Revista ALCONPAT
www.revistaalconpat.org
eISSN 2007-6835
Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción

Multifunctional conductive concretes: advances, applications, and challenges for smart infrastructure.

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DOI: https://doi.org/10.21041/ra.v16i1.876

Received: 15/07/2025 | Received in revised form: 24/11/2025 | Accepted 08/12/2025 | Published: 01/01/2026

ABSTRACT

This article presents the foundations and evolution of research into the main functionalities developed using conductive cementitious materials. Multifunctional conductive concrete represents an innovation in the field of cement-based materials, exhibiting not only structural capabilities but also electrical, thermal, and sensing functions. The addressed functions are: a) strain and structural damage sensing in a load bearing structure without the need for any attached or embedded sensor; b) heating and de-icing function through the Joule effect, for applications such as surface de-icing or building heating; and c) electromagnetic interference (EMI) shielding provided by the conductive structure itself.
Keywords: conductive concrete, multifunctionality, piezoresistivity, heating and defrosting, shielding.

Cite as: Garcés Terradillos1, P., Galao, O., Ubertini, F. (2026), *"Multifunctional conductive concretes: advances, applications, and challenges for smart infrastructure."*, Revista ALCONPAT, 16 (1), pp. 23 – 41, DOI: https://doi.org/10.21041/ra.v16i1.876

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Contribution of each author
In this work, Garcés contributed 50% to the original idea, data collection, manuscript writing, discussion, and conclusions. Galao and Ubertini contributed 25% each to the same activities.

Discussions and subsequent corrections to the publication
Any dispute, including the replies of the authors, will be published in the third issue of 2026 provided that the information is received before the closing of the second issue of 2026.

Hormigones conductores multifuncionales: avances, aplicaciones y desafíos para una infraestructura inteligente.

RESUMEN

Este artículo plantea el fundamento y evolución en la investigación desarrollada de las principales funciones desarrolladas con materiales cementicios conductores. Los hormigones conductores multifuncionales representan una innovación en el campo de los materiales cementicios, con capacidades no solo estructurales, sino también eléctricas, térmicas y como sensor. Las funciones planteadas son: a) Función de percepción de la deformación y del daño estructural de una estructura al estar sometida esfuerzos, sin llevar algún sensor adherido o embebido en él mismo. b) Función de calefacción y deshielo por efecto Joule para aplicaciones como deshielo o calefacción en edificaciones. c) Función de apantallamiento de campos electromagnéticos (EMI) de la propia estructura conductora.

Palabras clave: hormigón conductor, multifuncionalidad, piezorresistividad, calefacción y deshielo, apantallamiento.

Concretos condutores multifuncionais: avanços, aplicações e desafios para uma infraestrutura inteligente.

RESUMO

Este artigo apresenta os fundamentos e a evolução das pesquisas sobre as principais funcionalidades desenvolvidas com materiais cimentícios condutivos. Concretos condutivos multifuncionais representam uma inovação no campo dos materiais cimentícios, apresentando não apenas capacidades estruturais, mas também propriedades elétricas, térmicas e sensoriais, atuando como materiais auto-sensores. As funções propostas são: a) Função de percepção de deformações e danos estruturais: capacidade de detectar deformações e danos em uma estrutura submetida a esforços, sem a necessidade de sensores aderidos ou embutidos no material. b) Função de aquecimento e degelo por efeito Joule: utilizada em aplicações como aquecimento resistivo (por exemplo, degelo ou aquecimento de edificações e infraestruturas). c) Função de blindagem contra interferência eletromagnética (EMI): baseada no efeito de blindagem que a própria estrutura condutiva exerce sobre o campo eletromagnético que a atravessa.

Palavras-chave: concreto condutivo, multifuncionalidade, piezorresistividade, aquecimento e descongelamento, blindagem.

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1. INTRODUCTION

For nearly 2,000 years concrete has served primarily as a structural material, valued chiefly for its load-bearing capabilities. As a dielectric material—i.e., a poor conductor of electricity—the addition of conductive elements such as carbon fibers, graphite powder, or steel fibers transforms it into a conductive material. This transformation enables the material to perform functions beyond the purely structural one, allowing it to become multifunctional. Among the possible functionalities of conductive cementitious materials, the following can be highlighted:

a) **Strain sensing** in the elastic regime of a structure subjected to external loads, without the need for any externally attached or embedded sensor (D'Alessandro et al. 2016).

b) **Structural damage sensing**, enabling real-time detection and the ability to differentiate between stationary, progressive, permanent, or reversible damage (Baeza et al. 2013; Chung 2024; Galao et al. 2014; Konsta-Gdoutos and Aza 2014).

c) **Heating and de-icing function** by resistive heating (e.g., for de-icing and heating in buildings and infrastructures) (Anur Oumer et al. 2024; D.D.L. Chung 2004; Yehia and Tuan 1999).

d) **Electromagnetic interference (EMI) shielding**, based on the shielding effect that a conductive structure exerts on electromagnetic fields passing through it (Chung 2000; Kumar et al. 2021; Zornoza et al. 2010).

e) **Anodic function for electrochemical chloride extraction and cathodic protection**, using a conductive cement paste that serves as the anode in electrochemical chloride extraction and cathodic protection applications (Bertolini et al. 2004; Carmona, Garcés, and Climent 2015; Pérez, Climent, and Garcés 2010; Tritthart 1998; Vennesland and Opsahl 1989).

Cementitious materials have received considerable attention due to their mechanical properties and their importance as structural materials. However, there is a growing recognition of the need for structural materials that can incorporate non-structural functionalities while retaining favorable mechanical performance. The use of a multifunctional structural material—i.e., one that integrates non-structural functional capabilities—rather than a combination of non-functional structural materials and non-structural functional materials, results in cost reduction, improved durability and reparability, increased functional volume, prevention of mechanical degradation, and simplified design (Chung 2024).

