

A Review on the Emerging Applications of Electrically Conductive Concretes in Smart Construction Systems

Mursal Rasikh 

Istanbul Aydin University, Faculty of Engineering, Department of Civil Engineering, Istanbul, Turkey

✉Corresponding author's Email: mursal.rasikh7@gmail.com

ABSTRACT

Electrically conductive concrete (ECON) is an emerging multifunctional material that extends the capabilities of traditional concrete by integrating electrical functionality with structural performance. This review presents a comprehensive analysis of ECON systems, emphasizing the types and properties of conductive additives, their effects on both electrical and mechanical behavior, and the key challenges in real-world implementation. Carbon-based materials—such as carbon fibers, carbon nanotubes (CNTs), and graphene—as well as metallic additives like steel fibers and powders, have been shown to significantly enhance electrical conductivity while maintaining or even improving mechanical properties. The importance of achieving a percolation threshold and ensuring uniform dispersion of conductive fillers is underscored as critical for optimal performance. Despite encouraging laboratory findings, large-scale applications remain limited due to high material costs, lack of standardized testing methods, and technical challenges in deployment. Geopolymer-based conductive concretes are also explored as sustainable alternatives, offering benefits such as lower carbon emissions and superior thermal resistance. Overall, ECON demonstrates considerable potential for smart infrastructure applications, including pavement de-icing, electromagnetic interference (EMI) shielding, and self-sensing systems. Future research should focus on developing cost-efficient mix designs, establishing standardized evaluation protocols, and leveraging AI-driven optimization techniques to enable reliable and scalable use of this technology.

Keywords: Electrically conductive concrete, Carbon fibers, CNT, Percolation threshold, Smart infrastructure

INTRODUCTION

Conductive concrete is synthesized by mixing certain amounts of electrically conductive components—such as graphite, steel slag, stainless steel fibers, and carbon fibers—into the concrete matrix (Cordon et al., 2019). The electrical properties of conductive concrete are related not only to the characteristics and proportions of the conductive materials added but also to the mixing parameters and the overall mixing process of the concrete. While being a functional type of concrete, conductive concrete also possesses structural concrete properties. Due to its electrical conductivity, electro-caloric effect, and electromagnetic behavior, conductive concrete is expected to be widely applied in various fields such as buildings, road engineering, electric power systems, hydraulic engineering, and electromagnetic shielding (Jiang et al., 2025). Ensuring that transportation infrastructure operates safely, sustainably, and without interruption under winter

conditions has become a crucial requirement in contemporary urban planning and civil engineering. In particular, snow and ice accumulation in areas such as airports, bridges, parking ramps, and pedestrian walkways can lead to transportation disruptions, an increase in accidents, and damage to infrastructure components (Chi et al., 2019). Traditionally, various methods such as snow plowing, salting, and chemical deicers have been employed to mitigate these adverse effects. However, these practices not only result in high labor and maintenance costs but also pose significant environmental risks. Moreover, such interventions can cause long-term physical damage to concrete surfaces (Malakooti et al., 2021). In this context, Electrically Conductive Concrete (ECON) systems have emerged as a significant alternative in the construction industry (Sassani et al., 2018). This technology has been developed by incorporating electrically conductive additives—such as carbon fibers,

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steel fibers, graphite, and carbon nanotubes—into a cement-based concrete mix. These additives reduce the electrical resistance of the concrete, allowing Joule heating to occur on the surface when alternating current (AC) or direct current (DC) is applied. As a result, the concrete surface can heat up on its own, functioning to melt snow and ice accumulations (Nahvi et al., 2018). When integrated with automation technologies, this system has the potential to achieve high efficiency with minimal human intervention (Farnam, 2016).

Applications of electrically conductive concrete were first developed in laboratory settings in the 1990s, and later tested in the field through various pilot projects, particularly in the United States. The results obtained from various studies and field applications have demonstrated that the system can also be effective in practice (Rahman et al., 2022). However, this technology remains an emerging field. The main challenges encountered during implementation include high costs, achieving homogeneous distribution of fibers within the concrete, energy efficiency, electrode placement, and performance discrepancies between field and laboratory conditions (Nahvi et al., 2018). Numerous studies related to this technology can be found in the literature. The majorities of these studies are conducted at the laboratory scale and focus on parameters such as different conductive filler materials, mix proportions, dispersion techniques, types of binders, and additives. However, the limited number of field applications raises questions about the large-scale practical applicability of the system. It is evident that future research should focus on developing more economically and technically feasible, standardized, and energy-efficient systems (Rahman et al., 2022). Numerous studies have been conducted on electrically conductive concrete. Some of these studies are as follows: Wu et al. (2015) investigated a three-phase conductive concrete system developed for melting snow and ice accumulated on road surfaces during winter months. This system was created by incorporating conductive additives such as carbon fibers, steel fibers, and graphene into the concrete matrix.

