Self-sensing concrete: from resistance-based sensing to capacitance-based sensing

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ABSTRACT
Self-sensing uses the cement-based material without sensor incorporation to sense itself. This paper reviews self-sensing cement-based materials, with coverage of the well-studied resistance-based sensing as well as the less-studied capacitance-based sensing. This review is the first that covers capacitance-based self-sensing. Capacitance-based sensing is advantageous over resistance-based sensing in that no particular admixture is required, so that it is applicable to both existing and new structures. In contrast, resistance-based sensing that is comparable to capacitance-based sensing in stress/strain sensitivity requires conductive admixtures, such as carbon fiber. Resistance-based strain sensing is based on piezoresistivity, which is associated with the resistance increasing upon tension and decreasing upon compression. Capacitance-based strain sensing is based on piezopermittivity, which is associated with the permittivity decreasing upon tension and increasing upon compression. Damage causes the resistance to increase and causes the permittivity to decrease. Increase in temperature decreases the resistance but increases the permittivity. This review also covers the methodology of the electrical measurements.

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1. Introduction

Smart structures refer to structures exhibiting certain functional behavior, so that they can respond to stimuli in a desirable fashion. The most basic functional property is sensing. In response to the information sensed, the structure may respond. For example, in response to the strain sensed, the structure may activate a mechanism to reduce the strain. In another example, in response to the damage sensed, the structure may activate a mechanism to repair or heal. It is important for the functional properties to be rendered without adversely affecting the structural behavior, which is critical to a structure.

The attributes sensed included stress/strain, temperature, and damage. Strain sensing is relevant to structural vibration control. Stress sensing is relevant to load monitoring and weighing. Temperature sensing is relevant to operation control. Damage sensing is relevant to structural health monitoring. Sensing can be continuous (in real time) or discontinuous (occasional). The former is attractive that is allowed timely response to the information sensed. Robots are a category of smart structures.

Concrete is a cement-based material that is dominantly used as a structural material for the civil infrastructure. This paper focuses on smart concrete. An application is the use of smart concrete to weigh trucks as they move (weighing-in-motion) for the purpose of avoiding highway damage by overweight trucks [1]. Another application is the use of smart concrete to weigh each room of a building, thereby providing real-time room occupancy information. This information may be used to control the heating, cooling, ventilation, and lighting to save energy. Much energy is wasted in buildings that are partially empty. The use of cameras for room occupancy monitoring is ineffective and usurps privacy. Yet another application is the monitoring of the condition of the cement in an oil well [2].

Self-sensing refers to the ability of a structural material to sense itself without sensor incorporation. This means that the structural material is multifunctional. Compared to the use of embedded or attached sensors, self-sensing is advantageous in the low cost, high durability, large sensing volume and the absence of mechanical property loss. Decrease in strength and modulus occurs in case of embedded sensors, particularly if the sensors are not microscopic in size. In spite of these advantages, the use of embedded or attached sensors is much more common than self-sensing. This is partly due to the fact that the self-sensing structural materials tend to differ in composition from those of the commonly used structural materials. The requirement for the composition to be special limits the applications to new structures. In contrast, the attachment of sensors is applicable to existing structures. The applicability to both existing and new structures greatly widens the scope of applications.

The first report of self-sensing cement-based materials was made by the author and her student in 1993 [3]. After this report, a large number of papers have been published by the author’s research group [4–9] and numerous other research groups in various parts of the world [10–13].

There are two approaches to achieve self-sensing. One approach involves electrical resistance measurement. The resistance relates to the resistivity, which pertains to the conduction behavior. The other approach involves capacitance measurement. The capacitance relates to the electric permittivity, which pertains to the dielectric behavior.

Resistance-based self-sensing is the original self-sensing approach and has been extensively reported in cement-based materials containing various electrically conductive
admixtures. The requirement of admixtures limits the application to new structures. Capacitance-based self-sensing has received much less attention, but it is highly attractive, due to its not requiring any particular admixture and the resulting applicability to both existing and new structures. This paper provides a review of self-sensing concrete and differs from all previous reviews [14–16] in that it addresses both resistance-based sensing and capacitance-based sensing. Previous reviews only address resistance-based sensing. In addition, this review covers the methodology of the resistance and capacitance measurements.

