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Review

A review of intrinsic self-sensing cementitious composites and prospects for their application in transport infrastructures

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ABSTRACT

Monitoring of transport infrastructures, in terms of early damage detection, can prevent the loss of life and economic damage associated with sudden infrastructure collapse and inform timely intervention, such as repair, to increase the sustainability and service life of infrastructures. Self-sensing cementitious geocomposites with the ability to detect stress, strain, and damage based on a piezoresistive mechanism enable the development of more integrated and viable geomaterial monitoring solutions than existing monitoring technologies. Self-sensing cementitious geocomposites are composed of conductive phases embedded in cementitious geomaterials that exhibit both sensing ability and superior mechanical properties. The states of stress, strain, displacement, and damage in infrastructures can be investigated by analysing the change in their electrical resistance. In this review, different types of self-sensing composites, their preparation, influential parameters, and associated theoretical investigations are discussed in detail to inform future advances in the development of self-sensing geocomposites. The challenges of this technology have also been summarised. This review is expected to stimulate and inform research that explores the development and application prospects of self-sensing cementitious geocomposites.

1. Introduction

Geomaterials, as an integral part of transport infrastructures, play a crucial role in the stability and safety of these structures. Structural monitoring enables the early detection of damage that, if addressed, reduces the risk of sudden collapses and associated economic damage and optimises the service life of structures. Furthermore, infrastructure monitoring systems are useful platforms for extracting current data at an operational level which have many benefits in various areas of smart cities management such as transportation, and traffic flow monitoring. Both of these aspects support the economic sustainability of societies and quality of life of members. In this regard, the integrated and real-time monitoring of stress, strain, and displacement in cementitious geocomposites, a widely used geomaterial, is the key factor. Internationally, significant research efforts are expended on developing innovative and smart infrastructure monitoring techniques [1,2] to meet ever-growing engineering demands and take advantage of relevant technological advances. Despite recent advances, most monitoring instrumentation or equipment, such as fibre Bragg grating sensors, electric strain gauges, and PZT-based piezoelectric sensors, involve the placement of a limited number of sensors in spot locations along applicable infrastructure. In addition, owing to the low durability and accuracy of these instruments, complexity and high cost of their production, and incompatibility of their detection mechanisms with geomaterial behaviour, many of these methods are considered insufficient. Among all the monitoring methods summarised in Table 1, considering the properties and nature of geomaterials, self-sensing composites with intrinsic sensing capabilities based on piezoresistive behaviour provide the most integrated, real-time, and practical solution for infrastructure monitoring and damage detection. This smart geomaterial can facilitate the development of intelligent infrastructure with sensing and structural health monitoring abilities, thus enhancing infrastructure safety, durability, serviceability, and reliability [3]. Self-sensing geocomposites (SSGs) offer a new approach to enhancing the sustainability of geomaterials. Self-sensing composites are formed by dispersing conductive phases in conventional cementitious composites that impart the ability to sense internal strain, stress, cracks, or damage while maintaining or even enhancing the physical properties and durability of the composite. The conductive phase generates an extensive network of conductive pathways based on percolation and quantum tunnelling mechanisms which is disturbed or changed if the composite is stressed or deformed under external force or environmental action, altering its electrical behaviour. Hence, stress (or external force), strain (or deformation), damage, and cracking under dynamic and static conditions can be detected by evaluating the electrical properties of the self-sensing

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Nomenclature

List of acronyms

AC	Alternating Current
ACIS	Alternating Current Impedance Spectroscopy
BCRs	Braided Composite Rods
CB	Carbon Black
CBP	Carbon Black Powder
CF	Carbon Fibre
CNF	Carbon Nanofibers
CNMs	Carbon Nanomaterials
CNT	Carbon Nanotube
CSF	Carbon Short Fibre
DC	Direct Current
ESD	Electrostatic Dissipative
GF	Gauge Factor
GFs	Glass Fibres
GNPs	Graphene Nanoplatelets
NCB	Nanocarbon Black
NP	Nickel Powder
NT	TiO_2
PZT	Lead Zirconate Titanate (piezoelectric ceramic material)
SF	Steel Fibre
SSG	Self-sensing Geocomposite

composite. SSGs can act as structural and sensing components, eliminating the need for additional sensors. Several studies have evaluated self-sensing materials featuring various composites such as concrete, cement paste, polymers, and asphalt [4,5]. However, to the best of the authors' knowledge, no reported study has assessed SSGs. Notably, the piezoresistive behaviour and sensitivity of composites are easily affected by multiple external and internal parameters such as the type and content of the conductive phase and non-conductive matrix, manufacturing methods (dispersion and curing methods), loading type, measurement method, and environmental conditions (humidity and temperature). This paper provides a systematic review of the main advances in self-sensing composite technology to inform the development of SSGs.

2. Metal-Based self-sensing composites

Initial investigations of cementitious self-sensing composites featured a cement matrix and metallic conductive phases such as steel fibres, steel shavings, and steel slag [6-8]. Steel fibres have been proven to be more effective than the other two steel forms in reducing the electrical resistivity of concrete, while enhancing the flexural and tensile strength owing to a pull-out effect [9]. The sensitivity of a cementitious composite reinforced by steel fibres reportedly improves with increasing fibre concentration up to, approximately, the percolation threshold. The performance of both macro steel fibres (diameter ≈ 0.25 mm to 0.64 mm and length ≈ 13 mm to 32 mm) and super-fine steel fibres (diameter ≈ 8 μm to 20 μm and length ≈ 10 mm) have been investigated in self-sensing composites. However, composites featuring super-fine steel fibres exhibit superior piezoresistive behaviour under cyclic loading. Moreover, the application of macroscale metallic conductive phases can promote microcrack formation in the composite and consequently impair its mechanical properties [10]. Notably, the piezoresistive behaviour of cementitious composites can be affected by the corrosion of metallic conductive phases. With the advancement of nanotechnology, metal nanomaterials such as nano TiO_2 (NT) and nano Fe_2O_3 are garnering significant attention as low-cost conductive fillers owing to their remarkable mechanical, electrical, and chemical features [11].

Table 1
Summary of major infrastructure monitoring methods and their advantages and limitations.

Sensors and technologies	Application method	Features and advantages	Limitations	Reference
Strain gauges	Attached to the surface, Embedded	Wide application, high flexibility, low cost, wide measurement range, non-destructive testing, soft robotics, low transverse effect, high permissible current.	Low durability, complex production, non-intrinsic mechanism, point sensors, sensitive to humidity and temperature, low resolution of strain, limited reliability and stability in highly explosive monitoring atmospheres, low measurement frequency.	[12,13]
Fibre optics	Embedded	High accuracy and sensitivity, non-conductive testing, easy installation, small size, highly resistant to electromagnetic interference (EMI), lightweight, long-distance monitoring, wide range of measurement, high elasticity.	High production costs, vulnerable, non-intrinsic mechanism, limited measurement resolution, and low measurement frequency, pretension required for measurement, loop optical fibre measurement, limited bending diameter.	[14-16]
Fibre Bragg gratings	Embedded	Multiplexed specifications, the ability of real-time and wireless monitoring, the capability of dynamic monitoring, small size and lightweight, wide range of measurement, resistant to EMI.	Point strain measurement, complex production and encapsulation, high production costs, pretension required for measurement.	[15]
Piezoelectric sensors	Embedded, Composite	Energy harvesting, easy fabrication, lightweight, low power consumption.	Point measurement, environmentally hazardous, low durability.	[17]
Piezoceramics	Embedded	Wide application, high sensitivity, appropriate durability, functional at high temperatures.	Point strain measurement, high cost, non-intrinsic mechanism, cannot be used on a curved or irregular surface (e.g. a weld or a corner).	[18-20]
Electrochemical and biosensors	Composite	Measuring chemical reactions, short response time, low energy consumption.	Low durability, environmentally hazardous, complicated encapsulation method, medium selectivity, signal sensitive to operation temperature and humidity.	[21]
Self-sensing composites	Composite	High sensitivity and durability, easy to manufacture, wide measurement range, appropriate sensitivity to dynamic load, high resolution, improves mechanical and physical properties of the composite matrix.	High production costs and pore formation in the case of high conductive-phase concentrations.	[4]
Shape memory alloy	Embedded	High sensitivity and accuracy, appropriate damping behaviour.	Point strain measurement, high cost, non-intrinsic.	[22]
X-ray or C-scan	Non-contact	Wide application, non-destructive testing.	High cost of production, extra analysis, and non–real time, radiative.	[23]
Camera	Non-contact	Convenient, simple operation.	High cost, vulnerable.	[24]

Owing to the small size of NT particles (approximately 20 nm), their addition improves the physical properties of cementitious composites by a functional filler mechanism and increases the initial hydration rate [25,26]. Although the electrical conductivity of metal nanomaterials is not as high as that of carbon nanomaterials (CNMs), previous studies have shown that nanometal fillers can significantly reduce the electrical resistivity of cementitious matrices [27-29]. However, their low durability, vulnerability to corrosion, and reactivity with environmental compounds have limited their application in geomaterials.

3. Carbon black–based self-sensing composites

Informed by earlier studies of self-sensing composites and motivated by their potential benefits, researchers have attempted to improve their sensitivity and electrical behaviour through the use of inexpensive fillers. Carbon black (CB), which is produced by the thermal decomposition of heavy petroleum products, is such a filler. CB or nanocarbon black (NCB) are types of paracrystalline carbon that are characterised by good conductivity, cost efficiency, and high specific surface area, albeit lower than those of carbon nanotubes (CNTs) and carbon nanofibers (CNFs) [30]. The incorporation of CB into cementitious composites enable quasi-static and dynamic monitoring based on piezoresistive behaviours [31,32]. However, the inclusion of CB does not enhance the mechanical performance of the composite, unlike the inclusion of other carbon-based materials [33,34].

Although the chemical structure and geometric properties of CB, as a filler, increase its dispersion potential in aqueous suspensions, large amounts are required to form conductive paths in composites [30]. In addition, CB-based self-sensing cementitious composites typically demonstrate lower strain and crack sensitivity than carbon nanotubes (CNT) and carbon nanofibers–based (CNF) self-sensing cementitious composites [30,35-39].

