical properties of cement-based composites with carbon nanotubes, graphene, and graphite nanofibers, Sensors 17 (5) (2017) 1064.
[103] X. Fan, X. Dong, M. Sun, Z. Li, Research on the electric characteristic and pressure sensitivity of graphite-cement based composites, J. Wuhan Univ. Technol. 31 (2009) 14–19.
[104] H. Du, S.T. Quek, S. Dai Pang, Smart Multifunctional Cement Mortar Containing Graphite Nanoplatelet, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2013, International Society for Optics and Photonics, 2013, 869238.
[105] S. Sun, B. Han, S. Jiang, X. Yu, Y. Wang, H. Li, J. Ou, Nano graphite platelets-enabled piezoresistive cementitious composites for structural health monitoring, Construct. Build. Mater. 136 (2017) 314–328.
[106] Z. Qin, Y. Wang, X. Mao, X. Xie, Development of graphite electrically conductive concrete and application in grounding engineering, New Build. Mater 11 (2009) 46–48.
[107] R. Rao, J. Fu, Y. Chan, C.Y. Tuan, C. Liu, Steel fiber confined graphite concrete for pavement deicing, Compos. B Eng. 155 (2018) 187–196.
[108] S.K. Yee, M.Z.M. Jenu, Shielding effectiveness of concrete with graphite fine powder in between 50MHz to 400MHz, 2013 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), IEEE (2013) 1–4.
[109] H.-W. Yuan, C.-H. Lu, Z.-Z. Xu, Y.-R. Ni, X.-H. Lan, Mechanical and thermal properties of cement composite graphite for solar thermal storage materials, Sol. Energy 86 (11) (2012) 3227–3233.
[110] S.P. Wu, P. Wang, B. Li, L. Pang, F. Guo, Study on Mechanical and Thermal Properties of Graphite Modified Cement Concrete, Key Engineering Materials, Trans Tech Publ, 2014, pp. 84–88.
[111] Y. Ding, Y. Yang, R. Liu, T. Xiao, J. Tian, Study on pressure sensitivity of smart polymer concrete based on steel slag, Measurement 140 (2019) 14–21.
[112] G. Yıldırım, M.H. Sarwary, A. Al-Dahawi, O. Öztürk, Ö. Anıl, M. Şahmaran, Piezoresistive behavior of CF-and CNT-based reinforced concrete beams subjected to static flexural loading: shear failure investigation, Construct. Build. Mater. 168 (2018) 266–279.
[113] X. Liu, S. Wu, Study on the graphite and carbon fiber modified asphalt concrete, Construct. Build. Mater. 25 (4) (2011) 1807–1811.
[114] A. Belli, A. Mobili, T. Bellezze, F. Tittarelli, P. Cachim, Evaluating the self-sensing ability of cement mortars manufactured with graphene nanoplatelets, virgin or recycled carbon fibers through piezoresistivity tests, Sustainability 10 (11) (2018) 4013.
[115] S. Wu, L. Mo, Z. Shui, Z. Chen, Investigation of the conductivity of asphalt concrete containing conductive fillers, Carbon 43 (7) (2005) 1358–1363.
[116] J. Chen, D. Zhao, H. Ge, J. Wang, Graphene oxide-deposited carbon fiber/cement composites for electromagnetic interference shielding application, Construct. Build. Mater. 84 (2015) 66–72.
[117] G.M. Kim, B.J. Yang, G.U. Ryu, H.K. Lee, The electrically conductive carbon nanotube (CNT)/cement composites for accelerated curing and thermal cracking reduction, Compos. Struct. 158 (2016) 20–29.
[118] Y. Perets, L. Aleksandrovych, M. Melnychenko, O. Lazarenko, L. Vovchenko, L. Matzui, The electrical properties of hybrid composites based on multiwall carbon nanotubes with graphite nanoplatelets, Nanoscale Res. Lett. 12 (1) (2017) 1–10.
[119] W. Li, W. Dong, L. Shen, A. Castel, S.P. Shah, Conductivity and piezoresistivity of nano-carbon black (NCB) enhanced functional cement-based sensors using polypropylene fibres, Mater. Lett. 270 (2020), 127736.
[120] J.L. Luo, Z.D. Duan, T.J. Zhao, Q.Y. Li, Self-sensing Property of Cementitious Nanocomposites Hybrid with Nanophase Carbon Nanotube and Carbon Black, Advanced Materials Research, Trans Tech Publ, 2011, pp. 644–647.