The study evaluated the potential of these conductive additives to enhance the electrical conductivity of concrete and determined the optimal dosage rates. Additionally, the effects of parameters such as electrode spacing and applied voltage on snow and ice melting performance were examined. The results demonstrated that, with appropriate additive ratios and system design, the three-phase conductive concrete possesses effective snow and ice melting capacity at low temperatures. This study

highlights the potential of conductive concrete technology to improve road safety under winter conditions and makes a significant contribution to the literature in this field (Wu et al., 2015). Yehia and Tuan (2000) conducted a comprehensive investigation into the mix design, optimization, and performance characteristics of conductive concrete overlays developed to prevent icing on bridge decks.

In the study, conductive concrete mixtures containing steel fibers and steel shavings were prepared, and the electrical conductivity as well as mechanical strength of these mixtures were evaluated. Based on tests performed on over one hundred trial mixes, it was determined that mixtures incorporating 15–20% steel shavings by volume and 1.5% steel fibers exhibited mechanical and physical properties that meet both ASTM and AASHTO standards. After determining the optimal mix ratios, 9 cm thick overlays were produced using these conductive concrete mixes, and their heating performance was tested with both AC and DC power sources. The experiments demonstrated that these overlays could effectively prevent snow and ice accumulation by generating an average power output of 591 W/m². This study reveals that conductive concrete overlays can serve as an effective and cost-efficient solution for preventing icing on bridge decks, and it makes a significant contribution to the literature in this field (Yehia, 2000).

Sassani et al. (2018) conducted a comprehensive study on the development and performance of a carbon fiber-reinforced Electrically Conductive Concrete (ECON) heated pavement system (HPS), applied for the first time at an airport in the United States. The main objective of the study was to design and field-test an electrically conductive concrete mix with snow and ice melting capabilities for implementation at Des Moines International Airport. In this context, various ECON mixes were prepared in the laboratory using different cement-based materials, aggregate systems, water/binder ratios, carbon fiber dosages, and additives. The mechanical and electrical properties of these mixes were evaluated to determine the most suitable ECON mix for field application. As a result of the laboratory tests, a mix exhibiting an electrical resistivity of 115 Ω -cm, along with adequate mechanical strength and workability, was selected. This mix was applied in the general aviation apron area at Des Moines International Airport as a 9 cm thick ECON layer placed over a 10 cm thick normal concrete base. In the field application, the electrical resistivity of the ECON layer was measured at 992 Ω -cm; however, despite this increase, the system performed

successfully in terms of snow and ice melting. This study demonstrated that carbon fiber-reinforced conductive concrete can be effectively used on airport pavements for snow and ice melting purposes and can deliver successful performance under real-world conditions. Furthermore, it was shown that the system could be developed and implemented in compliance with Federal Aviation Administration (FAA) standards. In this regard, the study makes a significant contribution to the practical applications of conductive concrete technology (Sassani et al., 2018).

This review study aims to systematically evaluate the current state of electrically conductive concrete technology by examining material compositions, types of conductive additives, electrical and mechanical performance characteristics, and existing field applications. In doing so, it highlights the key challenges in large-scale implementation—such as cost-effectiveness, dispersion techniques, energy efficiency, and standardization—and explores emerging solutions, including geopolymers-based systems and AI-assisted mix designs. The review also identifies research gaps and future directions for developing scalable and sustainable ECON systems for smart infrastructure.

ELECTRICAL CONDUCTIVITY FUNDAMENTALS

Types of electrical conductivity

Electrical conductivity refers to a material's ability to conduct electric current and is generally classified into three main categories: conductors, semiconductors, and insulators. This classification is based on the material's energy band structure and the presence of free carriers (electrons or holes). Many factors, such as the atomic-level structure of the material, electron density, temperature, and environmental conditions, directly influence these types of conductivity (Raza, 2020). Conductors, especially metals, possess high free electron density, resulting in very high electrical conductivity. These electrons can move freely under an electric field, allowing easy current flow. Metals such as copper, aluminum, and silver fall into this category and are widely used in electrical transmission lines due to their low electrical resistance (Lee, 2021). Semiconductors, though having low conductivity in their pure form, can achieve enhanced conductivity through doping with impurity atoms. Semiconductors such as silicon and germanium can form both n-type and p-type carriers through doping, making them the foundation of modern electronic devices.