Monteiro et al. reported that the percolation threshold of a cementitious mortar containing CB is approximately 10%. Moreover, the composite achieves a gauge factor of approximately 23.14, at this concentration [31]. Another study lowered the percolation threshold to 6.5% by reducing the temperature to 15 °C, resulting in a gauge factor of approximately 50 at this temperature [32].

However, high concentrations of CB can impair the physical and mechanical properties, and durability of cementitious composites owing to the formation of agglomerates and pores [40,41]. This is especially important in cement-stabilised geomaterials in which low amounts of cement and water are used since the consequent low amounts of cement hydration products are not sufficient to envelop all the CB particles, resulting in an incoherent microstructure.

4. Carbon fibre–based self-sensing composites

4.1. Carbon short fibres

Carbon short fibres (CSFs) are fibrous materials that are highly suitable fillers for self-sensing composites owing to characteristics such as corrosion resistance, high-temperature tolerance, low electrical resistance, and high thermal conductivity. In addition, carbon fibres (CFs) have a high tensile modulus and long-axis strength that improve the mechanical properties of composites to a certain extent; hence, they have been widely used as conductive phases in cementitious, polymer, and asphalt composites [30,33,42-45]. However, the relatively high price of these fibres limits their extensive application [46].

Studies have found that the volume percentage of CSFs required to achieve self-sensing cementitious composites with appropriate sensitivity ranges from approximately 0.5 to 3% [4,33,47,48]. However, increasing the CSF volume percentage beyond 1.0–1.5%, usually causes some agglomeration [49,50]. Furthermore, the incorporation of high amounts of CSFs reduces the workability of cementitious matrices necessitating the use of superplasticisers [51]. Studies have shown that the geometrical dimensions and aspect ratios of CSFs significantly affect the percolation threshold, sensitivity, and physical properties of composites [52-54].

As demonstrated in Fig. 1, the electrical resistivity of a cementitious composite reinforced with CSFs decreases from 8×10^6 to 6×10^6 Ω·m with increasing CSF aspect ratio from 2:1 to 12:1.

The effects of the aspect ratio on the piezoresistive behaviour of CSF-reinforced, cement-based mortar under different cyclic compression loads were evaluated by Baeza et al. [52]. They prepared composite specimens (160 × 40 × 40 mm in size) incorporating 0.5–1 wt% of CSFs (7.2 µm in diameter and 3, 6, and 12 mm in length) and measured their mechanical and strain sensitivity.

They found that the percolation threshold and piezoresistive response of the composite decrease with increasing aspect ratio of the fibres, while relatively high fibre lengths reduce the compressive strength of cementitious mortar. A maximum sensitivity (gauge factor) of approximately 32 is achieved by a composite containing 0.5 wt% of CSFs, 12 mm in length. In general, composites incorporating fibres with high aspect ratios demonstrate lower electrical resistance than composites incorporating fibres with low aspect ratios that realise an equivalent total fibre length [4,52,57]. However, CSFs are hydrophobic and their dispersion in water becomes more difficult with increasing fibre length and aspect ratio.

The piezoresistive behaviour and mechanical properties of cementitious mortar containing 2, 3, and 4 wt% of CSFs (relative to the weight of the cement) with length and diameter of 6 mm and 7.5 µm, respectively, were evaluated by Donnini et al. [47]. Although the incorporation of CSFs into cementitious mortar at these weight percentages generally decreases the compressive strength of the mortar due to an increase in its porosity, the electrical conductivity of the composite reduces significantly with increasing CSF content such that the percolation threshold achieved is approximately 3%. They showed that the electrical conductivity of a specimen containing 1 wt% of CSFs decreases with increasing cement hydration time, while the electrical resistance of specimens containing 3 and 4 wt% of CSFs reaches a constant value after 60 days of hydration. In addition, optimum sensitivity under cyclic compression loading is achieved by a specimen reinforced with 3 wt% of CSFs, determined by measuring the fractional change in its electrical resistivity using a two-probe method and alternating current (AC). In this study, the cement:sand and water:sand ratios were approximately 66.7:100 and 42.7:100, respectively.

A correlation between the fractional change in the electrical resistivity and the change in the strain of concrete reinforced with 0.5, 1, 1.5, and 2 wt% CSFs (relative to the weight of the cement) has been reported by Cholker et al. [58]. They used CSFs with a diameter and length of 7 µm and 6 mm, respectively. Although the compression

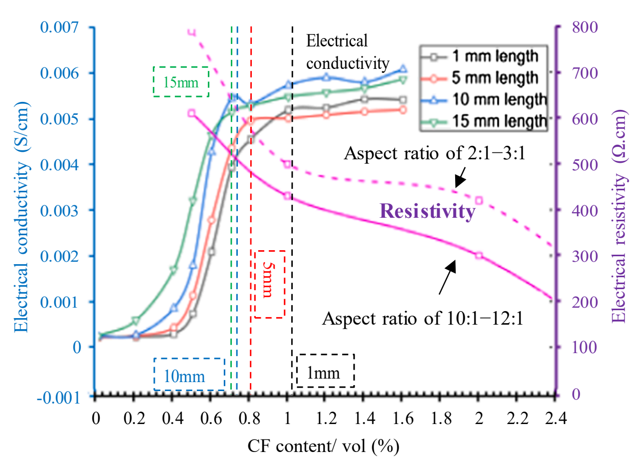


Fig. 1. The effect of CSF aspect ratio on electrical resistivity and conductivity of cementitious composites, [4,55,56].

strength of the composites decreases with increasing CSF content, the composites containing 1.5 and 2 wt% of CSFs demonstrate appropriate piezoresistive behaviour, as shown in Fig. 2.

Combining CSFs with other conductive fillers such as steel fibres or carbon nanomaterials (CNMs) is also an effective way to increase the sensitivity of a composite and reduce its percolation threshold [48,59-61]. A summary of studies that have investigated the damage-monitoring performance of CSF-reinforced cementitious matrices is presented in Table 2.

The combination of different conductive material with different geometrical shape and scale not only increase specific surface area and caused an increment in the conductive paths but also facilitate their dispersal process. This is especially important in geotechnical construction that often use optimally low amounts of water and cement, since the dispersion of carbon conductive fillers in aqueous suspensions is one of the most common dispersion methods in cementitious composites [67-69]. Although existing research on the effect of cement content on the piezoresistive behaviour of cementitious composites is limited, available reports of studies suggest that a coherent and stable structure is required to maintain the microscale conductive network formed by CFs. Reducing the cement content increases the percolation threshold necessitating the use of greater amounts of fibres [56]. Besides, by reducing the amount of cement, the possibility of porosity formation due to the presence of micro filers increases.

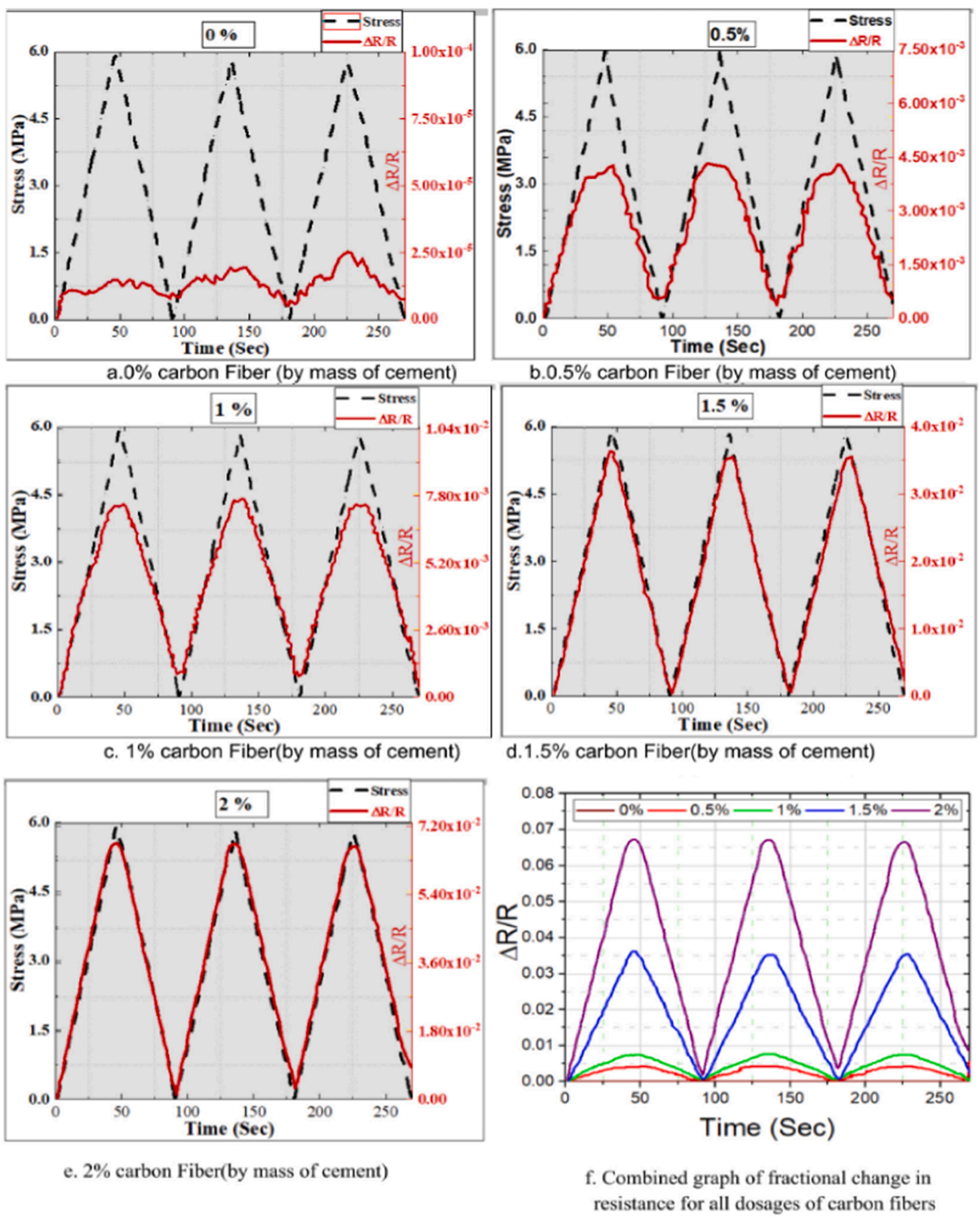


Fig. 2. Correlation between strain, stress, and electrical resistance [58].