Multifunctional conductive concrete has been developed in response to the need for structural materials capable of actively interacting with their environment. This capability is achieved through the incorporation of conductive additives into the cementitious matrix, allowing the concrete not only to bear structural loads, but also to transmit electrical signals, generate heat, or work as a sensor for Structural Health Monitoring (SHM) applications. This multifunctionality positions it as a key component in the development of smart and resilient infrastructure (Qin et al. 2024). However, its large-scale implementation still faces significant challenges, such as the high cost of nanostructured materials, the need for wired electrodes and the difficulty of achieving uniform dispersion of conductive fillers (see Figure 1).

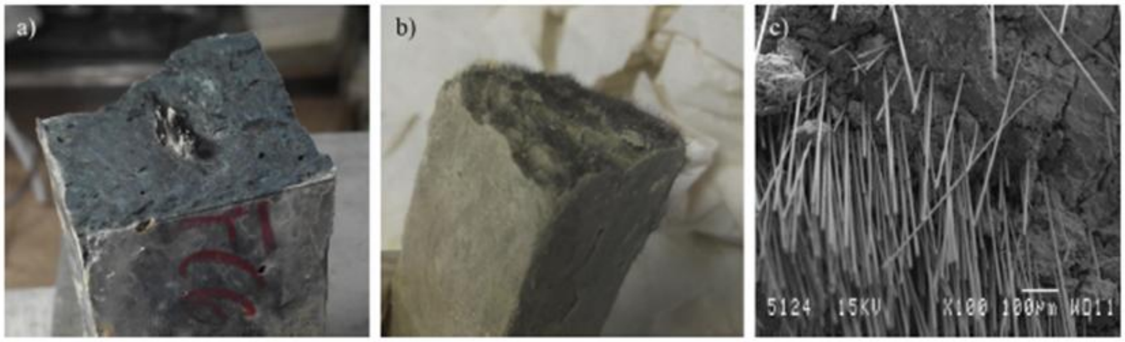

Figure 1. (a) Fiber agglomeration due to poor dispersion. (b) Specimen with preferential fiber alignment along the longitudinal axis. (c) SEM image of an alkali-activated cement paste with carbon fibers (Vilaplana et al. 2016).

Nevertheless, advances in materials research and construction processes offer a promising outlook for the adoption of these technologies. The development of such materials is expected to impact a wide range of industries, including construction, heating, energy transportation, power generation, telecommunications, electronics, and safety (Segundo et al. 2021; Song, Li, and Xu 2024).

2. PIEZORESISTIVITY IN CONDUCTIVE CEMENTITIOUS MATERIALS: STRAIN AND DAMAGE SENSORS.

The strain sensing function refers to the ability of a structural material to detect its own deformation when subjected to external loads. Strain perception (which is related to, but distinct from, stress or damage detection) is particularly relevant for applications such as structural vibration control, SHM or traffic monitoring and management.

Conventional applications of stress or strain sensors range from components in the aerospace or automotive industries to sensors for civil engineering structures, such as viaducts, and even weigh-in-motion sensors for highway traffic that do not require vehicles to stop. In the first category, small sensors are typically employed (usually based on cement pastes or mortars), which must compete with silicon pressure sensors. In other cases, larger sensors can be used (e.g., prefabricated concrete or mortar elements), competing with acoustic, silicon-based, pneumatic, or inductive sensors (Baeza et al. 2011; Ivorra et al. 2010; Shi and Chung 1999).

It has been observed that cementitious materials with the addition of short carbon fibers, carbon nanofibers, or carbon nanotubes can sense their own deformation (see Figure 2). This capability is made possible by variations in their electrical resistivity (Camacho-Ballesta et al. 2016). Laboratory tests have shown that under tensile stress, resistivity increases due to the formation of microcracks or even the pull-out of fibers from the matrix (Han, Ding, and Yu 2015). Conversely, when the material is subjected to compressive stress, the opposite effect occurs: resistivity decreases, which is associated with the re-bridging of fibers as the microcracks close. This electromechanical phenomenon is known as piezoresistivity, and it enables the use of electrical resistance measurements (both DC and AC) to monitor the strain state of specimens, with the cementitious material itself functioning as a strain sensor.

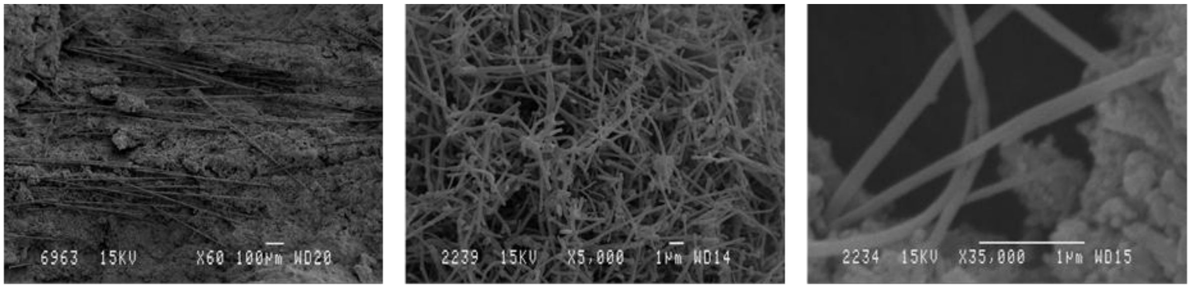

Figure 2. Images of carbon fibers (left) and carbon nanofibers (center and right) embedded in cementitious matrices.

One of the most interesting parameters in the phenomenon of strain sensing is the minimum and maximum amount of conductive material required to exhibit this behavior. The percolation threshold is defined as the minimum quantity of fibers needed to create a continuous conductive path throughout the material—that is, to ensure contact between fibers without discontinuities. Beyond this threshold, further additions of conductive material do not significantly alter the electrical conductivity of the composite. The percolation threshold is typically expressed as a percentage by weight or volume relative to the amount of cement in the mix. Before reaching this threshold, even small amounts of conductive additives cause a steep decrease in electrical resistance (see Figure 3), and the material's resistivity can, in some cases, reach values on the order of a few ohm·cm. In the case of short carbon fibers, for a given volume fraction, the percolation threshold largely depends on fiber length and aspect ratio, and it typically lies between 0.1% and 0.5% by volume. As fiber length increases, the percolation threshold decreases. Notably, it is not necessary to reach the percolation threshold to achieve strain-sensing functionality in the composite material, since high conductivity is not required to observe piezoresistive behavior (Baeza et al. 2010).