2. Resistance-based self-sensing

2.1 Basic concepts

The self-sensing that has been extensively reported since 1993 is based on the measurement of the effect of a stimulus (such as strain) on the electrical resistivity of the cement-based material. Hence, by measuring the electrical resistance, one obtains information on the stimulus. The effect of strain on the resistivity of a material is known as piezoresistivity, which is unrelated to piezoelectricity. However, the temperature [17] and damage [18] also affect the resistivity. Damage increases the resistivity irreversibly, whereas elastic strain affects the resistivity reversibly. The irreversible resistivity change correlates with the irreversible strain, whereas the reversible resistivity change correlates with the reversible strain [19]. Thus, by distinguishing between reversible and irreversible effects, elastic strain, and damage effects can be distinguished. In cyclic tensile loading at the same stress amplitude, the first cycle of loading gives minor damage, which results in an irreversible resistivity increase, whereas the subsequent cycles do not give additional damage and hence no irreversible resistivity increase [20]. This indicates the high effectiveness for the sensing of even minor damage.

Increase in temperature decreases the resistivity, due to the activation energy associated with the electrons jumping across interfaces in the cement-based material [17]. In the case of fiber-reinforced cement, the fiber–matrix interface and fiber–fiber interface are relevant. In case of unreinforced plain cement paste, diffuse interfaces exist. The temperature effect means that the cement-based material serves as a thermistor.

Both elastic strain and temperature give reversible effects on the resistivity. As a result, their decoupling needs an additional means, such as an additional mean of temperature measurement.

2.2 Electrically conductive admixtures

In order to enhance the piezoresistivity of a cement-based material, an electrically conductive admixture is added. As reported in 1993 [3], short (discontinuous, e.g. 5 mm long) carbon fiber is effective as a conductive admixture. When the fiber content is in the vicinity of the percolation threshold [21–23], the resistivity is particularly low and the piezoresistivity is particularly strong, so that the resistivity changes greatly with the strain. The use of fiber volume fractions above the percolation threshold is not recommended, due to the reduced sensing effectiveness and higher cost. For carbon fiber cement-based materials, the fiber content of 0.5% by mass of cement is effective. Although the sensing
effectiveness is greater at a fiber content of 1.0% by mass of cement, the cost is much increased [1]. A fiber content of 0.50% by mass of cement corresponds to 0.53 vol.% in case of cement paste, 0.24 vol.% in the case of mortar, and 0.19 vol.% in the case of concrete [24].

Conductive admixtures can be in the form of short fibers or particles. An example of particles is carbon black, which is more attractive than most other particles due to its low cost [25,26], though it delays the hydration and hardening of the cement [27]. Another example is carbon black rubber-matrix composite particles of size comparable to that of sand [28]. The aspect ratio of a fiber is much greater than that of a particle. The large aspect ratio of the conductive fiber enables the percolation threshold to be low, so that the required fiber volume fraction is low. A low fiber content is beneficial for lowering the material cost and reducing the air void content, which tends to increase with increasing fiber content. The fiber addition improves the tensile properties and tends to degrade slightly the compressive properties due to the increased air void content. Furthermore, the fiber addition decreases the workability of the cement mix, with the workability decreasing with increasing fiber content. For these reasons, it is desirable to minimize the fiber content. The synergistic use of particles (e.g., carbon black) and fiber (e.g., carbon nanotube) is attractive [29].

The environmental impact in terms of the greenhouse gas emission during the manufacture of materials is of increasing concern. Due to the large negative impact of cement production, the impact of the carbon filler production is negligible in comparison, as shown for carbon in the form of graphite nanoplatelet [30].

Conductive admixtures have a further problem of their dispersion in the cement mix. The smaller is each unit of the admixture, the more challenging is the dispersion. For example, carbon nanofibers and carbon nanotubes are more difficult for dispersion than carbon fibers, which have diameter in the micrometer scale. The addition of silica fume to the cement mix helps the dispersion, due to the fine particulate nature of silica fume helping to loosen the clumps of the conductive admixture as mixing takes place [31]. In addition, the silica fume causes the pores in the cement-based material to be small, thus reducing the water permeability and improving the corrosion resistance of the steel that may be embedded in the cement-based material. Although the conductive admixture increases the conductivity of the cement-based material, the decrease in water permeability due to the silica fume causes the corrosion resistance to be adequate, even in the presence of the conductive admixture.