Additionally, they are sensitive to external stimuli such as temperature and light (Zhou et al., 2019).

Insulators are materials that do not conduct electric current or conduct at very low levels. The movement of electrons is restricted due to the energy band gap. Materials such as plastic, glass, and ceramics fall into this group. Insulators are preferred in applications where electrical safety is a priority (Park et al., 2023).

Some special materials exhibit mixed conductivity characteristics, where both ionic and electronic carriers contribute to overall conductivity. Such behavior is particularly critical in battery systems and ionic sensor applications (Singh & Thomas, 2022).

Electrical conduction mechanisms in concrete

Electrical conduction mechanisms in concrete vary depending on the composition of the concrete, its moisture content, and the presence of admixtures. In its natural state, concrete is generally a good insulating material. However, under certain conditions or with the incorporation of specific additives, it can become conductive. Electrical conduction typically occurs through two main mechanisms: Ionic Conduction (Electrolytic conduction) and Electronic Conduction (Li et al., 2024). This type of conduction occurs through the water and dissolved ions (e.g., Na^+ , K^+ , OH^-) present in the porous structure of concrete. In humid environments, the electrical resistivity of concrete decreases, and its conductivity increases (Li et al., 2024). This mechanism refers to the direct transfer of electrons between solid internal phases, particularly enabled by carbon-based additives (e.g., carbon nanotubes, graphene, steel fibers). These additives enhance the conductivity of concrete, granting it a semiconductive or conductive nature (Fulham et al., 2020). Numerous studies have been conducted on the electrical conduction mechanisms in concrete. One such study investigates the effect of conductive admixtures on the mechanical properties and microscopic mechanisms of concrete. The paper examines how conductive materials such as carbon nanotubes, graphite, and carbon fibers—used to enhance concrete's electrical conductivity—affect its mechanical properties and microstructure. The research aims to reveal the positive impacts of these additives on durability, crack resistance, and overall performance. In this study, conductive materials were added in specific proportions to concrete mixtures to produce test specimens. Advanced methods such as ultrasonic mixing were used to ensure the homogeneous dispersion of the additives within the concrete.

During the experimental phase, two primary tests were conducted to assess mechanical properties: compressive strength testing after a 28-day curing period, and three-point bending tests to evaluate flexural strength. To determine electrical conductivity, electrical resistivity measurements were performed using the four-probe direct current (DC) method. In terms of microstructural analysis, Scanning Electron Microscopy (SEM) was used to observe the distribution of conductive additives within the concrete, while Energy-Dispersive X-ray Spectroscopy (EDS) was employed to analyze their chemical compositions and interactions with the cement matrix. Thanks to this comprehensive experimental approach, both the structural strength and conductivity performance of the concrete were thoroughly evaluated.

According to the study's findings, conductive additives significantly improved both the mechanical and electrical properties of the concrete. From a mechanical standpoint, the additives had especially positive effects on compressive and flexural strength. The inclusion of carbon nanotubes increased the durability of the concrete and substantially inhibited the formation and propagation of microcracks. Regarding electrical conductivity, the additives notably enhanced the electrical performance of the concrete, enabling advanced features such as self-sensing. Microstructural analysis with SEM and EDS confirmed that the conductive materials were evenly distributed within the matrix, bridged microcracks, and thus improved the structural integrity of the concrete. These developments suggest that conductive concretes can be utilized in a variety of engineering applications. For instance, smart concretes allow for real-time structural monitoring, and high-strength conductive concretes can be reliably used in critical infrastructure. Additionally, due to their conductivity, these materials can also serve as effective shields against electromagnetic waves. Overall, this study demonstrates that concrete enhanced with conductive admixtures holds significant potential for the development of both functional and durable structures (Li et al., 2023).