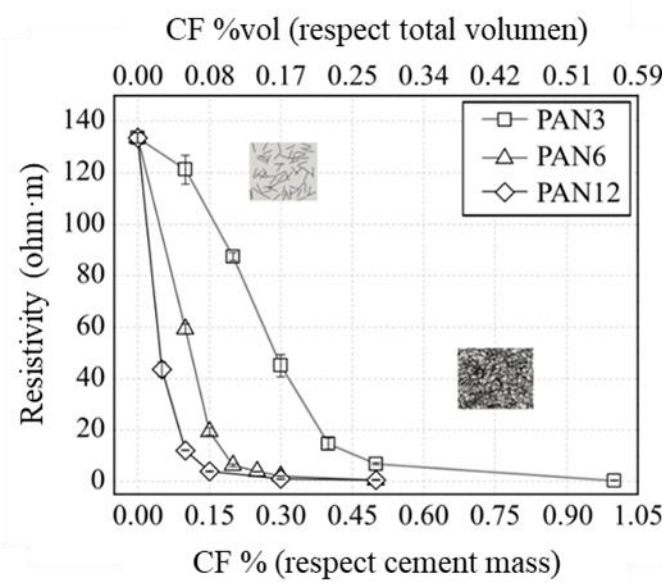

Figure 3. Detection of the percolation threshold through resistivity in a cement paste with added carbon fibers of 3 mm, 6 mm, and 12 mm in length. CF % corresponds to the percentage content of carbon fibers (CF). PAN refers to the type of carbon fiber identified by its precursor (polyacrylonitrile).

Particularly, the optimal gauge factor—defined as the strain sensitivity expressed as the relative change in resistivity per unit strain—is typically achieved near the percolation threshold. Beyond this point, the gauge factor tends to decrease as the conductive network becomes more stable and less sensitive to deformation (García-Macías et al., 2017). The fibers themselves are not sensors; rather, they boost the piezoresistivity of the composite material, which is the true sensor. Therefore, using the minimum possible amount of conductive material is always preferable, as it results in lower manufacturing costs and better workability. Figure 4 shows an example of how the electrical resistance of the conductive cementitious material correlates with the stress and strain during compressive testing in the elastic regime (del Moral et al. 2021). An almost perfect correlation between mechanical and electrical parameters is observed. This would clearly make it possible to determine the stress state of a structural element with reasonable accuracy by measuring its electrical resistance at a given moment.

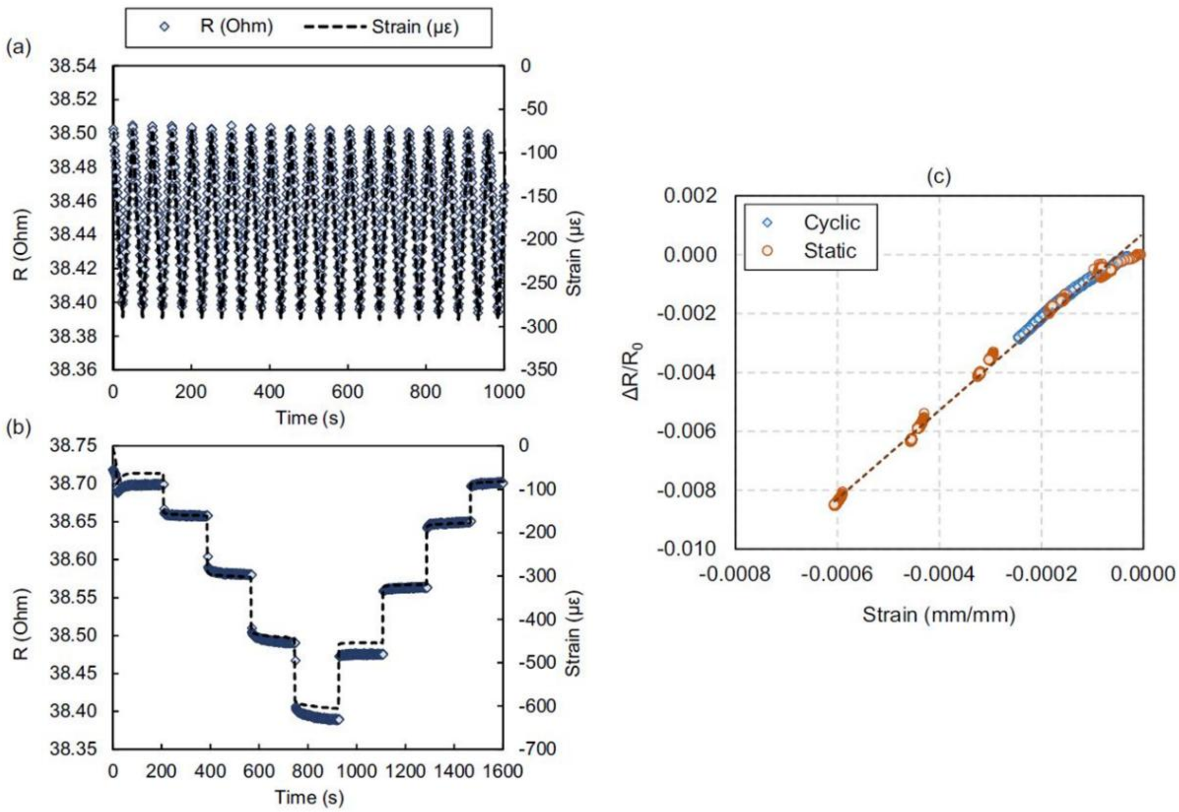

Figure 4. (left) Electrical resistance data (ohms) and applied compressive stress (MPa) as a function of time (s) in a 20-cycle loading-unloading test using cement paste specimens with a hybrid addition of carbon nanotubes and graphite powder. (right) Stress versus strain during the test (Adapted from del Moral et al., 2021).