The combined use of silica fume (15% by mass of cement) and methylcellulose (dissolved in water, 0.4% by mass of cement) is more effective for promoting the fiber dispersion than the use of silica fume without methylcellulose, as shown by the lower resistivity and greater resistance-based sensitivity to damage [24]. The use of latex (20% by mass of cement) in place of silica fume and/or methylcellulose is relatively expensive and gives relatively low values of the gage factor [4,5]. The combined use of latex and silica fume is not effective.

Surface treatment of the carbon fiber to enhance it hydrophilicity also helps the fiber dispersion [32,33]. Ozone treatment imparts oxygen-containing functional groups on the surface of the carbon fiber, thereby enhancing the hydrophilicity [32]. Silane treatment is also effective for enhancing the hydrophilicity, though it is expensive. The use of silane treatment after the ozone treatment enhances the tensile strength and modulus and decreases the air void content [33].

Sonication is most commonly used for dispersing nanoscale admixtures such as carbon nanotube [34–36], but it is not practical for field application. The growth of carbon nanotubes
on the surface of cement particles is a method of dispersion that is very expensive, due to the elevated temperature and controlled atmosphere required for the growth [37]. A related method involves the coating of sand particles with carbon nanotubes [38], though this method suffers from the fact that sand is a major ingredient in concrete and the transportation of the specially modified sand from the city where the modification takes place to the city of the construction will add to the cost. Yet another method of fiber incorporation involves the manual placement of the discontinuous fibers in the form of layers that are sandwiched by the cement mix, as shown for conductive rubber fibers with diameter in the millimeter range [39], but this method is not practical in the field.

Carbon nanotubes have received much more attention than carbon nanofibers (originally known as carbon filaments), partly because of the fame of the former. The latter is less expensive, though typically larger in diameter. For example, the diameter of carbon nanofiber is 60–150 nm, and that of carbon nanotube is 20–40 nm; the length is comparable for nanofiber and nanotube, e.g. 10–100 μm [40]. The carbon layers in a nanotube are concentric cylinders, whereas those in a nanofiber commonly exhibit the fishbone morphology. This fishbone morphology is akin to a stack of ice cream cones with the tip of each cone cut off. Due to the non-axial orientation of the carbon layers, the layer edges are exposed for a nanofiber. However, the degree of crystallinity of the nanofiber depends on the heat treatment that the nanofiber has experienced. Resistance-based self-sensing has been reported for carbon nanofiber cement [41,42]. In addition, the carbon nanofiber helps resist the fracture of the cement-based material [43]. The combined use of carbon nanotube and carbon nanofiber can be attractive, due to the difference in aspect ratio and cost [40].

Low cost is critical to the commercial viability of a cement-based material. Carbon fibers with typical diameter around 10 μm are much less expensive than carbon nanofibers or carbon nanotube. The effectiveness of recycled carbon fibers for resistance-based sensing adds to the economic attraction of using carbon fibers [44]. The use of carbon fiber cement as embedded sensors in a concrete structure is another approach for reducing the cost [45].

In the absence of a conductive admixture, the strain-sensing performance is less satisfactory, as shown by comparing Figure 1a and b [4], and by the lower signal-to-noise ratio [46]. However, damage sensing, which tends to be less demanding than strain sensing, can be feasible, as shown by the resistance-based sensing of the damage during freeze-thaw cycling in the absence of a conductive admixture (Figure 2) [47]. Both temperature sensing and damage sensing are demonstrated in Figure 2, with the decrease in temperature causing an increase in the resistivity (due to the thermally activated nature of the charge movement associated with the conduction) and damage causing a slight irreversible increase in the resistivity after a cycle. Resistance-based damage sensing in the absence of a conductive admixture has also been shown during static and cyclic loading [48,49]. The presence of alkali-activated slag can enhance the sensing effectiveness in the absence of a conductive admixture [50].