Table 2
Summary of studies investigation carbon short fibres in cementitious matrices.

Composite type	Conductor type	CSF length (mm)	Concentration (%) (by volume (vol.) or weight (wt.))	Electrical factors			References
				$\Delta R/R_0$ (%)	Gauge factor	Resistivity (Ω·cm)	
Concrete	CSF	5	0.5 of vol.	0.37	–	–	[62]
			2.0 of vol.	1.01	–	–	
			3.0 of vol.	1.32	–	–	
Cement paste	CSF	5	15.0 of wt.	–	55.3	–	[56]
			20.0 of wt.	–	3707	–	
			25.0 wt	–	51.9	–	
Cement paste	CSF	7	1.0 of vol.	–	–	675	[63]
			3.0 of vol.	–	–	66	
			5.0 of vol.	–	–	17	
Cement paste	CSF + CNT	10	15 of vol (CSF)	26	–	–	[61]
			15 of vol. (CSF) + 1 of vol. (CNT)	23	–	–	
Cement paste	SF + CSF	10	0.36 of vol.	–	–	57	[64]
			0.72 of vol.	–	–	16	
Mortar	CB + SF + CSF	5	15 of wt. (SF) + 0.5 of wt. (CB)	–	1.6	–	[65]
			15 of wt. (SF) + 0.5 of wt. (CSF)	–	327	–	
			15 of wt. (SF) + 1 of wt. (CSF)	–	332	–	
			15 of wt. (SF) + 0.5 of wt. (CB) + 0.5 of wt. (CSF)	–	17	–	
Mortar	Conductive clay + CSF	5	50 of vol. (clay) + 0.6 of vol. (CF)	13	–	–	[66]
			30 of vol. (clay) + 0.6 of vol. (CF)	17	–	–	
			30 of vol. (clay) + 0.9 of vol. (CF)	16	–	–	

Therefore, the amount of cement, a determining factor of the strength of cementitious composites, plays a crucial role in the piezoresistive performance of a CF- based composite. However, composites with greater ductility show better piezoresistive behaviour due to premature nanoscale cracks that form during the early stages of loading. These cracks might cause residual strain and/or fractional change in electrical resistivity and disturbance. Notably, the use of CSFs reduces the sensitivity of the microscale conductive networks to such cracks and increases composite ductility, which is one of the advantages of CFs. In cementitious geocomposites, the conventional amount of cement used for stabilisation is approximately 5–12% of the soil mass [70,71]. It is, accordingly, not feasible to incorporate high amounts of CSFs or CSFs with long lengths in stabilised soils.

Generally, interactions between fibres and soil grains are strongly dependent on the size and geometrical shape of the grain [72]. The presence of fibre agglomerates among soil grains increases the gaps between them and consequently decreases the density of the specimen, which can greatly reduce the cohesion and physical characteristics of cementitious geocomposites. Therefore, the application of a conductive phase that combines CSFs and CNMs in cementitious geocomposites with low cement and water content might mitigate the disadvantages associated with high CSF content.

4.2. *Continuous carbon fibres*

4.2.1. *Non-polymeric, continuous carbon fibre–based, self-sensing cementitious composites*

Owing to the unique mechanical and electrical properties of continuous CF, they can be used in the production of multifunctional cementitious composites as woven or non-woven elements. However, the absence of polymeric support increases the effect of moisture on the sensing ability of the composite. Self-sensing concretes with strain-sensing ability have recently been developed by incorporating continuous CF–based textiles, as shown in Fig. 3. The difference between the strains measured by strain gauges and the textile sensor is approximately 5%, which indicates a good correlation. In addition, the gauge factor for this smart concrete was reported to be approximately 10. A hybrid continuous carbon and glass fibre (GF) textile was developed by Goldfeld et al. [73] for moisture and damage sensing in a concrete beam. They achieved an electromechanical sensing gauge factor of approximately 1 and detected a humid environment by fractional changes in electrical resistance in the order of 10^{-5}, applying the Wheatstone bridge principle. Non-polymeric continuous CF composites are also suitable for the development of multifunctional cementitious geocomposites, especially fine-grain geomaterials, owing to the higher interaction and consolidation ability of these types of composites. However, this type of composite is sensitive to environmental factors.

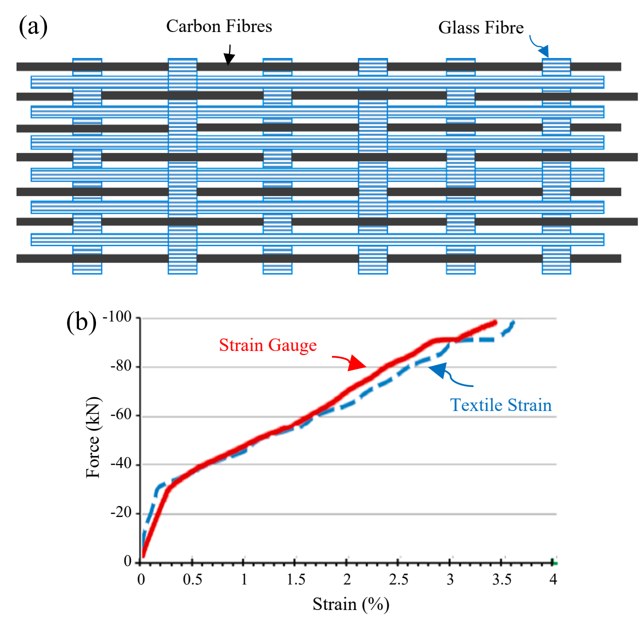


Fig. 3. (a) Continuous carbon fibre textile (b) Correlation between strains measured by strain gauges and a textile sensor [73].

Polymeric, Continuous Carbon Fibre–Based, Self-Sensing Cementitious Composites

CF-reinforced polymers are composites produced by combining different forms of the carbon fibres, including textile fabrics or unidirectional tows (either knitted or woven), and polymeric resin under appropriate conditions [42]. These composites are characterised by low density, high rigidity, high strength, excellent damping or energy dissipation, high resistance to impacting and corrosion, and modifiable thermal expansion [74]. In addition, because of the presence of conductive CFs in their structures and their piezoresistive behaviour which is affected by strain, stress, displacement, and damage, these composites have attracted the attention of many researchers engaged in the development of self-sensing composites [75-77]. Furthermore, hybrid composites of carbon and other fibres (e.g., aramid, polypropylene, and glass) have also been developed with enhanced sensing capability and strength. The strain-sensing capability and properties of CF-reinforced polymers depend on the arrangement of the composite structure components [78]. The strain sensitivity of unidirectional, CF-reinforced epoxy composites is reportedly in the fibre direction. Tensile loading reversibly reduces the longitudinal electrical resistance, whereas the transverse electrical resistance increases with increasing strain. This can be attributed to changes in the electrical contacts of the CFs owing to changes in fibre alignment. The degree of alignment of fibres in a composite subjected to tensile loading increases in the loading direction which increases the electrical contacts of the fibres and causes a reduction in resistance [79]. However, an excessive increase in the load can lead to a decrease in the fibre cross sections and an increase in the electrical resistance. Generally, the gauge factors of these types of CF-reinforced polymers in the longitudinal and transverse directions range from − 35.7 to − 37.6 and + 34.2 to + 48.7, respectively. Hence, they are highly suitable for sensing applications in geomaterials in transport infrastructures, especially railway foundations. Plastic laminates reinforced with CFs are reportedly effective at detecting cracks, delamination, and different types of damage that occur within their structures [80-82]. However, CF-reinforced polymers are brittle and exhibit low ductility. Recently, researchers have attempted to engineer lightweight ductile multifunctional reinforcements as replacements for steel to avoid its characteristic corrosion and associated defects. Hybrid continuous CF–epoxy composites were developed with high breaking strains, ductility, and tailorable mechanical properties. Subsequent studies have explored the modification of hybrid continuous CF–epoxy composites with other materials to improve their strength and self-sensing performance [83,84]. The proportion of constituent fibres, their properties, and their arrangement within composites are crucial factors affecting the ductility and detection capabilities of the composite. GFs, as one of the most conventional and widely available type of fibre, have attracted the attention of many researchers for the development of hybrid polymeric CF–GF composites with superior ductility and sensitivity [85,86]. As illustrated in Fig. 4(a), these composites are composed of CF cores that are enclosed in GFs.

The composites exhibit appropriate piezoresistive behaviour under cyclic and monotonic tensile loading. Fig. 4(b) shows that the electrical resistance of the composite increases sharply during the breakage of CFs, this behaviour can be used as an alarm signal. Such an alarm signal is obtained near the composite failure load of a composite with a CF and GF content of 2.4 and 49 vol%, respectively. However, the electrical resistance of composites with lower CF contents (i.e. 0.2 vol% (GF: 48 vol%) or 0.6 vol% (GF: 48 vol%), rises sharply under loads considerably less than their failure load. Hence, suitably designed, hybrid CF–GF–epoxy self-sensing composites are viable candidates for monitoring the structural health of civil infrastructure. However, hybrid CF–GF–epoxy composites are not able to detect damage at an early stage, the fractional changes in their electrical resistance under strain of less than 0.6% are approximately 1%, limiting their application. Appropriate strain detection under low strain is only achieved under prestressed conditions by calculating the residual resistance of the CF–GF composites [88].

Hence, to increase the strain sensitivity of CF–GF self-sensing composites, continuous CFs were replaced with carbon particles (Fig. 5) which increased the fractional change in electrical resistance by approximately 6.2% under 0.6% strain and enhanced the ability of the composite to detect damage at early stages [89].

Braided composite rods (BCRs) are self-sensing, hybrid continuous CF–GF composites that show high sensitivity under low strain [90-93]. In BCRs, a specific combination of CFs and GFs are impregnated with a polymeric resin and axially over-braided using polyester filaments (Fig. 6). The resulting structures are cured to manufacture composite rods.