As already mentioned, to quantify the sensing capability of the material via piezoresistive effect, the so-called gauge factor is used. Similar to traditional strain gauges (e.g., constantan or chrome-nickel), the sensitivity factor of the gauge is defined as a constant K, which is the ratio between the fractional change in resistivity and the fractional longitudinal strain of the wire when the gauge is subjected to deformation. Mathematically, the gauge factor (λ) is expressed as:

$$\lambda = \frac{\frac{d\rho}{\rho}}{\frac{dL}{L}}$$

where dρ/ρ is the fractional change in electrical resistivity, and dL/L is the axial strain in the case of 1D stress state.
The change in electrical resistance of the material under stress is due to a modification of its resistivity, meaning it is an intrinsic property of the material. This is what enables the observation of this behavior. Figure 5 presents different configurations for the application of so-called self-sensing cementitious composites (in bulk—i.e., the structural material itself acts as the sensor—with continuous sensors on the top and bottom surfaces, or with small bonded sensors), as published by Han et al. (2015).

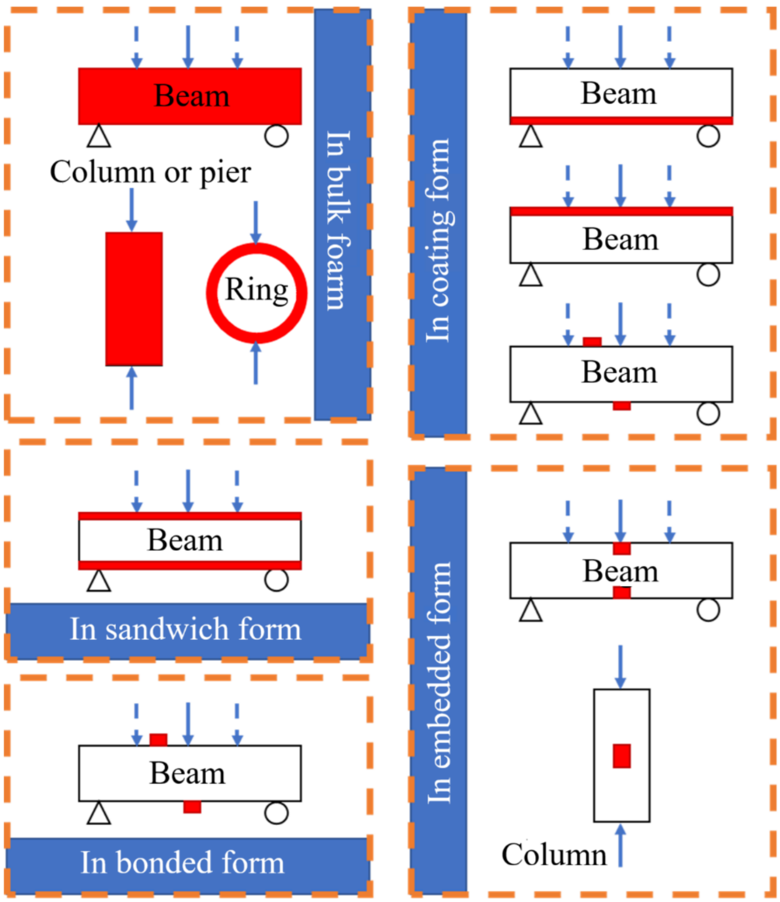

Figure 5. Application methods of self-sensing cementitious composites. (Adapted from Han, B. et al., 2015, in Elsevier).

Early detection of structural damage is a key factor in preventing major failures in infrastructure. This requires the sensing system to register damage occurring at the microscopic level within the material. Recent studies have shown that these materials can be effectively integrated with SHM technologies, thereby reducing maintenance costs and improving real-time safety (Baeza et al., 2013; Galao et al., 2014; Konsta-Gdoutos and Aza, 2014).
Several applications have been developed using conductive cement pastes as sensors in real structural elements. For instance, Garcés et al. instrumented a reinforced concrete beam with various cement paste sensors incorporating short carbon fibers (see Figure 6). A clear linear correlation between strain and electrical resistance was observed (Garcés et al., 2010).

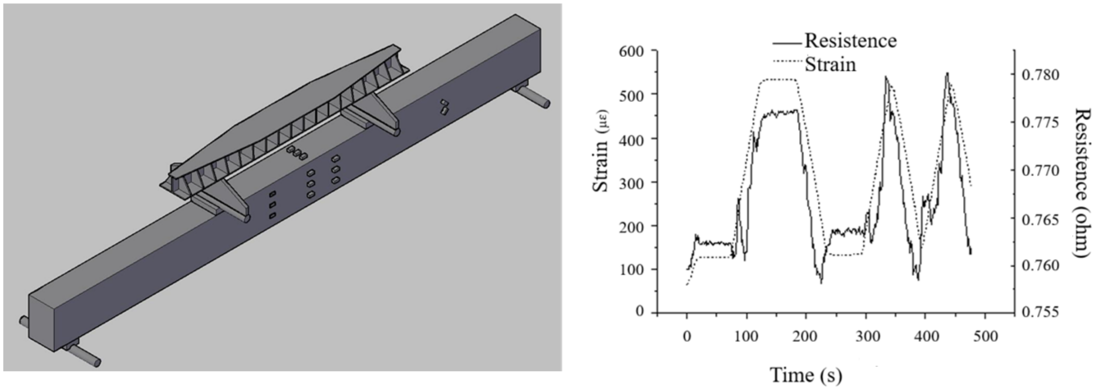

Figure 6. (left) Arrangement of conductive cement paste strain gauges on a reinforced concrete beam subjected to flexural testing. (right) Diagram showing the monitoring of strain and electrical resistance over time for one of the sensors attached to the tested beam.

As outlined in the introduction, traffic monitoring—an essential aspect of traffic management and control—requires real-time visualization, which depends on the use of strain sensors. These sensors may be optical, electrical, magnetic, or acoustic, and are typically adhered to or embedded in the roadway pavement. However, such sensors have significant limitations: (i) limited range, (ii) low durability, and (iii) high cost that restricts widespread use. Thanks to emerging technology, the pavement concrete itself can now serve as a sensor, eliminating the need for additional embedded or attached sensors. Since the structural material acts as the sensor, it becomes possible to monitor the entire infrastructure (see Figure 7) with high durability and minimal cost increase; thus, overcoming the aforementioned limitations of traditional sensor systems (Han et al., 2015; Shi and Chung, 1999, Birgin et al., 2022).