In the absence of a conductive admixture, the conduction mainly involves ions (rather than electrons) and the resistivity is consequently strongly affected by the moisture content. The dependence on the moisture content complicates the sensing application. In contrast, in the presence of a conductive admixture at a volume fraction in the vicinity of the percolation threshold, the electrical conduction involves mainly electronic conduction [51], thereby greatly reducing the moisture dependence. The effect of moisture on the sensing effectiveness is small [24], although the moisture dependence is not eliminated [52].
Figure 1. Effect of tensile strain at progressively increasing amplitude. Solid curve: fractional change in resistivity. Dashed curve: longitudinal strain. (a) Longitudinal resistivity of cement paste with ozone-treated short carbon fiber (0.5 vol.%). The ozone treatment enhances the fiber-matrix bond and the fiber dispersion. (b) Longitudinal resistivity of cement paste without any conductive admixture. (c) Transverse resistivity of cement paste with ozone-treated short carbon fiber (0.5 vol.%). The transverse strain is compressive (hence negative) [4].
2.3 Sensing characteristics

The effectiveness of resistance-based sensing has been shown for carbon fiber cement-based materials under compression, tension, and flexure. Under uniaxial tension or compression, the volume resistance is measured \([4,5]\). The resistance increases upon tension and decreases upon compression. The effect is highly reversible upon unloading, as shown in Figure 1(a) for cement paste with carbon fiber under tension. Without a conductive admixture, the resistance change is much smaller and less reversible (Figure 1(b)). Under flexure, the surface resistance is measured on the compression surface and tension surface of the beam separately by using electrical contacts that are on the two surfaces [7]. The surface resistance of the tensile surface increases upon flexure, while that of the compression surface decreases upon flexure.

The degree of piezoresistivity is described by the gage factor, which is defined as the fractional change in resistance (not resistivity) per unit strain, with the strain being positive for elongation (uniaxial tension or longitudinal tension under flexure) and being negative for contraction (uniaxial compression or longitudinal compression under flexure). In the absence of the resistivity changing with strain, the resistance still changes with strain, due to the effect of the dimensions on the resistance. However, in the absence of the resistivity changing with strain, the gage factor is around 2, with the exact value...
depending on the Poisson’s ratio. In the presence of the resistivity changing with strain, the gage factor can exceed 2 greatly.

Piezoresistivity refers to the phenomenon in which the resistivity changes reversibly with strain. Therefore, the gage factor should be determined under the condition of reversible change in the resistivity upon stress/strain application. In other words, it should be determined in the elastic deformation regime. The gage factor would be much higher if the deformation is in the plastic or damage regime and thus should not be considered as the true gage factor. In order to ensure that the resistivity change is reversible upon unloading, the resistance measurement should be conducted upon loading and subsequent unloading at progressively increasing strain amplitudes, rather than measuring the resistance upon static loading up to failure.

For carbon fiber cement, the gage factor is positive under both uniaxial compression and uniaxial tension in the longitudinal direction (i.e., with the resistance and strain in the same direction) [4,5]. Note that this corresponds to the longitudinal resistance decreasing upon compression (positive gage factor) and increasing upon tension (also positive gage factor). However, unexpectedly, the transverse resistance (perpendicular to the uniaxial stress direction) also decreases upon compression (negative gage factor due to the transverse strain being opposite in sign from the longitudinal strain) and increases upon tension (also negative gage factor) (Figure 1(c)) [5]. This suggests that the volumetric shrinkage due to the uniaxial compression causes the resistance in both longitudinal and transverse directions to decrease, whereas the volumetric expansion due to the uniaxial tension causes the resistance in both longitudinal and transverse directions to increase. The magnitude of the gage factor is greater under compression than tension, whether the longitudinal or transverse resistance change is considered. For example, with carbon fiber cement containing silica fume (which helps the fiber dispersion), the longitudinal gage factor is 350 under compression [5] and 89 under tension [4]. Under flexure, the surface resistance changes more on the compression surface than the tensile surface [24], as expected based on the abovementioned results under uniaxial compression and uniaxial tension [4,5]. In relation to damage sensing, the stress/strain for the onset of irreversible resistance increase is greater under compression than tension [24], as expected from the well-known fact that damage under tension occurs more easily than damage under compression for a brittle material. In relation to elastic strain sensing, the gage factor decreases with increasing strain [53], but the effect of damage on the gage factor has not been reported [53–55]. Nevertheless, the strain-sensing ability remains strong even at the end of the fatigue life [55].

Steel fiber with diameter in the micrometer scale is also effective as a conductive admixture for rendering strain-sensing ability [56], but it is more expensive than carbon fiber. Steel fibers with diameter in the millimeter range are much less effective than those with diameter in the micrometer range for decreasing the electrical resistivity and for providing strain sensing. However, they can provide damage sensing and the use of carbon black, carbon fiber and/or carbon nanotube together with such steel fibers helps [57–60].