Doğan et al. (2022) investigated the utilization of carbon fiber, a conductive material, in various mixture designs for the development of electrically conductive cementitious composites. However, the potential use of ferrochrome slag as a recycled aggregate in these specialized concretes had not yet been explored. In their study, electrically conductive mortars were produced by incorporating 100% recycled ferrochrome slag aggregate (particle size < 1 mm) as the fine aggregate and adding carbon fiber at four different ratios: 0%, 0.5%, 0.75%, and

1%. To assess the electrical conductivity behavior, the resistivity of the samples was measured at five different ages ranging from 2 to 180 days. In addition, comprehensive mechanical and microstructural characterizations were conducted, including 28-day compressive strength, flexural strength, dynamic resonance, ultrasonic pulse velocity, Leeb hardness, scanning electron microscopy (SEM), and X-ray diffraction (XRD) analyses. The results, when compared to existing literature, demonstrated that ferrochrome slag could serve as a viable aggregate in conductive mortar production. The influence of curing age on electrical resistivity was found to be minimal in carbon fiber-reinforced mixtures. Notably, with the incorporation of 1% carbon fiber, the resistivity values decreased by approximately 40 times compared to the control sample. Moreover, SEM images of the 0.75% carbon fiber sample revealed the formation of a conductive network, where the fibers adhered between components within the compact ferrochrome-based matrix (Doğan et al., 2022). The resistivity values obtained in the relevant study are summarized in Fig. 1.

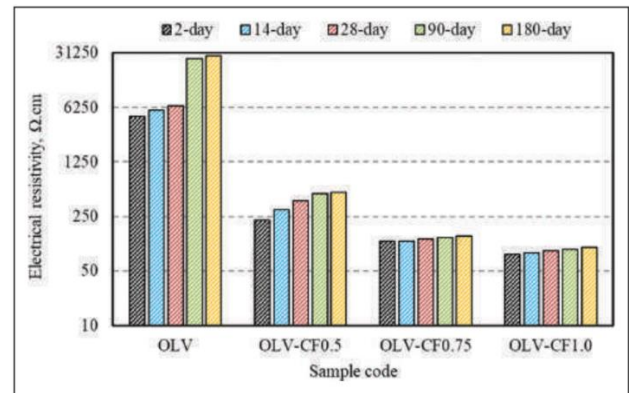


Figure 1. Electrical resistivity results from mortar specimens (Doğan et al., 2022).

Percolation theory

Percolation theory analyzes the formation of connections among randomly distributed components in a system and the threshold at which these connections form a continuous network throughout the system, known as the percolation threshold. From a materials science perspective, this refers to the point at which conductive particles in an insulating matrix reach a critical density, rendering the system electrically conductive (Stauffer & Aharony, 2018). In cement-based composites such as concrete, the addition of conductive materials like carbon nanotubes, graphene, graphite, carbon fibers, or other conductive additives alters the system's electrical

properties. At low volume fractions, these additives behave like insulators; however, once a certain critical volume fraction is exceeded, the material abruptly becomes conductive. This critical density is referred to as the percolation threshold (Sahimi, 1994). Numerous studies and investigations have been conducted on percolation theory. Winslow et al. (1994), titled “Percolation and Pore Structure in Mortars and Concrete”. This experimental research thoroughly investigated the pore structure and percolation behavior of mortar and concrete materials. In the study, nine mortar samples with varying sand contents were prepared, and six of these were selected for microstructural analysis. The pore structures of the samples were examined using Mercury Intrusion Porosimetry (MIP); this method enabled the measurement of pore volume distributions based on pore diameter, thereby revealing microstructural characteristics within the concrete.

The experimental data were compared with advanced computer models, allowing for the determination of percolation threshold values in mortar and concrete materials. The results showed that increasing aggregate content caused significant and noticeable changes in the pore structure of the mortar samples. Specifically, when the aggregate volume reached 15.7%, a critical threshold diameter in the pore distribution disappeared, and larger diameter pores became dominant. This transition represents a microstructural shift that directly affects the physical and mechanical properties of the concrete. The strong correlation between computer simulations and experimental results demonstrated that the interfacial transition zones (ITZ) around aggregate particles play a crucial role in percolation behavior. This study confirmed that both the content and distribution of aggregates have a direct and substantial impact on the pore structure and, consequently, on the percolation properties of concrete. These findings are critically important for improving concrete’s durability, water permeability, and other physical performance characteristics. Moreover, they emphasize the necessity of implementing such microstructural analyses to extend the service life of concrete, reduce maintenance needs, and design more resilient structures. Through this approach, the long-term performance and reliability of concrete in engineering applications can be significantly enhanced (Winslow et al., 1994).