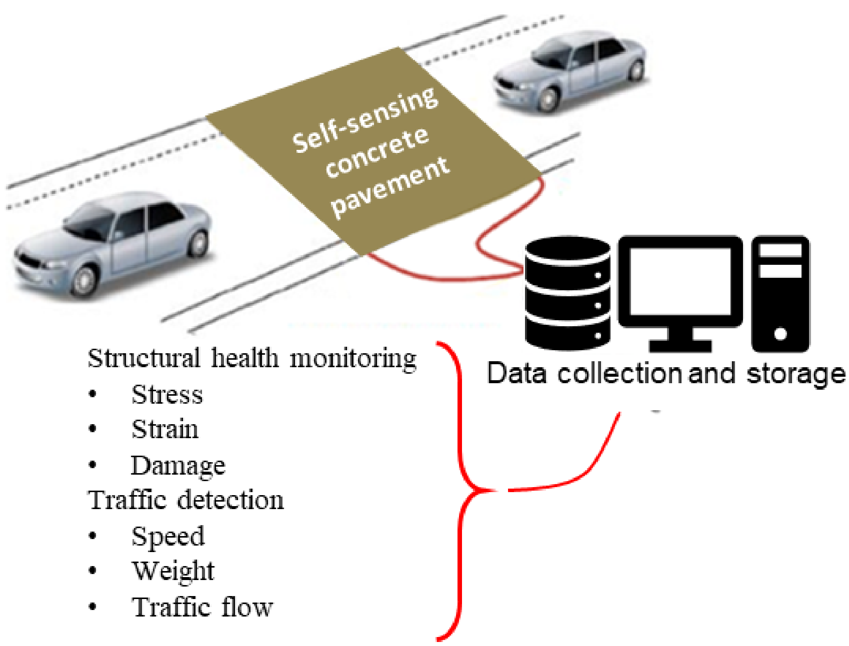

Figure 7. Schematic diagram of the application of sensing capability in concrete pavements (Adapted from Han et al., 2015).

A novel application of the sensing function was developed by García-Macías and Ubertini (2019) through the use of smart bricks to monitor masonry buildings. Similar to strain-sensitive conductive concrete, smart piezoresistive bricks incorporating special high-temperature-resistant steel fillers can function as stress sensors, as shown in Figure 8.

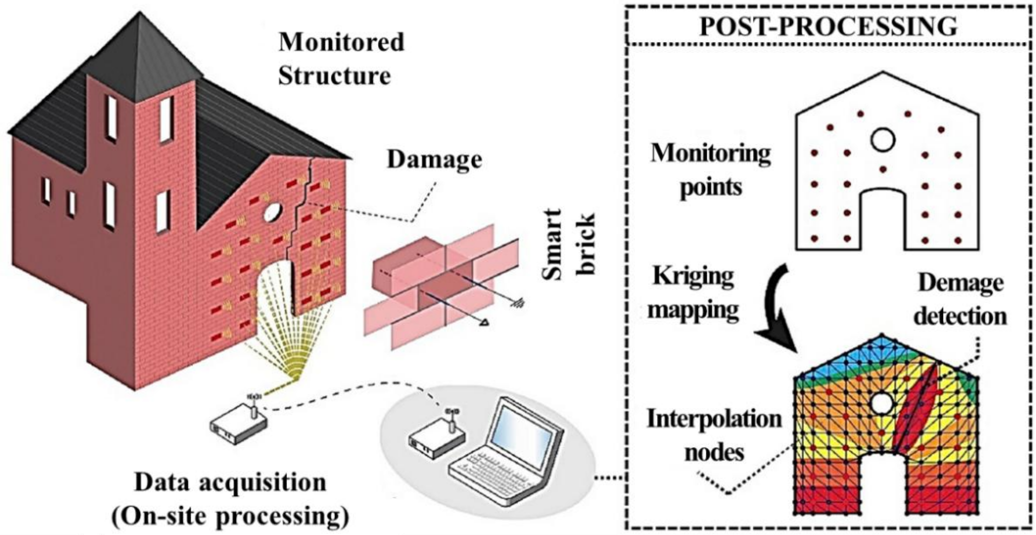

Figure 8. Application scheme of smart bricks for structural health monitoring in masonry buildings (Adapted from García-Macías and Ubertini, 2019).

Numerical simulation results confirmed the feasibility of these sensors for damage detection in both new and existing buildings, which is of particular interest for the preservation of historical masonry structures (Downey et al., 2018; García-Macías and Ubertini, 2019). Recently, a field validation on a full-scale masonry building has further confirmed the effectiveness of smart bricks for SHM purposes under real world environmental conditions (Meoni et al., 2025).

3. HEATING AND DEICING FUNCTION.

One of the most promising capabilities of cement-based conductive materials is their heating function. The temperature increase is based on the Joule effect when an electric current is applied, wherein heat is generated by the flow of current through a conductor. The heating capacity of electrically conductive cement-based materials is associated with their electrical resistance, as described by Joule's First Law (Anur Oumer et al., 2024; Park et al., 2024). By controlling the supplied electric power, the temperature of the composite can be regulated (see Figure 9). When applied to structural materials, this principle allows the material itself to melt ice on its surface—or prevent its formation (Farcas et al., 2021).