Steel rebars are more widely used than any type of steel fiber for reinforcing concrete. In contrast to the steel fibers, the rebars are continuous and large in diameter. The presence of the rebars would not interfere the resistance-based self-sensing of the concrete, if the surface resistance rather than the volume resistance is measured [7]. This is because the depth of penetration of the surface current is limited, and, as a consequence, the surface
current would not reach the rebars embedded in the concrete. The surface resistance determined by using the surface current is useful for sensing flexural strain and damage.

Carbon fiber-reinforced cement is also effective as a strain-sensing coating [61]. The self-sensing ability rendered by the carbon fiber admixture remains in the presence of steel rebars [7].

2.4 Measurement techniques

The use of the four-probe method is much more reliable than the two-probe method for measuring the resistance [8]. In the four-probe method, four electrical contacts are used, with the outer two for passing current and the inner two for measuring the voltage. In the two-probe method, two electrical contacts are used, with each contact used for both current passing and voltage measurement. The superiority of the four-probe method is due to the contact resistance essentially excluded from the measured resistance. In contrast, the contact resistance is included in the contact resistance in the two-probe method. The contact resistance can change during strain application. By using an array of contacts, with the outermost two contacts used for passing current and the inner contacts used two at a time for measuring the voltage, spatially resolved sensing can be performed [62]. Resistivity tomography can be performed by using a two-dimensional or three-dimensional array of contacts [63].

The measured resistance can be DC or AC. The DC method is advantageous for its greater degree of current penetration, while the AC method is advantageous for the lower degree of electric polarization. Polarization refers to the movement of charges (e.g., ions) so that an electric dipole is formed. Polarization occurs during resistance measurement, which involves the application of a small current provided by the measurement meter for the duration of the measurement. The longer is the time of the measurement, the more is the polarization. Depolarization occurs upon reversal of the polarity of the current. The dipole impedes conduction, thus causing the measured resistance to be higher than the true resistance. In order to measure the true resistance, the resistance should be measured within the first few seconds of resistance measurement, before polarization becomes appreciable. Alternatively, the current polarity can be reversed and the average of the measured resistance immediately before the reversal and that immediately after the reversal gives the true resistance [64,65] (Figure 3). In both DC and AC methods, the removal of the contact resistance from the measured resistance is important. The AC resistance is to be distinguished from the AC impedance, which is a complex quantity that reflects both the real part (resistance) and imaginary part (reactance).

2.5 Sensing mechanism

In spite of the self-sensing effectiveness of short carbon fiber cement-based materials (Sec. 2.4), continuous carbon fiber cement-based materials are not effective for sensing [66], though they are effective as a reinforcement in the form of a fabric [67]. This is partly because of the difficulty of the cement paste to enter the small space among the fiber in the same tow (bundle). Furthermore, the fabrication of the continuous fiber cement-based materials is complicated with the infeasibility of incorporation of the continuous fiber by mixing. In addition, continuous fibers are more expensive than the corresponding short fibers.
The mechanism behind the piezoresistivity in short carbon fiber cement involves the slight loosening of the fiber–matrix interface upon tension and the consequent increase in the interface resistivity [68,69]. The interface resistivity increase results in an increase in the volume resistivity. The opposite occurs upon compression. The effect of damage on the resistivity has been modeled using a resistor mesh model [70].

3. Capacitance-based self-sensing

3.1 Sensing characteristics

The first report of capacitance-based self-sensing of cement-based materials concerns this ability of carbon fiber cement [71]. The report was made by the author’s research group in 1997 and shows that compressive damage increases the magnitude of the reactance (the imaginary part of the complex impedance), i.e. decreasing the capacitance. Consistent with this observation is the report in 2017 that the electric permittivity (material property that relates directly with the capacitance) decreases when the cement-based material is artificially made defective by the incorporation of porous gypsum pellets [72]. The permittivity also decreases with increasing aggregate proportion in the cement-based material [73], meaning that the cement paste rather than the aggregates play the dominant role in affecting the permittivity.

The first report of the effect of stress/strain on the permittivity of cement-based materials occurs in 2002 [74]. In this report made by the author’s research group, the permittivity in the stress/strain direction (measured using sandwiching electrodes) increases with increasing compressive stress/strain for both plain cement paste and cement paste with carbon fiber. Consistent with this trend is the decrease in the capacitance in the transverse direction (measured using coplanar electrodes, which are more
practical than sandwiching electrodes) upon compression in the axial direction, as observed for plain cement paste (Figure 4) [75,76]. Due to the Poisson’s effect, axial compression is associated with transverse compression.