ELECTRICALLY CONDUCTIVE CONCRETE CLASSIFICATION

Carbon-based conductive concretes

1) Carbon fiber reinforced concretes

Carbon fiber reinforced concrete is a composite material that combines the properties of carbon materials with concrete. This combination provides high electrical conductivity, mechanical strength, and durability

(Lövgren, 2005; Lee, 2023). As a specialized type of FRC composites, carbon fiber reinforced concrete composites can be used in various forms such as discontinuous fibers, rods, tubes, fiber bundles, textiles, and fabrics. These forms are placed in the main stress direction and only in the required regions, offering advantages over traditional reinforcement methods (Chung & Lövgren, 2005). Thanks to their superior mechanical, electrical, and chemical properties, these materials possess significant potential for the reinforcement of concrete structures and the assessment of structural safety in civil engineering applications (Jang et al., 2022). However, the use of carbon fibers and carbon-based reinforced concretes is limited due to the high cost of these materials (Jun et al., 2023).

One of the studies on carbon fiber reinforced concretes is titled “*Mechanical properties of carbon fiber reinforced concrete (CFRC) after exposure to high temperatures.*” In this study, seven concrete mixtures with varying carbon fiber contents and lengths were prepared. The carbon fiber ratios in these mixtures ranged from 0.5% to 3.5%, while the fiber lengths were selected as 6 mm, 10 mm, and 12 mm. The prepared specimens were exposed to temperatures of 200°C, 400°C, 600°C, and 800°C for 2 hours. To evaluate the mechanical properties, compression, flexural, and tensile strength tests were conducted in accordance with ASTM and ACI standards. In microstructural analyses, a Scanning Electron Microscope (SEM) was used to examine the distribution of carbon fibers within the concrete matrix and the fracture modes. The results showed that the addition of carbon fibers had a limited effect on compressive strength but significantly improved flexural and tensile strength, particularly when using 1.0% of 10 mm-long fibers. SEM analyses revealed that the fibers were homogeneously distributed in the concrete matrix and that the fracture occurred due to fiber pull-out and breakage under thermal loading. Furthermore, it was observed that the enhancing effect of carbon fiber reinforcement on mechanical properties diminished at elevated temperatures. This study highlights the potential of carbon fibers to enhance the mechanical performance of concrete and emphasizes the importance of determining the optimal fiber content and length. It also concludes that carbon fiber reinforced concretes may offer advantages in applications requiring high thermal resistance (Guo et al., 2021).

2) Carbon nanotube reinforced concretes

Carbon nanotube (CNT) reinforced concrete is a material that has attracted significant attention in recent

years, yet only a limited number of studies have been conducted on its modeling. Most of these studies are limited to modeling cement mortars reinforced with CNTs (Sindu, 2012; Papadopoulos, 2017). These studies generally employ homogenization techniques or micromechanical approaches. On the other hand, multiscale strategies of plain concrete—such as detailed modeling of aggregates and the derivation of homogenized compressive and tensile nonlinear structural behaviors—have attracted considerable attention (Wriggers, 2006; Wittmann, 1993). In recent years, carbon nanotube reinforced concrete (CNTC) has been investigated by researchers worldwide, producing a wealth of data and theoretical insights. Although the International Organization for Standardization (ISO) has published various standards characterizing the internal structure and composition of CNTs, standards characterizing the effects of CNTs on concrete properties are not yet fully developed, and research on CNTC is still in the exploratory phase. Therefore, summarizing the current findings in this area is necessary to fully understand the role of CNTs in enhancing concrete properties (Zhang et al., 2023).

The use of carbon nanotubes in concrete technology has expanded significantly in recent years, offering notable contributions particularly in the development of high-performance and specialty concretes. Due to their high tensile strength, elastic modulus, and micro-scale crack-bridging capability, CNTs can significantly improve both the mechanical and durability properties of concrete. In this context, experimental studies examining the behavior of CNT-reinforced concretes under high temperatures provide critical information for the design of fire-resistant structural elements. In this regard, a study by Zolfaghari et al. (2022), published on the ScienceDirect platform, investigated the effects of carbon nanotubes on lightweight structural concrete in detail. In the study, CNTs were added at a ratio of 0.02% by the weight of cement, and expanded clay aggregate (LECA) was used as coarse aggregate. The specimens were subjected to various temperature levels (100°C–800°C), during which their mechanical and thermal performance was assessed through tests such as compressive strength, tensile strength, and thermal conductivity. Experimental findings revealed that CNT-modified concretes minimized strength losses under high temperatures, especially by bridging microcracks through CNTs and thus preserving the integrity of the structure. It was also observed that CNTs reduced the thermal conductivity coefficient, thereby enhancing the thermal insulation performance of the

concrete. In this respect, CNT reinforcement stands out as a promising method for developing fire-resistant building materials (Zolfaghari et al., 2022).