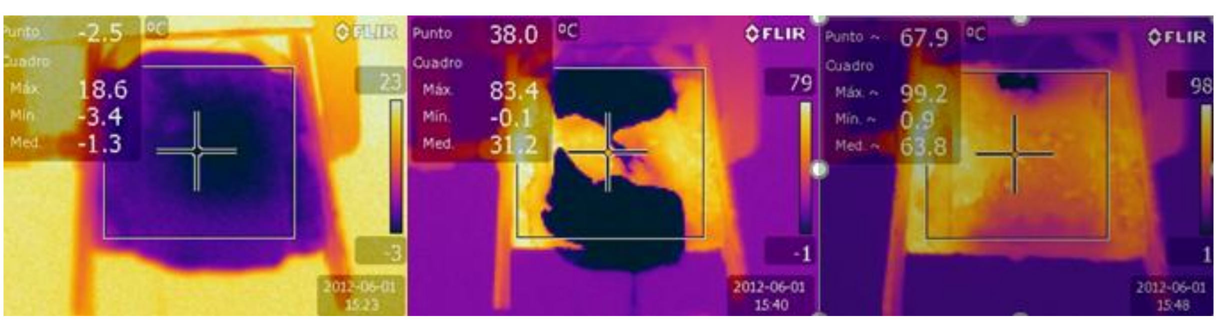

Figure 9. Temperature evolution control using thermographic imaging.

Traditional building heating systems include underground piping, infrared heating lamps, heated fluids, and solar energy. However, these systems often pose complex installation requirements, high costs, and low integration with the original structure, limiting their applicability. In contrast, multifunctional cement-based composites exhibit high structural integrity with existing cementitious structures (see Figure 10). That is, damage caused by thermal expansion during heating is negligible, since their thermal expansion coefficient is similar to that of conventional cementitious materials (D.D.L. Chung, 2004a).

Figure 10. Real-world application of deicing using conductive pavements
(Adapted from Tuan and Yehia, 2004).

Using such materials to increase surface temperature in transportation infrastructures such as bridges or airports—could eliminate the need for corrosive salts that damage steel reinforcement, concrete, and the surrounding environment. These materials can therefore be applied to raise ambient temperatures in indoor spaces or to prevent ice formation and promote deicing in civil engineering infrastructure.

Initial studies on this topic (Chung, 2004b; Yehia and Tuan, 1999) highlighted the potential of conductive cementitious composites for self-heating applications via the Joule effect. Subsequently, various conductive additives have been incorporated into heating cementitious composites, with extensive experimental studies conducted in laboratories (Farcas et al., 2021; Galao et al., 2016; Gomis et al., 2015) (see Figure 11).

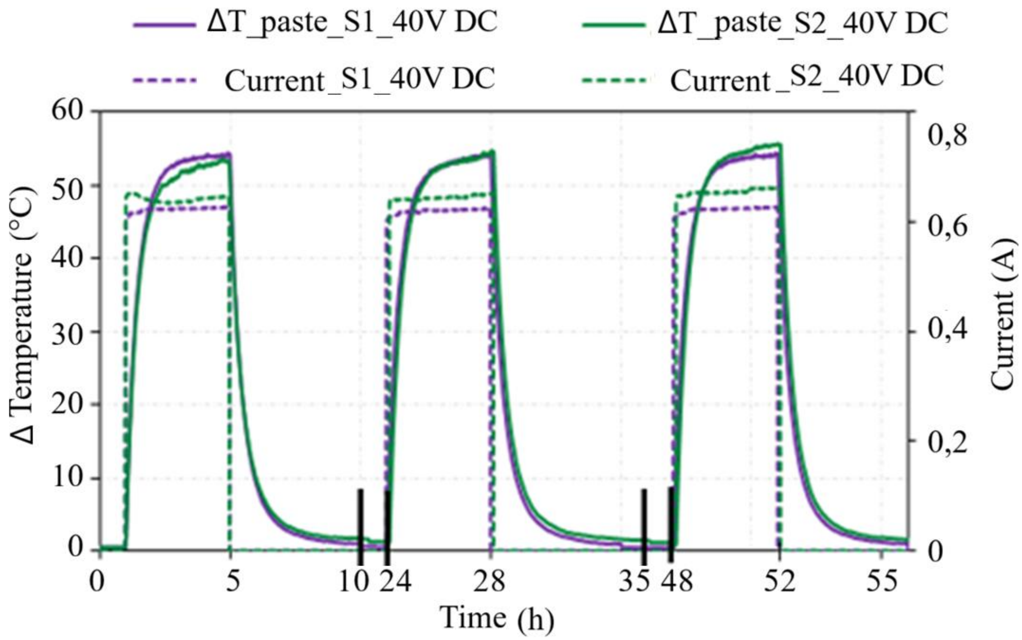

Figure 11. Variation of temperature (°C) and electric current (A) over time (h) during three consecutive DC tests at 40 V on two cement paste specimens (Farcas et al., 2021).

Numerous studies have confirmed the effectiveness of these materials for heating and deicing applications (Rahman et al., 2022). However, challenges remain regarding large-scale implementation, such as controlling concrete temperature and determining optimal mix designs to ensure durability. Deng's studies introduced an innovative approach to actively control concrete temperature by designing a self-regulating mix capable of responding to extreme temperature variations (Deng et al., 2023). Park et al. (2024) investigated the use of embedded multi-walled carbon nanotube (MWCNT) modules in concrete slabs for large-scale deicing, demonstrating thermal efficiency under real-world conditions. Another significant case involved the installation of a heated parking ramp in China using heating concrete under very low temperatures. The ramp surfaces reached a power density of 200–300 W/m², sufficient for effective ice removal under winter conditions (Rao et al., 2018). Sassani et al. (2018) described the full design, production, placement, and performance evaluation of the first heated concrete pavement system using electrically conductive concrete (ECON) with carbon fibers at a U.S. airport. Despite the high resistivity of the plant-mixed ECON, the installed heating system reliably delivered a surface power density of 300–350 W/m², effectively melting snow and ice. Li et al. (2022) developed conductive asphalt concrete by incorporating graphite and carbon fiber blend as conductive additives. The resulting asphalt concrete effectively melted snow and ice when poured over metallic bridge decks during winter. Their optimized mix (CGA-10), combining 0.4% carbon fiber and 30% graphite, formed a robust conductive network within the asphalt matrix. Carbon fibers mitigated the negative effects of graphite on mechanical performance, enhancing the mixture without compromising conductivity. Under test conditions, CGA-10 achieved a thermal conversion efficiency of 78.85% and melted 50.03% of ice in standardized tests. Faneca et al. (2020) conducted both laboratory and field studies to develop conductive concrete based on recycled carbon fibers for use in outdoor urban furniture under freezing temperatures, with promising results. More recently, Anur Oumer et al. (2024) published a comprehensive review on electrically conductive cementitious concrete (ECCC), covering methods to enhance conductivity, analysis of heat transfer behavior, and performance evaluations from lab and small-scale field tests.