Figure 4 shows that, in the low-stress regime, the capacitance change is completely reversible, but is not completely reversible in the high-stress regime. This suggests that the high-stress causes a degree of damage, thus causing a degree of irreversibility in the capacitance change. As shown in Figure 4(b) for the low-stress regime, the smallest stress change detected is 0.2 kPa (i.e. the increase in stress from 3.4 to 3.6 kPa). This is at least as sensitive as the highest sensitivity provided by the resistance-based stress sensing of carbon fiber cement [1].

The effect of stress/strain on the permittivity is known as piezopermittivity, which is to be distinguished from the direct piezoelectric effect. The piezoelectric effect involves a change in charge rather than a change in permittivity due to the stress or strain. However, this distinction is often not made in the literature.

The permittivity of cement paste (whether plain or one containing carbon fiber) increases with increasing temperature [77]. This is probably due to the increasing mobility of the ions as the temperature increases. The effect of temperature on the permittivity is known as pyropermittivity, which allows capacitance-based temperature sensing. Pyropermittivity differs from the pyroelectric effect, which involves the charge rather than the permittivity changing with temperature. However, this distinction is often not made in the literature.

### 3.2 Measurement techniques

The measurement of the permittivity is complicated by the contribution of the interfacial capacitance at each electrode to the measured capacitance. The volume capacitance of the cement-based material is in series with the two interfacial capacitances, whether the electrodes are sandwiching or coplanar. In case of sandwiching electrodes, the capacitance is perpendicular to the plane of the cement-based material (i.e., perpendicular to the plane of the electrodes). However, in case of coplanar electrodes, the capacitance is in the plane of the cement-based material. According to the well-known equation for capacitors in series,

$$\frac{1}{C_m} = \frac{1}{C} + \frac{2}{C_i} \tag{1}$$

where $C$ = the cement-based specimen volumetric capacitance, and $C_i$ = the interfacial capacitance for one interface. The relative permittivity $\kappa$ of the cement-based specimen is related to $C$ by the equation

$$C = \varepsilon_o \kappa A/l \tag{2}$$

where $\varepsilon_o$ = the permittivity of free space ($8.85 \times 10^{-12}$ F/m), $l$ = the inter-electrode distance (L, 2 L or 3 L), and $A$ = the area of the specimen in the plane perpendicular to the direction of capacitance measurement. Combining Eq. (1) and (2) gives

$$\frac{1}{C_m} = \frac{l}{(\varepsilon_o \kappa A)} + \frac{2}{C_i} \tag{3}$$

The lower is $C_i$, the more influential is $C_i$. A plot of $1/C_m$ vs. $l$ gives a line of slope equal to $1/(\varepsilon_o \kappa A)$. From the slope, $\kappa$ is obtained [78].
Figure 4. Effect of the applied normal compressive loading at progressively increasing stress amplitude, with the baseline stress level being 3.4 kPa. The dashed curve gives the stress; the solid curve gives the capacitance. (a) High-stress regime. (b) Low-stress regime [75].
In an alternate method $l$ is fixed but $A$ is varied. Since the different parts of the area are capacitances in parallel, the measured capacitance $C_m$ is given by

$$C_m = (\varepsilon_o \kappa A/l + C_o,$$  \hspace{1cm} (4)

where $C_o$ is the capacitance at $A = 0$. The higher is $C_o$, the more influential is $C_o$. Hence, a plot of $C_m$ vs. $A$ gives a line of slope equal to $(\varepsilon_o \kappa)/l$. From the slope, $\kappa$ is obtained [78]. This alternate method is easier to implement on a structure than the first method [72, 73, 75], as it can be implemented by using two electrode strips, with each strip divided into squares along the length of the strip, and with the number of squares used for each strip used to give different areas.

In case that the cement-based material is not highly conductive and the electrodes are smaller is area that the cement-based specimen, fringing electric field is substantial and causes the measured $\kappa$ to be too high. Although this value is not the true $\kappa$, but the apparent value, the fractional change in the apparent $\kappa$ is still meaningful when the effect of stress/strain, damage, or temperature is investigated [78].