[121] W. Dong, W. Li, N. Lu, F. Qu, K. Vessalas, D. Sheng, Piezoresistive behaviours of cement-based sensor with carbon black subjected to various temperature and water content, Compos. B Eng. 178 (2019), 107488.
[122] P. Chen, D. Chung, Concrete as a new strain/stress sensor, Compos. B Eng. 27 (1) (1996) 11–23.
[123] V. Parvaneh, S.H. Khiabani, Mechanical and piezoresistive properties of self-sensing smart concretes reinforced by carbon nanotubes, Mech. Adv. Mater. Struct. 26 (11) (2019) 993–1000.

[124] Z. Liu, Y. Zhang, L. Liu, Q. Jiang, An analytical model for determining the relative electrical resistivity of cement paste and C–S–H gel, Construct. Build. Mater. 48 (2013) 647–655.
[125] Y. Liu, M. Wang, W. Tian, B. Qi, Z. Lei, W. Wang, Ohmic heating curing of carbon fiber/carbon nanofiber synergistically strengthening cement-based composites as repair/reinforcement materials used in ultra-low temperature environment, Compos. Appl. Sci. Manuf. 125 (2019), 105570.
[126] J. Xu, W. Zhong, W. Yao, Modeling of conductivity in carbon fiber-reinforced cement-based composite, J. Mater. Sci. 45 (13) (2010) 3538–3546.
[127] A. Downey, A. D'Alessandro, F. Ubertini, S. Laflamme, Automated crack detection in conductive smart-concrete structures using a resistor mesh model, Meas. Sci. Technol. 29 (3) (2018), 035107.
[128] F. Azhari, N. Banthia, A 3D percolation model for conductive fibrous composites: application in cement-based sensors, J. Mater. Sci. 50 (17) (2015) 5817–5821.
[129] E. García-Macías, A. D'Alessandro, R. Castro-Triguero, D. Pérez-Mira, F. Ubertini, Micromechanics modeling of the electrical conductivity of carbon nanotube cement-matrix composites, Compos. B Eng. 108 (2017) 451–469.
[130] W. Bao, S. Meguid, Z. Zhu, M. Meguid, Modeling electrical conductivities of nanocomposites with aligned carbon nanotubes, Nanotechnology 22 (48) (2011), 485704.
[131] S. Jang, D. Hochstein, S. Kawashima, H. Yin, Experiments and micromechanical modeling of electrical conductivity of carbon nanotube/cement composites with moisture, Cement Concr. Compos. 77 (2017) 49–59.
[132] S. Wen, D. Chung, Model of piezoresistivity in carbon fiber cement, Cement Concr. Res. 36 (10) (2006) 1879–1885.
[133] P. Zhang, S. Lei, W. Fu, J. Niu, G. Liu, J. Qian, J. Sun, The effects of agglomerate on the piezoresistivity of conductive carbon nanotube/polyvinylidene fluoride composites, Sensor Actuator Phys. 281 (2018) 176–184.
[134] E. García-Macías, A. D'Alessandro, R. Castro-Triguero, D. Pérez-Mira, F. Ubertini, Micromechanics modeling of the uniaxial strain-sensing property of carbon nanotube cement-matrix composites for SHM applications, Compos. Struct. 163 (2017) 195–215.
[135] E. García-Macías, A. Downey, A. D'Alessandro, R. Castro-Triguero, S. Laflamme, F. Ubertini, Enhanced lumped circuit model for smart nanocomposite cement-based sensors under dynamic compressive loading conditions, Sensor Actuator Phys. 260 (2017) 45–57.
[136] A. D'Alessandro, F. Ubertini, A.L. Materazzi, S. Laflamme, M. Porfiri, Electromechanical modelling of a new class of nanocomposite cement-based sensors for structural health monitoring, Struct. Health Monit. 14 (2) (2015) 137–147.
[137] P. Yang, S. Chowdhury, N. Neithalath, Strain sensing ability of metallic particulate reinforced cementitious composites: experiments and microstructure-guided finite element modeling, Cement Concr. Compos. 90 (2018) 225–234.
[138] E. García-Macías, R. Castro-Triguero, A. Sáez, F. Ubertini, 3D mixed micromechanics-FEM modeling of piezoresistive carbon nanotube smart concrete, Comput. Methods Appl. Mech. Eng. 340 (2018) 396–423.