Overall, the findings confirm that ECCC pavements can significantly improve road management during winter, enhancing safety and reducing delays due to weather, while offering an eco-friendly alternative to chemical and mechanical deicing methods. Despite these benefits, widespread adoption is still limited by challenges related to cost-effective construction practices, ensuring long-term durability, and maximizing energy efficiency. Addressing these barriers is critical for broader implementation of ECCC technology.

4. ELECTROCHEMICAL TECHNIQUES USING CONDUCTIVE CEMENT PASTES AS ANODE.

When corrosion affects the steel reinforcement in a reinforced concrete structure, repair becomes necessary to extend its service life; otherwise, the risk of structural failure significantly increases. The traditional method for chloride-contaminated structures involves replacing the corroded structural elements. However, emerging methods such as cathodic protection, electrochemical realkalization, or electrochemical chloride extraction (ECE) offer alternatives that avoid structural replacement. These techniques, collectively known as Electrochemical Maintenance Methods, are valued for their ability to remove aggressive agents while preserving the concrete cover and repassivating the reinforcement.
They essentially consist of applying an electric field between the steel reinforcement (negative pole or cathode) and an external electrode placed on the concrete surface (positive pole or anode), which can be a layer of conductive cementitious material containing conductive additives such as graphite. Since chlorides are negatively charged ions, the applied electric field causes their migration from the rebar toward the external electrode through the concrete’s pore network. Subsequently, maintaining the electric field at lower intensity allows cathodic protection of the reinforcement to be applied (see Figure 12).

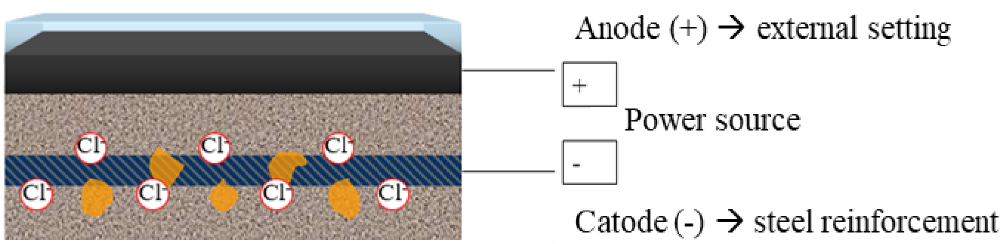

Figure 12. Schematic of the electrochemical chloride extraction technique.

Figure 13 shows an example of ECE applied to cylindrical column specimens, presenting Cl^- concentration profiles before and after ECE, as well as efficiency profiles. A $Ti\text{-}RuO_2$ mesh anode and a sprayed layer of cement-graphite conductive paste with continuous humidification were used. The average efficiency reached 79.44% (Carmona et al., 2015).

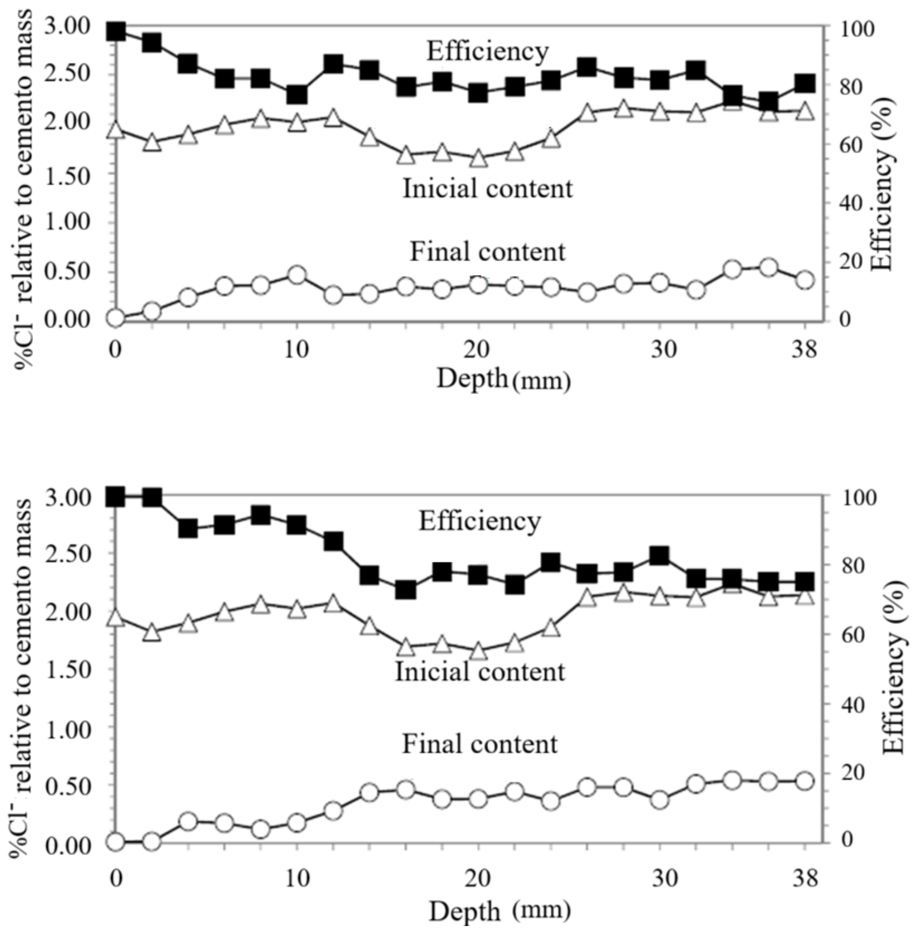

Figure 13. ECE test on cylindrical concrete columns: (a) Ti-RuO_2 mesh anode; (b) sprayed layer of cement-graphite paste; showing Cl^- percentage relative to cement mass (anode) and efficiency (%) versus sampling depth (mm) (Carmona et al., 2015).