In this technique, the introduction of a certain degree of axial CF misalignment, through the adjustment of the braiding parameters of the polyester filaments (including tension and speed), changes the electrical contacts of the CFs in the BCR and, concomitantly, the electrical resistance under low strain. In these composites, a reduction in the CF content increases the strain-sensing capability of the BCRs, and a maximum gauge factor of approximately 24 is achieved under a flexural strain of 0.5%.

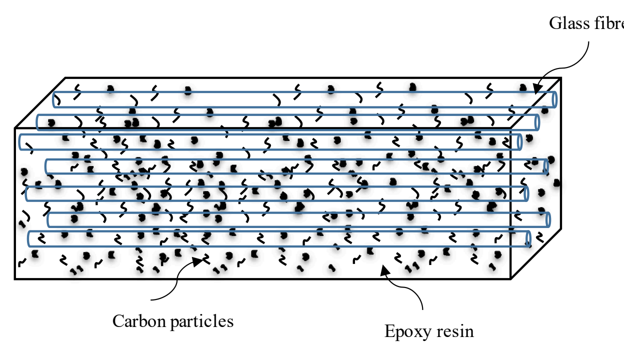


Fig. 5. Schema of hybrid carbon particle–GF self-sensing bars [88].

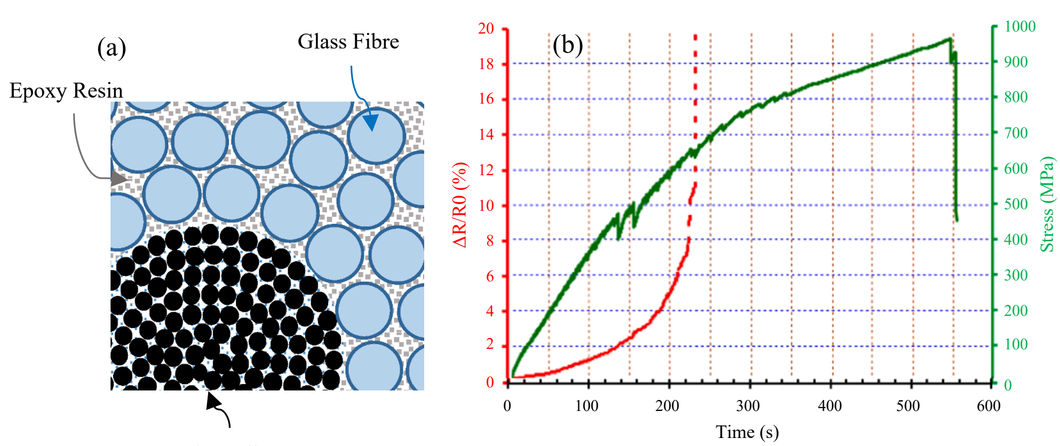


Fig. 4. (a) Morphology of hybrid CF–GF composite rods (b) Variation of stress (solid line) and frictional resistance (dotted line) during monotonic tensile testing of hybrid GF–CF rods with GF and CF contents of 48 and 0.2 vol%, respectively, [87].

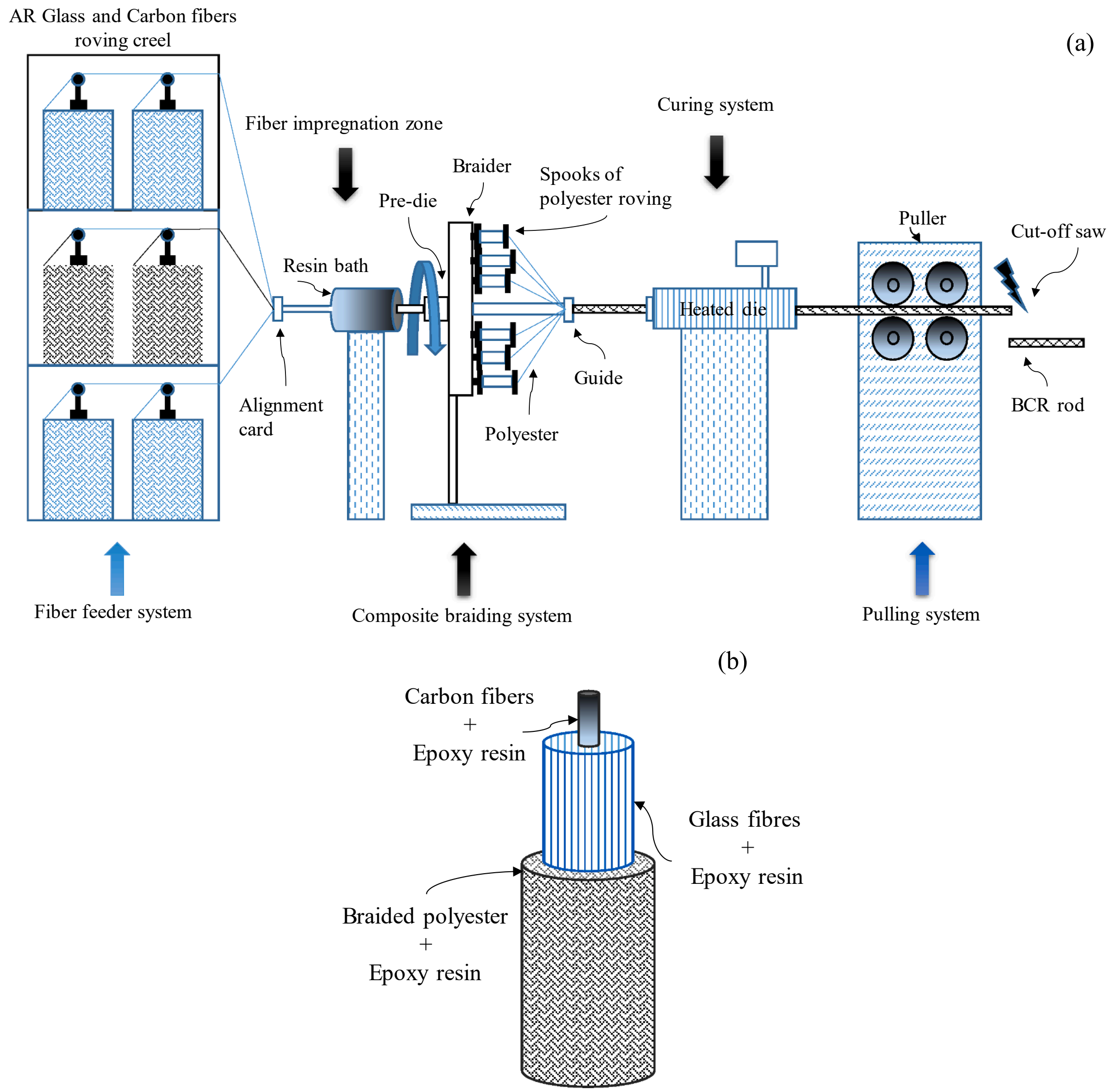


Fig. 6. (a) Manufacturing process of a BCR. (b) Cross-section and braided surface [93].

5. Carbon nanotubes and carbon nanofiber –based, self-sensing cementitious composites

CNTs and CNFs are one-dimensional nanomaterials that, along with advances in nanotechnology, enable the development of a wide range of multifunctional cement-based materials. CNTs are composed of single or multiple layers of graphene that are wrapped in the shape of a cylinder, whereas in CNFs, the graphene layers are arranged similar to stacks of cups, plates, or cones to create a nanoscale rod. These nanostructures are responsible for the remarkable physical, electrical, and thermal properties of CNTs and CNFs that have attracted the attention of researchers [1,2,94-98].

These conductive CNMs, once incorporated into non-conductive cementitious composites, form numerous nanoscale conductive paths owing to their high aspect ratios and specific areas. The sensitivity of these nanoscale conductive networks to low stress and strain increase the detection performance of a composites such that it is able to detect nanoscale cracks in the early stages of damage. In addition, reinforcing composites with certain amounts of CNTs and CNFs improves their physical and mechanical characteristics. However, the high price of CNTs and CNFs and their dispersion challenges limit the use of these nanomaterials.

Strong Van der Waals forces between the nanocarbon particles and the high specific surface areas of these nanomaterials greatly increase their tendency to agglomerate. In addition, the hydrophobicity of CNTs and CNFs retards their dispersion in aqueous suspensions.

Although techniques have been developed to promote the dispersion of CNMs in solutions, many of these adversely affect the intrinsic physical and/or electrical properties of the matrix and/or CNMs. Hence, an affordable and compatible dispersion technique is required to effectively impart the CNM properties to the composites. This is especially important when relatively high amounts of CNMs are used to achieve high sensitivity. High amounts of CNMs promote the formation of agglomerates which impair the physical properties of the composite matrix. However, the combination of these CNMs with conductive materials with different geometrical properties could resolve the dispersion difficulties and reduce production costs. To date, multiple multifunctional composites featuring CNTs, CNFs, or combinations of these CNMs have been developed for the detection of stress, strain, displacement, and cracks.

A hybrid smart composite rod with self-sensing capability was developed by Nanni et al. [89] to detect damage to a concrete beam. This hybrid composite consists of a conductive CNM-based core (5 wt% of CNMs, 30 nm in diameter) enclosed in an insulating GF–epoxy skin

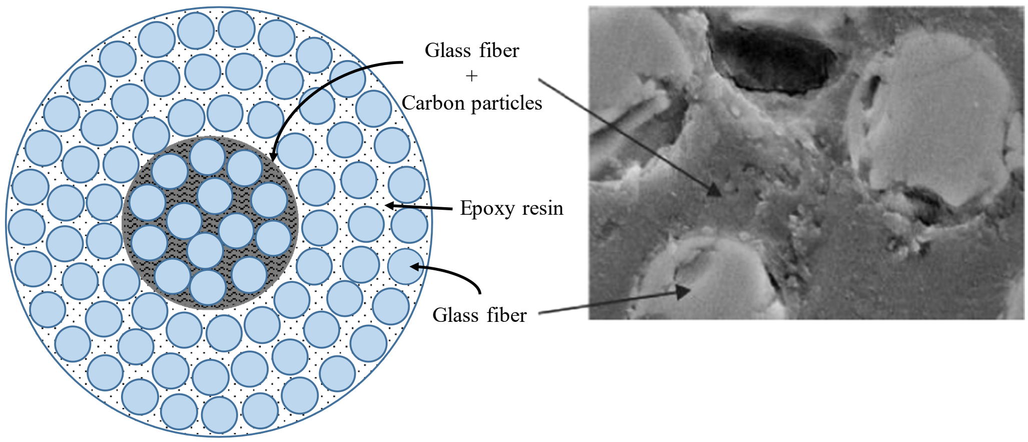


Fig. 7. Components of hybrid GF–CNM self-sensing rod [89].