[139] Z. Wang, Z. Wang, M. Ning, S. Tang, Y. He, Electro-thermal properties and Seebeck effect of conductive mortar and its use in self-heating and self-sensing system, Ceram. Int. 43 (12) (2017) 8685–8693.
[140] A. Sassani, A. Arabzadeh, H. Ceylan, S. Kim, S.S. Sadati, K. Gopalakrishnan, P. C. Taylor, H. Abdualla, Carbon fiber-based electrically conductive concrete for salt-free deicing of pavements, J. Clean. Prod. 203 (2018) 799–809.
[141] C. Chang, M. Ho, G. Song, Y.-L. Mo, H. Li, A feasibility study of self-heating concrete utilizing carbon nanofiber heating elements, Smart Mater. Struct. 18 (12) (2009), 127001.
[142] A. Sassani, H. Ceylan, S. Kim, A. Arabzadeh, P.C. Taylor, K. Gopalakrishnan, Development of carbon fiber-modified electrically conductive concrete for implementation in Des Moines International Airport, Case Stud. Construct. Mater. 8 (2018) 277–291.
[143] Q. Zhang, Y. Yu, W. Chen, T. Chen, Y. Zhou, H. Li, Outdoor experiment of flexible sandwiched graphite-PET sheets based self-snow-thawing pavement, Cold Reg. Sci. Technol. 122 (2016) 10–17.
[144] J. Gomis, O. Galao, V. Gomis, E. Zornoza, P. Garcés, Self-heating and deicing conductive cement, Exp. Study Model. Construct. Build. Mater. 75 (2015) 442–449.
[145] Q. Liu, E. Schlangen, Á. García, M. van de Ven, Induction heating of electrically conductive porous asphalt concrete, Construct. Build. Mater. 24 (7) (2010) 1207–1213.
[146] A. García, M. Bueno, J. Norambuena-Contreras, M.N. Partl, Induction healing of dense asphalt concrete, Construct. Build. Mater. 49 (2013) 1–7.
[147] Á. García, E. Schlangen, M. van de Ven, Q. Liu, Electrical conductivity of asphalt mortar containing conductive fibers and fillers, Construct. Build. Mater. 23 (10) (2009) 3175–3181.
[148] Q. Liu, Á. García, E. Schlangen, M. van de Ven, Induction healing of asphalt mastic and porous asphalt concrete, Construct. Build. Mater. 25 (9) (2011) 3746–3752.
[149] H. Jahanbakhsh, M.M. Karimi, B. Jahangiri, F.M. Nejad, Induction heating and healing of carbon black modified asphalt concrete under microwave radiation, Construct. Build. Mater. 174 (2018) 656–666.
[150] M.M. Karimi, H. Jahanbakhsh, B. Jahangiri, F.M. Nejad, Induced heating-healing characterization of activated carbon modified asphalt concrete under microwave radiation, Construct. Build. Mater. 178 (2018) 254–271.
[151] Y. Pamulapati, M.A. Elseifi, S.B. Cooper III, L.N. Mohammad, O. Elbagalati, Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers, Construct. Build. Mater. 146 (2017) 66–75.
[152] S. Wen, D. Chung, A comparative study of steel-and carbon-fibre cement as piezoresistive strain sensors, Adv. Cement Res. 15 (3) (2003) 119–128.
[153] E. Teomete, O.I. Kocyigit, Tensile strain sensitivity of steel fiber reinforced cement matrix composites tested by split tensile test, Construct. Build. Mater. 47 (2013) 962–968.
[154] J. Lataste, M. Behloul, D. Breysse, Characterisation of fibres distribution in a steel fibre reinforced concrete with electrical resistivity measurements, NDT E Int. 41 (8) (2008) 638–647.
[155] B. Han, Y. Yu, B. Han, J. Ou, Development of a wireless stress/strain measurement system integrated with pressure-sensitive nickel powder-filled cement-based sensors, Sensor Actuator Phys. 147 (2) (2008) 536–543.
[156] B. Han, B. Han, J. Ou, Experimental study on use of nickel powder-filled Portland cement-based composite for fabrication of piezoresistive sensors with high sensitivity, Sensor Actuator Phys. 149 (1) (2009) 51–55.
[157] H. Xiao, M. Liu, G. Wang, Anisotropic electrical and abrasion-sensing properties of cement-based composites containing aligned nickel powder, Cement Concr. Compos. 87 (2018) 130–136.