The earliest known investigations of this method date back to the 1970s. Lankard, Morrison, and other American researchers at Battelle Columbus Laboratories (Ohio) conducted initial ECE trials on reinforced concrete specimens intentionally doped with chlorides (Lankard et al., 1975). Meanwhile, Slater from the Kansas Department of Transportation applied the method to chloride-contaminated bridge decks. In 1989, the first U.S. patent for this method was filed under the name "NORCURE," titled Removal of Chlorides from Concrete (Vennesland and Opsahl, 1989). In 1998, Tritthart published a comprehensive review of ECE, addressing scientific aspects of the method. Following a detailed explanation of the technique and its history, this study analyzed ion migration and distribution during treatment, measured via changes in pore solution concentrations. It also discussed unintended side effects, such as potential alkali-aggregate reactions, reduced steel-concrete bond strength, and tensile strength loss in steel due to hydrogen generation (Tritthart, 1998). The research group led by Bertolini, Yu, and Page focused on the mechanical effects of treatments across current densities from 5 mA/m^2 (for cathodic protection) to 5 A/m^2 (for ECE) (Bertolini et al., 1996). In these studies, external anodes consisted of titanium mesh embedded in cellulose fiber mats covered with geotextile and soaked in saturated $Ca(OH)_2$ solution. Andrade, Castellote, and collaborators were the first to develop mathematical models for ECE. Using the Nernst-Planck equation, they derived formulas to calculate chloride transport numbers and migration coefficients for estimating treatment efficiency (Andrade et al., 1995). The French team led by Fajardo and Escadeillas examined the steel-concrete interface microstructure after ECE using X-ray spectroscopy and scanning electron microscopy (Fajardo et al., 2006). Climent, Garcés, and others published studies in 2005 and 2006 investigating how reinforcement configuration and sampling methods affect ECE efficiency (Garcés et al., 2005; Climent et al., 2006).

It is essential to distinguish that Cathodic Protection is applied to existing chloride-contaminated structures to control corrosion, while Cathodic Prevention targets new structures susceptible to chloride ingress, using lower current densities to increase durability. A key reference by Lazzari and Pedeferri outlines the limitations and controls of these techniques, including operational potential/current conditions, extraction capacity issues, and risks of hydrogen embrittlement in prestressed concrete. The study also includes examples of design, application, and monitoring for both cathodic protection and prevention (Lazzari and Pedeferri, 2006).

By the late 1990s, conductive cementitious materials began to be considered as potential anodes in cathodic protection systems. Two notable studies emerged: Fu and Chung (1995) showed that carbon fiber-reinforced mortar, applied as an overlay, reduced contact and bulk resistivity. Bertolini et al. (2004) later examined the performance of conductive cement mortars with nickel-coated carbon fibers as anodes in cathodic protection of steel reinforcements. Pérez et al. (2010) were the first to apply conductive cement paste anodes in ECE.

5. OTHER APPLICATIONS.

There are numerous applications beyond those previously discussed. For example, grounding is essential in buildings and structures housing electrical equipment. Lightning protection is critical in tall structures. Traditionally, metals like steel are used in such systems. However, employing electrically conductive concrete can reduce the amount of metal required, offering advantages in cost, durability, and installation simplicity (Chung, 2003). Dr. Chung has recently published studies on the capacitive and piezopermittive properties of concrete for stress self-sensing applications (Chung and Ozturk, 2024; Ozturk and Chung, 2024). Additional research efforts are focusing on the energy aspects of multifunctional concrete (Abden et al., 2024).

Finally, early efforts to 3D print conductive and self-sensing concretes are noteworthy, as they demonstrate promising potential for creating structures in which locally critical areas can be transformed into sensing nodes. These nodes could be instrumental in monitoring both the printing process and the structure's serviceability and safety throughout its lifespan (Liu et al. 2024; Sousa et al., 2024).

6. CONCLUSIONS AND FUTURE OUTLOOK.

The development of conductive concretes with advanced functionalities represents a growing and promising field in infrastructure material engineering. These materials not only serve traditional structural purposes but also incorporate intelligent capabilities that enable active responses to environmental stimuli. Key applications include:

a) Structural health monitoring through piezoresistivity, strain measurement and damage detection, and integration with energy systems and sensors.
b) Joule-effect heating and deicing. Electrically conductive concrete pavements for heating and deicing present a promising solution for smart infrastructure in cold climates. However, large-scale applied research remains essential to optimize performance, ensure cost-effectiveness, and evaluate long-term environmental impacts.
c) Use as an anode in electrochemical techniques. Conductive cement paste is emerging as a promising solution for implementing more effective and durable electrochemical techniques, while enhancing functional integration between system components and the structural substrate.

Despite significant advances in the formulation and characterization of these materials, their large-scale implementation still faces technical and economic challenges. These include difficulties in achieving homogeneous dispersion of conductive materials in the cement matrix, increased costs associated with functional additives, use of contact and wired electrodes and the need to ensure long-term durability and electrical performance under real service conditions.
Nevertheless, ongoing research continues to explore new combinations of conductive materials—such as carbon nanotubes, graphene, metallic fibers, and recycled materials—and innovative manufacturing techniques, including 3D printing, aimed at improving efficiency and reducing environmental impact. In this context, conductive concrete is poised to become a key component in the development of intelligent, resilient, and sustainable infrastructure.

7. ACKNOWLEDGEMENTS.

F. Ubertini would like to gratefully acknowledge the support of the Italian Ministry of University and Research (MUR) via the FIS2021 Advanced Grant "SMS-SAFEST - Smart Masonry enabling SAFEty-assessing STructures after earthquakes" (FIS00001797).

P. Garcés and O. Galao would like to gratefully acknowledge the support of the Spanish Ministry of Science, Innovation and Universities through the grant "Knowledge Generation Projects and Actions for the Training of Predoctoral Research Staff Associated with these Projects", within the framework of the State Program for Research and Experimental Development, under the State Plan for Scientific, Technical and Innovation Research 2024-2027 (Reference: PID2024-159695OB-C21), and also the financial support received from European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 760940.

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