On the other hand, the effective dispersion of CNTs within the concrete and the formation of a homogeneous matrix are critical for achieving the desired performance. In this context, a second study by Konsta-Gdoutos et al., (2010) explored the relationship between the dispersion quality of CNTs in cement paste and the resulting mechanical properties. In the study, functionalized CNTs were dispersed using polycarboxylate-based superplasticizers and ultrasonic energy. Different levels of ultrasonic energy were applied, and parameters such as workability, elastic modulus, flexural strength, and fracture energy were measured. The results showed that when an optimal level of ultrasonic energy was applied, CNTs were homogeneously dispersed, leading to significant improvements in the mechanical properties of the cement paste. However, it was also emphasized that excessive ultrasonic energy could damage CNT structures and reduce their positive contribution to performance. Additionally, although the addition of CNTs could negatively affect workability, it was noted that this effect could be controlled through the use of superplasticizers (Konsta-Gdoutos et al., 2010).

When both studies are evaluated together, it becomes evident that the contribution of carbon nanotubes to the performance of concrete depends not only on their presence but also on the mixing method and dispersion quality. While the first article demonstrates that CNTs improve resistance to high temperatures and help prevent microcracks, the second study emphasizes that a homogeneous distribution is a prerequisite for this contribution to be effective. Therefore, to enhance the performance of CNT-reinforced concretes, both material content and mixing technology must be optimized simultaneously. In this regard, further research on material characterization and production processes is necessary to expand the application of CNTs in concrete technology.

3) Graphene and graphite reinforced concretes

In recent years, graphene has emerged as a new star among carbon-based nanomaterials that can be infused into cement matrices to enhance the performance of cementitious composites in various aspects. The significant interest in incorporating graphene into cement-based components is associated with the following properties and contributions: (a) achieving improved mechanical properties of cementitious composites with very low doses of graphene infusion, thereby reducing

cement consumption; (b) enhancing the durability of cementitious composites under aggressive environmental conditions; (c) providing excellent electrical conductivity and sensitive piezoresistivity in cementitious composites, which supports the development of smart civil infrastructure as well as enabling static/dynamic wireless charging for electric vehicles through cement-based pavements; (d) preventing thermal cracking in large concrete structures and increasing fire resistance through superior thermal diffusivity, along with improving deicing applications in cement-based pavements to enhance traffic safety; (e) demonstrating exceptional electromagnetic interference (EMI) shielding capabilities in cementitious composites, thereby minimizing the effects of electromagnetic emissions on human health and optimizing user privacy; (f) allowing for relatively low-cost mass production while maintaining intrinsic properties (Lin, 2020; Wang, 2019; Luong, 2020).

Today, the use of nanomaterials in concrete technology is increasing, and particularly the potential of graphene oxide and its derivatives to enhance the mechanical and durability properties of concrete has attracted attention. In this context, a study investigated the effects of graphene oxide (GO) and hollow glass powder (HGP) additives on ultra-high-strength concrete (UHSC) in detail. The research assessed the workability, strength, and microstructural characteristics of concrete, with special attention to the distribution of the additives observed via SEM and MIP analyses. The results revealed that HGP improved workability, while GO significantly increased tensile strength. Furthermore, the combined use of these two additives led to a more than 20% reduction in porosity and a 40% improvement in air-tightness. These findings suggest that more effective and functional nano-

additives can be used as alternatives to traditional mineral additives (e.g., silica fume) (Kim & You, 2024). Similarly, the effect of graphene oxide on the structural behavior of reinforced concrete elements has been supported by experiments conducted on high-strength lightweight concrete (HSLWC) beams. In this study, beams containing 0%, 0.01%, 0.03%, and 0.05% GO were tested under four-point bending to observe their shear strengths. The experiments showed that all beams failed in shear-compression fracture mode, but the shear strength increased significantly with higher GO content. In particular, the specimen containing 0.05% GO exhibited a 39.2% higher load-carrying capacity compared to the control sample. Moreover, the inclusion of GO not only enhanced strength but also improved ductility, enabling reinforced concrete elements to become more resistant to earthquakes. The study also tested the applicability of modified calculation models developed in the research for engineering applications (Liu et al., 2024).