(Fig. 7). As shown in Fig. 8, the concrete beam exhibits good piezoresistive behaviour owing to the presence of these rods. The decay in the fractional change in resistance curves numbered from 1 to 4 represent different stages of damage, namely initial cracking, propagation, crack extension, and specimen failure, respectively.

A summary of other self-sensing composites featuring CNTs and CNFs is presented in Table 3.

Generally, CNFs and CNTs are the best conductive filler options for cementitious composites. The high aspect ratios and specific surface areas of these CNMs realise high piezoresistive behaviour under low strain, even at low concentrations. The nanoscale conductive paths formed by CNTs and CNFs remain stable in cement-stabilised sand with low cement content. However, the incorporation of CNMs generally can reduce the ductility of cementitious composites [99-104], the resulting brittleness of the composite leads to the formation of cracks during the initial stages of loading. In addition, the high costs of these CNMs and the challenges associated with their dispersion limit their application. While multiple studies have investigated different combinations of CNMs in terms of their self-sensing performances in cementitious composites, studies investigating the long-term piezoresistive behaviour of these particles are necessary to assess their suitability for the hostile environments of geomaterial infrastructures.

6. Graphene-based, self-sensing cementitious composites

Graphene or graphene nanoplatelets (GNPs) are monolayers of graphite. It is a carbon allotrope consisting of carbon atoms that are

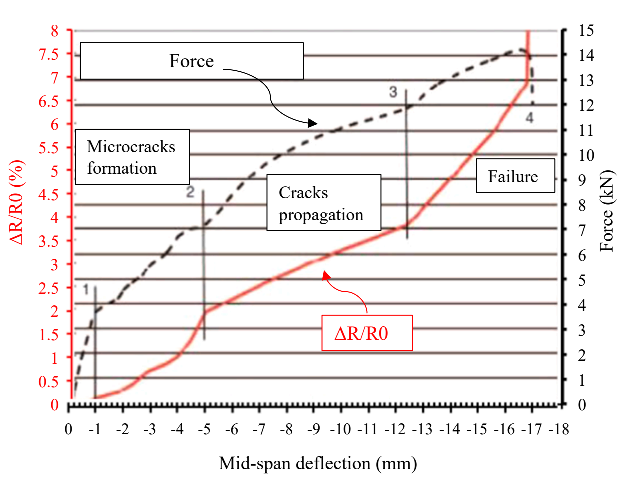


Fig. 8. Fractional change in electrical resistance and change in load, and midspan deflection state at points 1, 2, and 3, [87].

Table 3
Summary of studies investigating the damage monitoring performance achieved using CNTs and CNFs.

Composite type	Conductor type	Conductive filler concentration (%)*	Electrical factors		References
			$\Delta R/R_0$ (%)	Gauge factor	
Cement paste	CNT	0.2 of wt.	0.02	–	[105]
		0.3 of wt.	0.03	–	
Cement paste	CNT	0.6 of vol.	0.04	1	[106]
		0.7 of vol.	0.05	50	
		1.2 of vol.	0.06	2	
Cement paste	CNF	0.5 of wt.	0.07	–	[107]
		1.0 of wt.	0.08	–	
		2.0 of wt.	0.09	–	
Cement paste	CNT + CF	15 of vol. (CF)	0.10	–	[61]
		1 of vol. (CNT)	0.11	–	
Asphalt concrete	CNT	0.06 wt	8.8% at 5.2 MPa 10.3% at 8.6 MPa	–	[108]
		0.1 wt	8.4% at 5.2 MPa 11.4% at 8.6 MPa	–	
Mortar	CNT	2.14 vol	6.8% at 4 MPa	–	[109]
Mortar	CNT	1	–	150	[110]
Mortar	CNT	0.3	–	254.3	[111]
Mortar	CNT	1		166.6	[112]

* Relative to the weight of the cement or total volume.

tightly bound and arranged in a hexagonal two-dimensional (2D) lattice. It is sp^2 hybridised, has an extremely thin nuclear thickness (0.345 nm), and has a honeycomb structure that features atomic carbon–carbon bonds with a length of 0.142 nm. Single-layer graphene has a tensile resistance of 130 GPa, Young's modulus of 1.0 TPa, and a loading capacity ten times higher than that of steel. Moreover, it is 1,000,000 times more conductive than copper. These remarkable features of graphene have led to it being called "super carbon" [30,113,114].

The incorporation of GNPs into cementitious matrices significantly improves the conductivity of the composite and increases its stress/strain sensitivity more than the incorporation of CB, NCB, CNF, and CF [115-118]. Furthermore, the incorporation of GNPs into cementitious matrices enhances the physical and mechanical properties, and durability of the composite, as well as its thermal stability, thermal diffusivity, and heat resistance [119-123]. Lv et al. [124] showed how graphene regulates the nucleation and growth of the cement hydration products over time to achieve remarkable compressive strength (38.9%), tensile strength (78.6%), and flexural strength (60.7%) in cementitious mortar.

The inclusion of graphene as a conductive filler in a cementitious matrix not only imparts sensing ability to the composite but also enables the quantification of the degree of damage to the matrix. A correlation between fractional change in electrical resistance and degree of damage has been expressed by Le et al. [125] based on a mathematical analogy between a 2D static field and a 2D static field subjected to an antiplane shear load. The unique electrical conductivity of graphene makes it a suitable filler for electrostatic dissipative (ESD) applications. The vulnerability of a graphene-based cementitious self-sensing composite to interference is limited. By increasing the graphene concentration beyond the percolation threshold, factors, such as the water-to-cement ratio, moisture level, and hydration period, negligibly influences the composite sensing efficiency [126], which makes graphene an ideal conductive filler for geomaterials. However, the complexity of graphene production and the relatively high cost of this conductive filler limit its use. The high specific surface area of dispersed graphene facilitates the absorption of water during composite fabrication which thickens the consistency of the cementitious composite or even halts the hydration process of the cement, especially in cases with low water content [67,127,128]. Hence, it is advisable to combine graphene with other effective carbon conductive fillers to decrease its concentration and production costs without reducing the sensitivity of the composite or sacrificing the desirable properties of graphene [129]. The combination of 2D graphene with conductive fillers with different geometrical properties can also facilitate filler dispersion [68].

7. Influential factors

The process of self-sensing composite development, including composite design (in terms of sensing performance, physical and mechanical properties, and durability), composite preparation, and electrical resistance measurements, is informed by various factors which depend on the type and application of the composite. In this section, some influential factors and their mechanism are discussed by geotechnical approaches in transportation infrastructure applications.

7.1. Conductive filler dispersion

Several factors influence conductive filler dispersion, including 1) the geometrical and morphological properties of the conductive filler (such as length, softness, roughness, and mixing content), 2) viscosity of the suspension or medium, and 3) surface features of the conductive filler [130]. Available dispersion methods are categorised as 1) physical approaches (such as ultrasonication, shear mixing, ball milling, and raw material mixing), and 2) chemical approaches (such as covalent and non-covalent functionalisation, calendering and irradiation, and plasma). The advantages and limitations of the different methods of conductive filler dispersion are listed in Table 4. An ideal dispersion method exhibits minimal side effects and does not adversely affect the intrinsic properties of the conductive filler and/or composite, especially filler morphology because of its vital role in the sensing ability of the composite [131-133]. Among chemical dispersion methods, non-covalent functionalisation impairs the inherent electrical, optical, and mechanical properties of fillers and cementitious composites the least. Conductive fillers, especially CNMs, are commonly dispersed by pairing this technique with different surfactants, aromatic small molecules, polymers, the endohedral method, or bio-macromolecules [68,134-137]. A feasible, affordable, and compatible technique for conductive filler dispersion in cementitious composites typically combines a chemical treatment, such as surfactant addition, and a physical method, such as ultrasonication, to disperse the filler in an aqueous suspension. Surfactants usually have a polar molecular structure, the hydrophobic chain end attaches to the filler and the hydrophilic chain end bonds with water molecules. Surfactants are either anionic, cationic, or non-ionic, depending on their hydrophobic chain ends and their bonding mechanism with conductive fillers. In the case of non-ionic surfactants, π-π interactions are responsible for the adsorption of the surfactant molecule on the filler surface, especially in CNMs [68]. However, in dispersion processes featuring surfactants, the temperature and concentration of the surfactant are of particular importance [68,138]. Ultrasonication is one of the most commonly used physical dispersion methods. In ultrasonication, microbubbles are produced in the suspension by a cavitation effect that vibrate violently and release large amounts of energy. During this process, bundles of conductive fillers are exfoliated or unbundled, and the filler surface roughness increases to a certain extent. However, the applied acoustic energy should be reasonably controlled to prevent damaging the structural quality of the filler, such as the formation of edge-type defects, or reducing the aspect ratio and sp^2 domain crystallinity (La), which are detrimental to the electrical and mechanical performance of the filler, especially in the case of CNMs [139,140].

Acid treatment is a chemical technique that can be used to modify the surfaces of conductive fillers. In this process, a conductive filler is soaked in acid for a relatively short time during which functional groups form on the surface of the filler to increase its wettability [111,141]. However, this can adversely affect the conductivity and strength of the filler owing to the difficulty of regulating the degree of functionalisation [30].

7.2. Electrode configuration and resistance measurement

The configuration and status of the electrodes are one of the influential factors on the resistance measurement accuracy in self-sensing composites. As shown in Fig. 9, measurement methods employ four- or two-electrode configurations. In the four-electrode method, the current is typically applied to the outer electrodes, while the two inner electrodes are used to measure resistance or voltage. The materials used in the production of an electrode should exhibit several essential characteristics, including high and stable electrical conductivity. Electrodes, typically plate (such as tape, foil, flakes), grid, or rod-shaped and consisting of copper, steel, lead, brass alloy, or graphite, are either embedded into the composite or attached to its surface [142-146]. However, the electrical resistance measured using electrodes embedded

Table 4
Advantages and limitations of different conductive-filler dispersion methods.