[158] Z. Shi, D. Chung, Carbon fiber-reinforced concrete for traffic monitoring and weighing in motion, Cement Concr. Res. 29 (3) (1999) 435–439.
[159] B. Han, X. Yu, E. Kwon, A self-sensing carbon nanotube/cement composite for traffic monitoring, Nanotechnology 20 (44) (2009) 445501.
[160] J. Zhang, Y. Lu, Z. Lu, C. Liu, G. Sun, Z. Li, A new smart traffic monitoring method using embedded cement-based piezoelectric sensors, Smart Mater. Struct. 24 (2) (2015), 025023.
[161] D. Xu, S. Banerjee, Y. Wang, S. Huang, X. Cheng, Temperature and loading effects of embedded smart piezoelectric sensor for health monitoring of concrete structures, Construct. Build. Mater. 76 (2015) 187–193.
[162] M. Jung, Y. Lee, S. Hong, J. Moon, Carbon nanotubes (CNTs) in ultra-high performance concrete (UHPC): dispersion, mechanical properties, and electromagnetic interference (EMI) shielding effectiveness (SE), Cement Concr. Res. 131 (2020), 106017.
[163] J. Cao, D. Chung, Colloidal graphite as an admixture in cement and as a coating on cement for electromagnetic interference shielding, Cement Concr. Res. 33 (11) (2003) 1737–1740.
[164] Z. Liu, H. Ge, J. Wu, J. Chen, Enhanced electromagnetic interference shielding of carbon fiber/cement composites by adding ferroferric oxide nanoparticles, Construct. Build. Mater. 151 (2017) 575–581.
[165] H. Guan, S. Liu, Y. Duan, J. Cheng, Cement based electromagnetic shielding and absorbing building materials, Cement Concr. Compos. 28 (5) (2006) 468–474.
[166] D.D.L. Chung, Electrical applications of carbon materials, J. Mater. Sci. 39 (8) (2004) 2645–2661.
[167] D. Micheli, A. Vricella, R. Pastore, A. Delfini, R.B. Morles, M. Marchetti, F. Santoni, L. Bastianelli, F. Moglie, V.M. Primiani, Electromagnetic properties of carbon nanotube reinforced concrete composites for frequency selective shielding structures, Construct. Build. Mater. 131 (2017) 267–277.
[168] B. Wang, Z. Guo, Y. Han, T. Zhang, Electromagnetic wave absorbing properties of multi-walled carbon nanotube/cement composites, Construct. Build. Mater. 46 (2013) 98–103.
[169] A.P. Singh, B.K. Gupta, M. Mishra, A. Chandra, R. Mathur, S. Dhawan, Multiwalled carbon nanotube/cement composites with exceptional electromagnetic interference shielding properties, Carbon 56 (2013) 86–96.
[170] Ö.B. Ceran, B. Şimşek, S. Doruk, T. Uygunoğlu, O.N. Şara, Effects of dispersed and powdered silver nanoparticles on the mechanical, thermal, electrical and durability properties of cementitious composites, Construct. Build. Mater. 222 (2019) 152–167.
[171] W. Dong, W. Li, Z. Sun, I. Ibrahim, D. Sheng, Intrinsic graphene/cement-based sensors with piezoresistivity and superhydrophobicity capacities for smart concrete infrastructure, Autom. ConStruct. 133 (2022), 103983.
[172] J. Ou, B. Han, Piezoresistive cement-based strain sensors and self-sensing concrete components, J. Intell. Mater. Syst. Struct. 20 (3) (2009) 329–336.
[173] R. Mu, H. Li, L. Qing, J. Lin, Q. Zhao, Aligning steel fibers in cement mortar using electro-magnetic field, Construct. Build. Mater. 131 (2017) 309–316.
[174] W. Dong, Y. Huang, B. Lehane, G.W. Ma, XGBoost algorithm-based prediction of concrete electrical resistivity for structural health monitoring, Autom. ConStruct. 114 (2020), 103155.
[175] J. Chiou, Q. Zheng, D. Chung, Electromagnetic interference shielding by carbon fibre reinforced cement, Composites 20 (4) (1989) 379–381.
[176] T. Ebbesen, H. Lezec, H. Hiura, J. Bennett, H. Ghaemi, T. Thio, Electrical conductivity of individual carbon nanotubes, Nature 382 (6586) (1996) 54–56.