When both studies are evaluated together, it becomes clear that graphene oxide not only strengthens the microstructural integrity of concrete but also directly contributes to the load-bearing capacity of reinforced concrete elements. Additionally, when used in combination with secondary additives such as HGP, nanomaterials provide practical benefits beyond just strength, including improvements in workability and durability. In this regard, graphene oxide-reinforced concretes stand out as a highly promising area for research aimed at developing advanced construction materials (Kim & You, 2024; Liu et al., 2024).

The data obtained from recent studies on electrically conductive concretes are summarized in Table 1.

Table 1. Data Obtained from Recent Studies on Electrically Conductive Concretes

NO	REFERENCE	The conductive material that is used				R (resistivity)
		CF	CB	CNT	GO	
1	Guo et al. (2021)	✓	-	-	-	%1 → 820 $\Omega \cdot \text{cm}$ %5 → 78 $\Omega \cdot \text{cm}$
2	Liu et al. (2025)	✓	-	-	-	400 ila 1800 $\Omega \cdot \text{cm}$
3	Zhao et al. 2017)	-	✓	-	-	530 $\Omega \cdot \text{cm}$
4	Li et al. (2022)	-	-	-	✓	7.779 $\Omega \cdot \text{cm}$

Metal-Based conductive concretes

Metal-based conductive concretes are enhanced with metal additives such as steel fibers to increase their electrical conductivity. These types of concrete are particularly used in applications such as heated flooring

systems, electromagnetic shielding, and structural health monitoring (Cordon et al., 2019). Below is a summary of the key findings related to metal-based conductive concretes. In an experimental study aimed at developing and improving the performance of metal-based conductive

concretes, mixtures with high electrical conductivity were produced using nanographite and magnetite sand (Ren et al., 2023). In the study, magnetite sand was substituted for coarse aggregate at replacement levels of 40%, 60%, and 80%, and the properties of the resulting concretes were evaluated using different alkaline activators (sodium silicate, sodium hydroxide, and their combinations). After a 28-day curing period, tests revealed that the mixture with 60% magnetite sand had an electrical resistivity of 5,850 $\Omega \cdot \text{cm}$, which corresponds to a 55.7% reduction compared to the control concrete. In terms of mechanical performance, this same mixture achieved a compressive strength of 40.83 MPa and a flexural strength of 6.81 MPa. These results demonstrate that metal-based conductive concretes can maintain mechanical performance while achieving significant improvements in electrical conductivity.

Specifically, the mixture containing 6% nanographite and 60% magnetite sand showed the highest conductivity and strength, indicating that the optimization of these properties is possible through the appropriate combination of alkaline activation methods. These types of metal-reinforced conductive concretes offer practical and sustainable solutions, especially for applications such as snow and ice melting (Ren et al., 2023).

1) Steel fiber reinforced concretes

Steel Fiber Reinforced Concretes (SFRC) are composite materials obtained by adding steel fibers to concrete to improve its mechanical and durability properties. These fibers enhance the ductility of concrete by delaying the propagation of microcracks and preventing the spread of visible cracks. This feature also improves the concrete's resistance to impact and fatigue (Zheng, 2024). The inclusion of steel fibers can increase compressive strength by 10–25% and tensile strength by 31–47%, depending on the quantity and dimensions of the fibers used (Abbass, 2018). When exposed to high temperatures, SFRC has also shown improvements in mechanical properties such as compressive strength, tensile strength, and flexural toughness (Zhao, 2025). Steel fiber reinforced concretes are commonly used in tunnel linings, highway pavements, and railway sleepers. Moreover, the use of recycled steel in these mixtures contributes to environmental sustainability (Liu, 2022).