Categories	Dispersion technique	Advantages	Limitations
Chemical dispersion	Admixture Surfactant	Simple and affordable, compatible with cementitious composites in low concentration cases.	Less content cannot meet the requirement of dispersion, but more dosage can affect the filler and/or composite features.
	Conductive filler functionalisation	Relatively simple and affordable, short reaction time.	Damages filler morphology owing to difficulties in controlling degree of functionalisation.
Physical Method	Ultrasonication Optimising mixing sequence	Simple and affordable.	Poor dispersion, unstable over time.
Other	Combination of particles with different sizes.	Simple operation.	Poor dispersion, affected by the size of the particle.

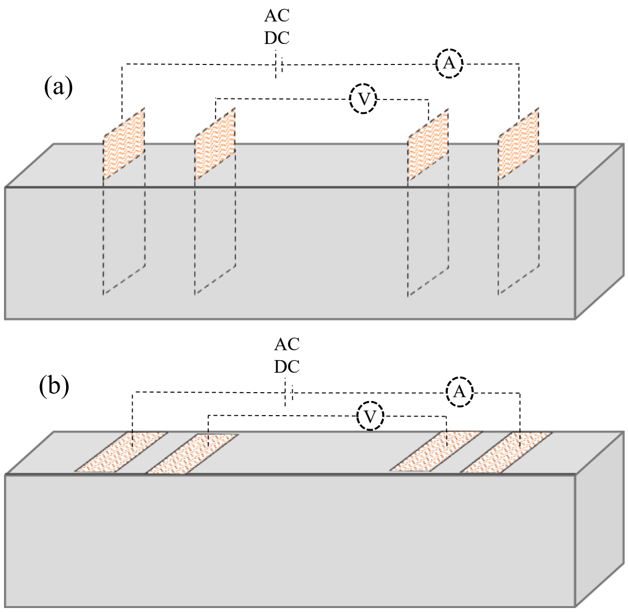


Fig. 9. Different electrode configurations for resistance / voltage measurements in cementitious composites.

into a matrix is significantly lower than the electrical resistance measured using electrodes attached to the surface of the composite owing to the greater contact of the embedded electrodes with the conductive paths in the composite [30,147].

A non-contact electrical resistance measurement technique has also been developed (Fig. 10) to avoid electrode arrangement difficulties. This measurement method is based on the transformer principle, obviating the need for electrodes, and achieves superior accuracy [148,149]. The type of current is also an important measurement factor that significantly affects the accuracy of sensing.

The application of a direct current (DC) usually increases polarisation effects and consequently increases the electrical resistance owing to the ionic conductivity of the cementitious self-sensing composite [56,150,151] while an AC can significantly eliminate polarisation effects during resistance measurement. The ability to adjust impedance by changing the current frequency is another advantage of using an AC during measurement [152]. Indeed, the microstructural changes of cementitious composites, such as carbonation, ion migration, steel corrosion, and cement hydration, can be analysed by regulating the AC frequency [153,154].

7.3. *Temperature*

In a self-sensing cementitious composite, the influence of temperature variations on its piezoresistive behaviour can be described in terms of a resistance–temperature mechanism, Seebeck effect, and electro-thermal mechanism. However, resistance changes associated with the electro-thermal mechanism are negligible and, therefore, ignored [30].

In terms of the resistance–temperature mechanism, increasing or decreasing the temperature in proportion to the coefficient of expansion and contraction of the composite causes microstructure contraction (due to the temperature reduction) or its expansion (due to increasing temperature), which changes the distance between the conductive filler particles distributed in the matrix. Temperature changes can also affect the electronic transitions and electron tunnelling mechanisms of the filler. In general, each of these phenomena affect the electrical resistance of the composite, and may be interconnected [30]. Hence, the effects of

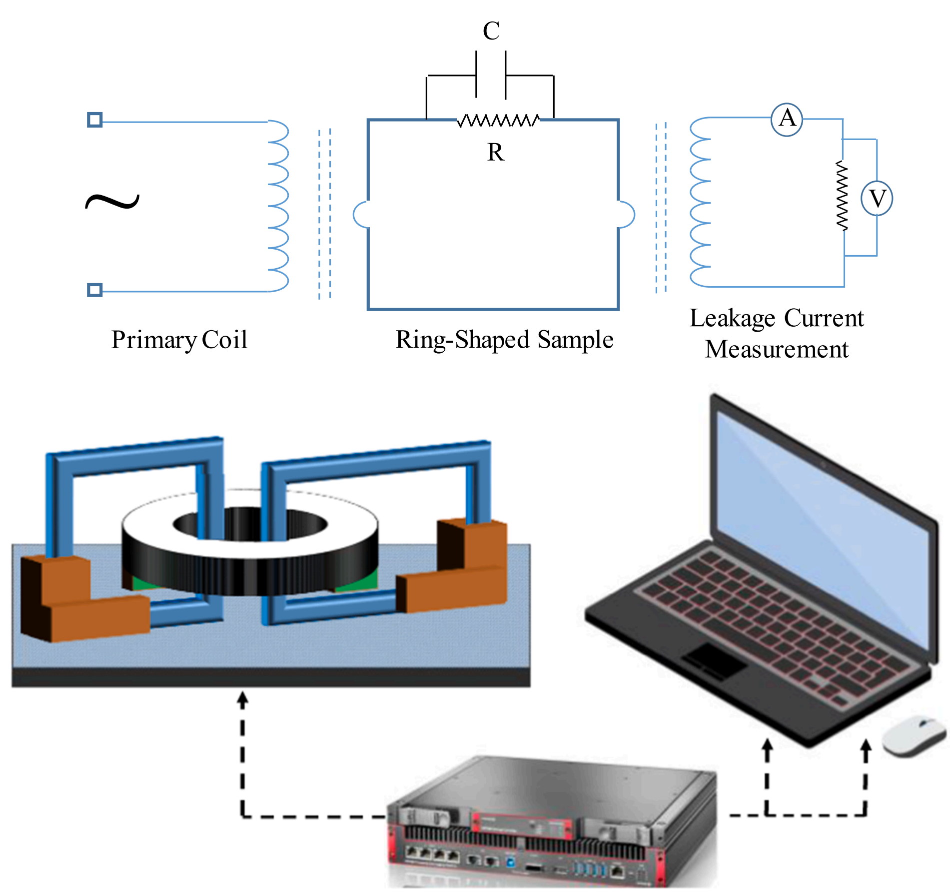


Fig. 10. Setup of a non-contact electrical resistance measurement device and its equivalent circuit.

temperature on the piezoresistive behaviour of self-sensing cementitious composites can vary and should be investigated based on parameters such as temperature range, rate of change, and types of filler [155].

When a composite is exposed to high temperature, the motion and vibration of electrons at the site increase. These excited electrons tend to migrate from these high temperature regions to lower temperature regions within the matrix. This phenomenon, which is called the Seebeck effect, causes an electromotive force that changes the electrical resistance of the composite [156,157].

7.4. Water-to-cement ratio

The water-to-cement (w/c) ratio is another important factor that affects the physical, mechanical, and piezoresistive behaviour of cementitious composites. Increasing the water-to-cement ratio greatly improves the dispersion status of conductive fillers, however, an excessive increase significantly reduces the microstructure cohesion and mechanical performance of the composite, which weakens its piezoresistive behaviour [11,158].

The selection of a (typically low) water-to-cement ratio to fabricate geotechnical transport infrastructures, depend on the fabrication method, and should be informed by the physical, mechanical, durability, and piezoresistive response requirements.

7.5. Sand-to-cement ratio

Evidence suggests that the sand-to-cement ratio does not significantly affect the percolation threshold of cementitious composites [5]. However, at a fixed conductive-filler concentration, the electrical resistance of a composite increases with increasing sand-to-cement ratio. Although an excessive increase in the sand-to-cement ratio reduces the electrical conductivity of the composite, an optimal ratio reduces the incidence of voids in the matrix and increases the physical performance of the composite which enhances its conductivity and piezoresistive behaviour.

7.6. Freeze–thaw cycles

Repeated freezing and thawing induce the cyclical deformation of a cementitious composite resulting in the formation of cracks in the composite microstructure due to stress differences. These cracks gradually expand under service loads with increasing number of freeze–thaw cycles, irreversibly impairing the electrical conductivity of the matrix and, hence, the piezoresistive performance and sensing ability of cementitious composite [5,143,159].

7.7. Dry–Wet cycles

In cementitious composites, the electrical conductivity in dry conditions is ascribed to the movement of electrons, whereas in wet or saturated conditions, the electrical conductivity is ascribed to the movement of ions. Furthermore, the frequent change in water content during dry–wet cycles, impairs the physical properties and, consequently, the durability of the cementitious composite, destructively impacting the conductive paths formed by its filler and reducing its conductivity and sensitivity [160,161].

8. Conduction theories and equivalent circuit models in self-sensing cementitious composites

8.1. Conduction theories

Generally, the formation of conductive paths in a self-sensing composite is described based on conduction theories. Currently, the literature references four main conduction theories, namely percolation theory, quantum tunnelling theory, electron field emission theory, and effective medium theory. The characteristics of the different conduction theories are listed in Table 5.

According to percolation theory, when the concentration of a conductive filler exceeds a certain threshold, the conductive filler particles are in physical contact or within 1 nm of each other, which form an extensive conductive network within the associated matrix [30]. This network dramatically changes the electrical resistivity of the composite, and the minimum concentration of conductive filler required to form such a network is called the percolation threshold [162]. However, when the concentration of the conductive filler is lower than the percolation threshold and the conductive paths do not form, the electrical conductivity of the matrix is described by quantum tunnelling theory. According to quantum tunnelling theory, the electrical conductivity of the composite is not enabled by the physical connection of conductive fillers, but the transfer of electrons between adjacent filler particles in the matrix under an external electric field.