In case that the cement-based specimen is conductive, a dielectric film should be positioned between the electrode and specimen. This is because an LCR meter is not designed for measuring the capacitance of a low-resistance material system. The effect of the dielectric film on $C_m$ is included in $C_i$ or $C_o$, so it does not affect the determination of $\kappa$ from the slope. Measurement of the capacitance of a low-resistivity cement-based material without a dielectric film tends to result in incorrectly high values of $\kappa$ [79].

Although the measurement of $\kappa$ is valuable for basic scientific understanding, the measurement of $C_m$ without determining $\kappa$ is still meaningful for the purpose of sensing, particularly in case that $C_i$ (Eq. (3)) or $C_o$ (Eq. (4)) is not affected by the stimulus (e.g., the stress), i.e., the electrodes do not experience the stimulus that the specimen experiences. By using coplanar electrodes, the stress can be applied to the specimen in the region away from the electrodes [72, 73, 75]. The capacitance-based sensing results obtained by using coplanar electrodes show $C_m$ (Figure 4), which is highly sensitive to the stress. Sensing involving $C_m$ measurement is simpler and easier to implement than sensing involving $\kappa$ measurement.

### 3.3 Functional admixtures

Functional admixtures are not required for capacitance-based sensing. They are not present in the main results presented in Sec. 3.1, particularly in Figure 4. Not requiring particular admixtures means that the sensing technology is applicable to both existing and new structures.

Cement-based materials are rendered piezoelectric by the incorporation of piezoelectric components, such as lead zirconotitanate (PZT) particles [80–86]. The piezoelectric behavior of the composite is derived from the admixture rather than the cement itself. The direct piezoelectric effect allows stress/strain sensing by sensing the voltage or current output. However, in order for these cement-based materials to be piezoelectric, they need to be poled by the application of a high electric field. The poling of a large structure is not feasible. Furthermore, depoling naturally occurs after poling. As a consequence of the depoling, repoling is necessary.
4. Comparison of resistance-based sensing and capacitance-based sensing

The sensitivity of stress/strain sensing is comparable for resistance-based sensing using carbon fiber cement and capacitance-based sensing using plain cement. Tomography can be conducted for the resistance as well as the capacitance. However, the capacitance-based sensing is more dependent on the moisture in the cement-based material than the resistance-based sensing. The main attraction of capacitance-based sensing over resistance-based sensing pertains to the absence of requirement for a particular admixture. Not requiring a particular admixture means that the sensing technology is applicable to both existing and new structures.

Resistance measurement requires the electrodes to be in intimate contact with the cement-based material. However, electrodes for capacitance measurement do not have to be in intimate contact with the cement-based material. For example, a dielectric film in the form of double-sided adhesive tape is positioned between the aluminum foil electrode and cement-based material surface for the purpose of capacitance measurement [75,76]. In contrast, a conductive paint (e.g. silver paint [4,5]) is needed to achieve an intimate contact for resistance measurement. The use of pressure in the absence of a conductive paint gives an electrical contact with a relatively high contact resistance [87].

5. Conclusions

Self-sensing uses the cement-based material without sensor incorporation to sense itself. It is advantageous to sensing by using embedded or attached sensors in the low cost, high durability, large sensing volume and the mechanical properties being not reduced. The attributes sensed include stress/strain, damage and temperature.

This paper reviews self-sensing cement-based materials, with coverage of the well-studied resistance-based sensing as well as the less-studied capacitance-based sensing. This review is the first that covers capacitance-based self-sensing. In addition to the self-sensing results, this review covers the methodology of the resistance and capacitance measurements.

Capacitance-based sensing is advantageous over resistance-based sensing in that no particular admixture is required, so that it is applicable to both existing and new structures. In contrast, resistance-based sensing that is comparable to capacitance-based sensing in stress/strain sensing effectiveness requires conductive admixtures, such as carbon fiber. The conductive admixture increases the cost and decreases the workability.

Stress/strain sensing and damage sensing have received more attention than temperature sensing. Resistance-based strain sensing is based on piezoresistivity, which is associated with the resistance increasing upon tension and decreasing upon compression. Capacitance-based strain sensing is based on piezpermittivity, which is associated with the permittivity decreasing upon tension and increasing upon compression. Damage causes the resistance to increase and causes the permittivity to decrease. Increase in temperature decreases the resistance but increases the permittivity.

Disclosure statement

No potential conflict of interest was reported by the author.
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