[177] A. Sedaghat, M.K. Ram, A. Zayed, R. Kamal, N. Shanahan, Investigation of physical properties of graphene-cement composite for structural applications, Open J. Compos. Mater. (2014), 2014.
[178] J. Wei, L. Zhao, Q. Zhang, Z. Nie, L. Hao, Enhanced thermoelectric properties of cement-based composites with expanded graphite for climate adaptation and large-scale energy harvesting, Energy Build. 159 (2018) 66–74.
[179] S. Wen, D. Chung, Piezoresistivity in continuous carbon fiber cement-matrix composite, Cement Concr. Res. 29 (3) (1999) 445–449.
[180] X. Fu, W. Lu, D. Chung, Improving the strain-sensing ability of carbon fiber-reinforced cement by ozone treatment of the fibers, Cement Concr. Res. 28 (2) (1998) 183–187.
[181] F.J. Baeza, O. Galao, E. Zornoza, P. Garcés, Effect of aspect ratio on strain sensing capacity of carbon fiber reinforced cement composites, Mater. Des. 51 (2013) 1085–1094.
[182] D. Gao, M. Sturm, Y. Mo, Electrical resistance of carbon-nanofiber concrete, Smart Mater. Struct. 18 (9) (2009), 095039.

[183] H. Wang, X. Gao, R. Wang, The influence of rheological parameters of cement paste on the dispersion of carbon nanofibers and self-sensing performance, Construct. Build. Mater. 134 (2017) 673–683.
[184] M.S. Konsta-Gdoutos, C.A. Aza, Self sensing carbon nanotube (CNT) and nanofiber (CNF) cementitious composites for real time damage assessment in smart structures, Cement Concr. Compos. 53 (2014) 162–169.
[185] A. D'Alessandro, M. Rallini, F. Ubertini, A.L. Materazzi, J.M. Kenny, Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications, Cement Concr. Compos. 65 (2016) 200–213.
[186] A.L. Materazzi, F. Ubertini, A. D'Alessandro, Carbon nanotube cement-based transducers for dynamic sensing of strain, Cement Concr. Compos. 37 (2013) 2–11.
[187] Q. Liu, R. Gao, V.W. Tam, W. Li, J. Xiao, Strain monitoring for a bending concrete beam by using piezoresistive cement-based sensors, Construct. Build. Mater. 167 (2018) 338–347.
[188] S. Wen, D. Chung, Partial replacement of carbon fiber by carbon black in multifunctional cement–matrix composites, Carbon 45 (3) (2007) 505–513.
[189] B. Chen, B. Li, Y. Gao, T.-C. Ling, Z. Lu, Z. Li, Investigation on electrically conductive aggregates produced by incorporating carbon fiber and carbon black, Construct. Build. Mater. 144 (2017) 106–114.
[190] B. Han, L. Zhang, S. Sun, X. Yu, X. Dong, T. Wu, J. Ou, Electrostatic self-assembled carbon nanotube/nano carbon black composite fillers reinforced cement-based materials with multifunctionality, Compos. Appl. Sci. Manuf. 79 (2015) 103–115.
[191] F. Azhari, N. Banthia, Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing, Cement Concr. Compos. 34 (7) (2012) 866–873.
[192] S. Lee, I. You, G. Zi, D. Yoo, Experimental investigation of the piezoresistive properties of cement composites with hybrid carbon fibers and nanotubes, Sensors 17 (11) (2017) 2516.
[193] Y. Hong, Z. Li, G. Qiao, J. Ou, W. Cheng, Pressure sensitivity of multiscale carbon-admixtures–enhanced cement-based composites, Nanomater. Nanotechnol. 8 (2018), 1847980418793529.
[194] M. Chen, P. Gao, F. Geng, L. Zhang, H. Liu, Mechanical and smart properties of carbon fiber and graphite conductive concrete for internal damage monitoring of structure, Construct. Build. Mater. 142 (2017) 320–327.
[195] W. Dong, W. Li, K. Wang, K. Vessalas, S. Zhang, Mechanical strength and self-sensing capacity of smart cementitious composite containing conductive rubber crumbs, J. Intell. Mater. Syst. Struct. 31 (10) (2020) 1325–1340.
[196] L. Zhang, S. Ding, B. Han, X. Yu, Y.-Q. Ni, Effect of water content on the piezoresistive property of smart cement-based materials with carbon nanotube/nanocarbon black composite filler, Compos. Appl. Sci. Manuf. 119 (2019) 8–20.