In some cases, an investigation of the voltage and current variation in a self-sensing composite shows that, contrary to Ohm's law, the voltage–current relationship is not constant. In these cases, electron field emission theory is used to describe the electrical conductivity of the composite. According to this theory, a relatively high applied current produces electron field emission between conductive fillers which increases the current resulting in a non-ohmic relationship between current and voltage [163].

The effective medium theory is another theory used to describe the electrical conductivity of a composite. This theory assumes that each composite particle is in an effective medium with identical conductivity. The composite conductivity can be assessed by evaluating the conductivity of various phases [164].

Generally, the conductive behaviour of cementitious composites is the result of various phenomena described by different theories, the dominant phenomenon depends on the conductive filler concentration [165]. Ion conduction, that is, Ca^{2+}, Na^{+}, K^{+}, OH^{-}, and SO_4^{2-}, also informs the electrical conductivity of cementitious composites, particularly in porous matrices [166]. External factors affect the sensing efficiency of the composite by suppressing electron and ion conduction. However, the existing theories of conduction only consider the directional electron movement of conductive fillers, not ionic conduction. The relationships between the different conduction theories and the role of ion conduction should be investigated to formulate a more general conduction theory that considers the effects of influencing factors in describing the conductive behaviour of cementitious matrices.

8.2. Equivalent circuits

The piezoresistive behaviour of a self-sensing cementitious composite not only enables the monitoring of stress and strain but also the detection of microstructural changes. By combining equivalent circuit modelling and AC impedance spectroscopy (ACIS), the electrical signal changes can be analysed to reveal microstructural changes. However, because of the complexity of ACIS results, this approach is only suitable for compounds with equivalent circuit models [167,168].

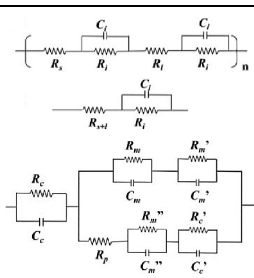
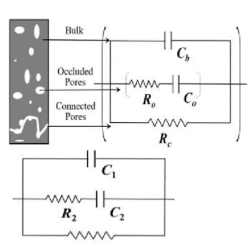
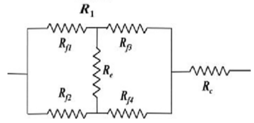
A complex electrochemical system is created within cementitious composites when subjected to an AC. The different components of the solid, liquid, and other phases of the composite and their electrical properties can be represented by different circuit elements such as capacitors, resistors, or inductors in series or parallel. However, it is difficult to simulate the electrical system of a cementitious matrix using an equivalent circuit model because of its complex microstructure [169].

In this review, equivalent circuit models are divided into three groups according to their basis of development and geotechnical application, namely a microstructure model, conductive path model, and conduction theory model, as shown in Table 6.

Table 5
Characteristics of different conduction theories.

Theory	Principal equations	Definition	Filler concentration	Voltage	Scale	Specifications
Percolation theory	$C = C_p[1 - V_p + V_p W\left(\frac{C_m}{C_p}\right)]$	C_m is the conductivity of the composite, V_p is the conductive filler volume fraction, and C_p is the conductive filler conductivity.	High	–	Macro	Expression and analysis of the abrupt shift in electrical resistivity associated with high conductive filler concentrations.
Effective medium theory	$\frac{(1-\varphi)\left(\sigma_L^{1/t} - \sigma_m^{1/t}\right)}{\sigma_L^{1/t} + A\sigma_m^{1/t}} + \frac{\varphi\left(\sigma_h^{1/t} - \sigma_m^{1/t}\right)}{\sigma_h^{1/t} + A\sigma_m^{1/t}} = 0$ $A = (1-\varphi_c)/\varphi_c$	φ is the conductive filler volume fraction, φ_c is the conductive filler critical volume fraction, σ_L is the low conductive phase conductivity, σ_h is the high conductive phase conductivity, σ_m is the composite conductivity, and t is the exponent.	–	–	–	Wide variety of applications
Quantum tunnelling theory	$J = J_0\{\overline{\varphi}\exp(-A\overline{\varphi}^{1/2}) - (\overline{\varphi}+eV)\exp[-A(\overline{\varphi}+eV)^{\frac{1}{2}}]\}$ $j(\varepsilon) = j_0\exp[-\frac{\pi XW}{2\left(\frac{\lvert\varepsilon\rvert}{\varepsilon_0}-1\right)^2}]J_0 = e/2\pi h(\beta\Delta s)^2 A = (4\pi\beta\Delta s/h)(2m)^{1/2}$, $X = \left(\frac{4\pi m V_0}{h^2}\right)^{1/2}$,	J is the density of the tunnelling current, e is the electronic charge, Δs is the barrier limit at Fermi level, h is Planck's constant, $\overline{\varphi}$ is the height of the average barrier, V is the voltage on both sides, $j(\varepsilon)$ is the tunnelling current when the intensity of the electric field between conductive filler particles is ε and the equivalent conductivity is j_0, W is the width of the gap between filler particles.	Low	Low	Micro	Describes the conductive behaviour when the conductive fillers do not physically touch.
Electron field emission theory	$J = AE^n\exp(-\frac{B}{E})$	J is the density of the current, E is the intensity of the field, A is the frequency of tunnel, B and n are characteristic constants of the composite.	Low	High	Micro	Describes a non-ohmic relationship between current and voltage.

Table 6
Characteristics of different equivalent circuit models.

Type of The Model	Impedance equation*	Equivalent circuit model	Definition	Specifications
Microstructure model	*ZL=RS+L+1/(RINT+jwCINT) RS+L=n(Rs+RL)R1=2n(Rint) C1=Cint/2n*Z=(RRCRCRCRC)(RC)		R_s is the solid-phase resistance, R_l is the liquid-phase resistance, R_{s+l} is the liquid-phase resistance plus the solid-phase resistance, C_i is the capacitance of the interface, R_i is the resistance of the interface, n is the number of units in the composite, C_m is the composite capacitance, R_m is the composite resistance, C_m' and R_m' are the capacitance and resistance increased by the conductive filler, R_m'' and C_m'' are the resistance and compensation capacitance, R_p is the conductive filler, R_c' and C_c' are the resistance and capacitance of the interface between the composite and conductive filler, R_c and Cc are the resistance and capacitance increased by polarisation effects	Used to investigate cement hydration and microstructural changes to inform structural health monitoring. Limited accuracy owing to the complexity of a cementitious matrix microstructure.
Conductive pathmodel	$Z \approx 1/\{jwC_1 + \frac{1}{R_1} + \frac{1}{\left[R_2 + \frac{1}{jwC_2}\right]}\}Z = \frac{1}{\frac{1}{R_1} + \frac{1}{\frac{R}{jwC_2}} + jwC_1}$		R_1 is the conductive path, C_2 and R_2 are the partially conductive paths, and C_1 is the non-conductive path-	Uses conductive paths to create an equivalent circuit model that ignores microstructural complexity.Considers microstructural conductivity changes on a macroscopic scale.
Conduction theorymodel	Rtotal=f(RL‹ RCRt)		R_f is the conductive filler electrical resistance, R_c is the contact resistance between the fillers, R_e is the electrical resistance affected by the tunnelling effect.	Considers both tunnelling and percolation theory.Is based on the conductive theory of CF cementitious composites.

* R is the resistance, Z is the total impedance, C is the capacitance, ω is the angular frequency, and j is imaginary.

9. Applications

With the advancement of self-sensing composite technology and the development of efficient smart cementitious composites, applications taking advantage of these materials have increased. The flexibility of self-sensing composites in terms of design and versatility in terms of project-specific engineering requirements have significantly widened the range of potential applications, some of which are briefly mentioned below.

9.1. Structural health monitoring

As indicated in Fig. 11, different configurations of the self-sensing composites, including bulk, coating, sandwich, bonded, and embedded forms, have been used for structural health monitoring. Bulk refers to the construction of entire structures or key parts with self-sensing composites, which not only satisfies structural engineering criteria but also enables efficient self-sensing [170]. In coating form, one surface of a component is covered by a layer of self-sensing composite, while in the sandwich arrangement, both the top and bottom surfaces of a component are covered by self-sensing composite layers. In bonded application forms, small, self-sensing composite sensors are attached to the surface of a component.

Another common self-sensing composite application is the embedding of small self-sensing composite sensors into a component. These sensors are typically as small as or slightly larger than conventional coarse aggregates [171,172].

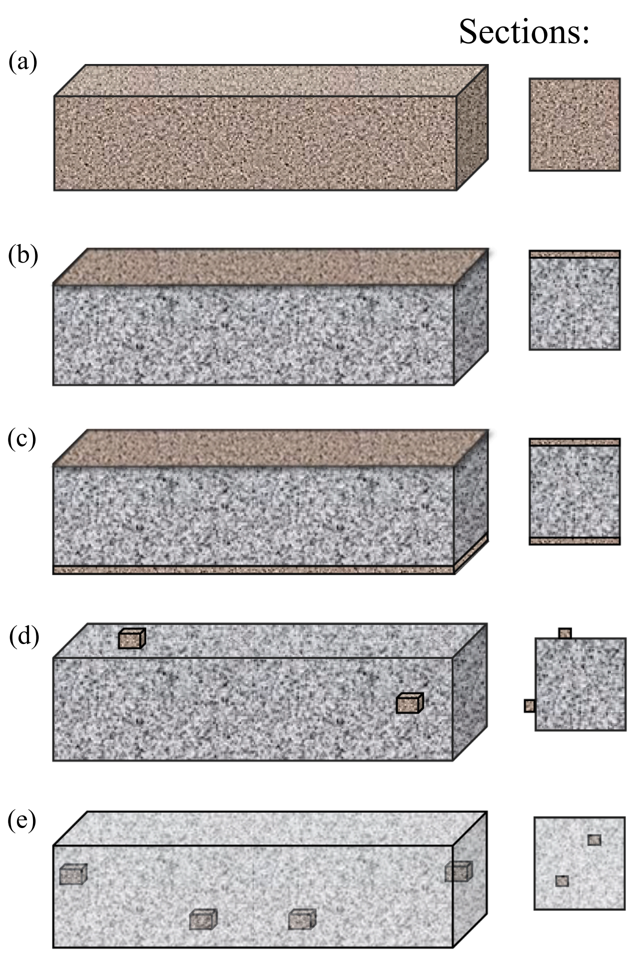


Fig. 11. Typical application forms of self-sensing composites for structural health monitoring: a) bulk form, b) coating form, c) sandwich form, d) bonded form, and e) embedded form.

The coating, sandwich, bonded, and embedded application forms can achieve wider monitoring at lower construction costs that the bulk application form, since these forms allow the targeted placement of self-sensing composites at key positions in the structural components. With these approaches, any risk to human safety and the deterioration of embedded steel caused by the electrical conductivity of self-sensing composites can be prevented [173]. The benefit of the bulk shape, however, is that it is simple to construct, unlike the other application forms, especially the coating and sandwich types [170,174-179].

Some of the applications of self-sensing cementitious composites in the field of structural health monitoring, as mentioned in previous studies, are summarised in Table 7.

9.2. Traffic monitoring

Traffic data, including vehicle speed, traffic density, traffic flow rates, can be extracted, and even dynamic weighing can be performed, by incorporating self-sensing composites in transportation infrastructure, such as pavements, rail tracks, or bridges. Such applications can be independent from or secondary to structural health monitoring (Table 8).

Variations in detection signals due to the polarisation of environmentally sensitive parameters are continuous and gradual, while vehicle load sensing signals are abrupt and transient. Hence, the former can be filtered out from the measured signals post-processing, and the accuracy of the monitoring will be unaffected. Accordingly, the monitoring performance of pavements or rail tracks integrated with self-sensing composites demonstrate appropriate resistance to polarisation caused by environmental factors and damage within the composite [180,181].

10. Challenges

Despite many advances in the development of various self-sensing composites, few studies have explored self-sensing cementitious geocomposites which can play a crucial role in the long-term sustainability of transport infrastructures. Given the similarity between cementitious geomaterials and cementitious composites such as mortar, it is reasonable for the outcomes of studies conducted on cementitious composites to inform the development of self-sensing cementitious geocomposites.

However, there are still some challenges and unknowns regarding the feasibility of SSGs based on piezoresistive behaviour, such as:

- The sensing properties of cementitious composites arise from conductive paths which the present review shows are strongly influenced by matrix aggregate type and size. Diverse grain properties are one of the inherent characteristics of geomaterials.
- Owing to the low cement concentration used in cementitious geocomposites, a low conductive filler can be incorporated into the matrix. Hence, the type and geometrical properties of the conductive filler should be considered in such a way that a cementitious geocomposite with superior physical–mechanical properties, durability, and sensitivity is obtained.
- As discussed, the cement content of a cementitious composite determines the cohesion of the microstructure formed and, concomitantly, the stability of the conductive paths and associated piezoresistive behaviour of the composite. The efficiency of different types of conductive filler in low cement-concentration matrices needs to be investigated because of the low cement content of cementitious geocomposites.
- The water content, as one of the parameters determining mixture consistency, the physical and mechanical properties, and piezoresistive behaviour of cementitious geocomposites, requires extensive evaluation.
- In the case of carbon-based conductive fillers, a novel, effective, and affordable dispersion method is required that is compatible with the low water content used in the fabrication of cementitious

Table 7
Summary of previous studies on cementitious self-sensing composites in different forms for structural health monitoring.

Application forms	Conductive filler type	Component	Loading method	Detected parameters	Reference
Bulk	CSF	Concrete beam	Bending (Four point)	Load, Deflection	[182]
		Concrete ring	Parallel plate loading	Load, Diameter change	
	CSF	Concrete beam (Reinforced)	Bending (Four point)	Load, Damage	[178]
	CSF	Concrete beam	Bending (Four point)	Load	[183]
	CSF	Concrete beam	Bending (Four point)	Elastic compressive stress in the pure bending region	[184]
	PAF	Concrete pier of the bridge	Lateral	Strain, Deflection	[179]
	CSF	Concrete beam	Bending (Four point)	Fatigue, Damage	[185]
	CSF	Concrete beam	Bending (Three point)	Load, Deflection, Fracture	[186]
	CNF	Concrete column	Compression	Strain	[170]
Coating	CSF	Concrete beam	Bending (Three point)	Compressive and tensile strain	[187]
	CSF	Concrete beam	Bending (Four point)	Load, Strain	[30]
	CSF	Concrete beam	Bending (Four point)	Load, Deflection, Damage	[30]
Sandwich	CSF	Concrete beam	Bending (Four point)	Load, Deflection, Damage, Cracks	[188]
	CSF	Concrete beam	Bending (Three point)	Strain, Stress	[30,176]
Bonded	CSF, CNF	Concrete beam (top, bottom, or side)	Bending (Four point)	Strain	[177]
Embedded	Hybrid CSF and CB	Concrete beam (embedded into the compressive zone)	Bending (Four point)	Strain, Stress	[189]
		Concrete column (embedded in its centre)	Compression (Uniaxial)	Strain, Stress	
	CSF	Concrete beam (embedded into the bottom)	Bending (Four point)	Strain, Stress, Crack	[190]
	CNT	Concrete beam (embedded into the bottom)	Bending (Three point)	Damage, Crack	[5]
	Hybrid CSF and GP	Concrete column (embedded into the centre)	Compression	Force	[191]

geocomposites and addresses the hydrophobic nature of carbon fillers. Especially since the degree of dispersion of the conductive fillers plays a crucial role in determining the physical and mechanical properties, durability, and piezoresistive behaviour of the composite.

- Considering the effects of fabrication on the piezoresistive behaviour of cementitious composites, their application in geocomposite technology requires further investigation, taking into account the various techniques used in geotechnical engineering.
- The effects of external environmental factors such as climate cycles, carbon dioxide, temperature, chlorine ions, and humidity on the piezoresistive behaviour of cementitious composites are still unclear. Moreover, the durability and long-term monitoring ability of cementitious geocomposites are of vital importance and must be determined.
- Current conduction theories are unable to describe the conductive and piezoresistive behaviours of cementitious geocomposites and the applicability of equivalent circuit models is limited. It is, therefore, necessary to develop a universal conductive theory and an equivalent circuit model that describes the conductivity behaviour of cementitious geocomposites.
- The design flexibility of self-sensing cementitious composites, in terms of satisfying the requirements infrastructure projects, means that they can not only be utilised in structural health monitoring of transport infrastructure (especially transition zones between structural layers), but also have the potential to detect structural damage in infrastructure such as roller-compacted concrete dams, rammed earth, and ground improvements. However, in-depth investigations on the application of self-sensing cementitious composites in the aforementioned fields are required. Future studies on the implementation of self-sensing cementitious composites should seek to develop a consistent method, guidelines, and specifications for the design and construction of self-sensing cementitious composite structures.

11. Concluding remarks

Self-sensing cementitious composites are multi-phase materials composed of cement-stabilised geomaterials, conductive phases, and the interfaces between conductive fillers and the composite. The sensing capability and conductive properties of self-sensing composites are determined by factors such as conductive filler type, manufacturing technique, and material proportions. All these parameters affect the piezoresistive behaviour of cementitious geocomposites in different ways and to different degrees. Regrettably, the research on self-sensing cementitious geocomposites is limited. However, their similarity to other cementitious composites has prompted this review of the most influential parameters determining the electrical properties and piezoresistive behaviour of cementitious composites to inform the future development of self-sensing cementitious geocomposites. In order to apply SSGs in large-scale structures, the technology must be environmentally friendly, simple to implement, and economical.

According to the literature, carbon-based self-sensing composites have superior mechanical and microstructural properties, are durable, demonstrate good detection sensitivity and are appropriately compatible with cementitious matrices. Consequently, their application in the monitoring of transport infrastructures is promising. However, the combination of nano- and microscale carbon fillers is recommended in order to minimise the cost of production and prevent the brittle behaviour that is observed in composites only filled with CNMs. Combining different conductive carbon fillers, while reducing the percolation threshold without undermining the composite sensitivity, can also facilitate their dispersion. However, a feasible and compatible dispersion method is still required to properly disperse conductive fillers; non-covalent functionalisation in conjunction with an appropriate physical method may offer an affordable, compatible, and effective approach to carbon-based filler dispersion. Studies have shown that four copper electrodes embedded in a self-sensing composite under a DC and an AC enables the accurate measurement of the fractional change in electrical resistance. Since the water and cement contents of cementitious geocomposites and conventional cementitious composites differ

Table 8
Previous research on self-sensing composites for traffic monitoring applications.

Type of conductive filler	Self-sensing composite application style	Type of test	Goal of detection	References
CSF	Self-sensing concrete roller.	Response of roller to a rotating car tire tested in lab.	Traffic monitoring Dynamic weighing	[192]
CSF + CB	Self-sensing concrete strip component integrated into pavement.	Response of specimens tested using testing machine in lab.	Vehicle speed detection	[193]
CSF	Self-sensing concrete strip component integrated into pavement.	Response of specimens tested using testing machine in lab.	Dynamic weighing	[5]
CSF + CBP	Self-sensing concrete strip component integrated into pavement.	Response of specimens tested using testing machine in lab.	Vehicle speed Vehicle weight Traffic flow detection Vehicle type judgement	[192,194,195]
CNT	Self-sensing concrete strip component integrated into a pavement test section at the Minnesota Road Research Facility.	Road test performed at a road research facility with a five axle semi-trailer truck and a van.	Traffic flow monitoring	[44,181]
NP	Self-sensing concrete arrays integrated into pavement.	Road test performed at outdoor lab with a car.	Passing vehicle detection	[196]

significantly, the effects of these two parameters on the sensitivity of geocomposites incorporating different conductive fillers need to be accurately evaluated. In addition, the effects of external environmental factors on the piezoresistive behaviour of cementitious composites have to be extensively investigated considering their intended application in the long-term monitoring of transport infrastructure. Indeed, despite the promising performance of piezoresistive-based self-sensing composites for the structural health monitoring of infrastructure and inability of existing technology to realise an integrated monitoring system compatible with the mechanisms and features of geomaterials, no studies have investigated the application of these composites for the structural health monitoring of infrastructure. Hence, extensive studies that investigate the capabilities and potential of geomaterial monitoring based on smart, piezoresistive, self-sensing composites are imperative.

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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