In experimental studies on the mechanical properties of SFRC, the effects of different steel fiber ratios on the strength and ductility of concrete have been extensively examined. In the study, concrete samples were prepared by incorporating steel fibers at volume fractions of 0.5%,

1.0%, 1.5%, 2.0%, and 2.5%. After curing periods of 7, 14, and 28 days, the samples underwent compressive strength, tensile strength, and flexural strength tests. The test results indicated a significant increase in mechanical properties with increasing fiber content. For instance, in samples with 2.0% steel fibers, compressive strength increased by 41.59%, and tensile strength by 124.6%. This enhancement is attributed to the steel fibers' ability to prevent crack propagation within the concrete and increase its load-carrying capacity. Additionally, in flexural strength tests, fiber-reinforced concretes demonstrated greater energy absorption and ductility, which enhances the deformation capacity of structural elements before failure. The study also revealed that, in addition to fiber content, the curing period has a significant effect on mechanical performance, with the 28-day curing period providing the most optimal strength. Overall, the results suggest that SFRC is an effective material for applications that require high strength and ductility, such as bridge girders and ground improvement works (Scientific.Net, 2024).

2) Metal powder-based systems

Metal powders, when added to concrete mixtures, form conductive networks that enable the transmission of electric current within the concrete. These additives improve the electrical properties of concrete and allow for various functional applications (El-Mir et al., 2024). Graphite powder is one of the most commonly used conductive additives in concrete. It enhances both the electrical and thermal conductivity of concrete. Its application is particularly widespread in roadway de-icing systems (El-Mir et al., 2024). Steel powder strengthens the mechanical properties of concrete while also improving its electrical conductivity. These powders form conductive networks within the concrete, facilitating the flow of electric current (Shishegaran et al., 2020). Aluminum powder is an effective additive for increasing the electrical conductivity of concrete. Additionally, it stands out as an environmentally sustainable option (Fathi et al., 2025). Comprehensive experimental studies on metal powder-reinforced concrete systems have examined the effects of various metal powders—particularly steel and graphite—on the electrical conductivity, mechanical strength, and overall durability of concrete. In the study, metal powders were used as partial replacements for fine aggregate at volumetric rates of 1%, 3%, 5%, and 7%, allowing for the assessment of how different concentrations influence concrete performance. The concrete samples were subjected to electrical conductivity, compressive strength,

tensile strength, and durability tests after a 28-day curing period. Results indicated a significant increase in electrical conductivity in graphite powder-containing concretes, particularly at a 7% concentration. This improvement is attributed to the continuous conductive networks formed by the graphite powder, which facilitate more efficient transmission of electric current. From a mechanical standpoint, samples containing steel powder exhibited notable improvements in compressive and tensile strengths. However, these enhancements varied depending on the type and dosage of the metal powder used.

Furthermore, the positive effects of metal powders on the durability characteristics of concrete were confirmed through experimental data. Concrete specimens with graphite powder showed increased resistance to abrasion and environmental degradation. The study highlights the crucial role of metal powder additives in enhancing both the functional and structural performance of concrete. However, it also emphasizes that the type and quantity of metal powder must be carefully selected based on the intended application of the concrete to achieve optimal performance. These findings provide valuable guidance for the use of metal powder-reinforced concretes in applications that require electrical conductivity and where durability is a critical factor (Adari et al., 2023).

Hybrid and multi-component systems

Hybrid and multi-component systems are developed by combining multiple conductive materials (such as carbon nanotubes, graphite, steel powder, aluminum powder). These combinations not only enhance the electrical conductivity of concrete but also improve its mechanical and thermal properties (Onthong et al., 2022). The combination of various carbon-based materials—such as carbon nanotubes, carbon fibers, and graphite—has proven effective in improving the electrical conductivity of concrete. The synergistic interaction among these materials ensures the continuity of the conductive network, resulting in reduced electrical resistance. For instance, multi-walled carbon nanotubes (MWCNTs) coated with polyvinyl acetate (PVAc) and polyindole (PIn) exhibit better dispersion and higher electrical conductivity within the concrete matrix (Onthong et al., 2022). The combination of steel fibers and carbon fibers enhances both the electrical conductivity and mechanical strength of concrete. These hybrid systems are especially preferred in heating and de-icing applications. Steel fibers reinforce the conductive network, while carbon fibers contribute to more homogeneous dispersion (Tian et al., 2021). In reactive powder concrete (RPC) systems, the combination

of steel fibers and carbon-based materials improves the electrical conductivity of concrete. These systems are typically used in high-performance concrete applications. While steel fibers strengthen the conductive network, carbon-based materials help achieve lower electrical resistance (Tian et al., 2021).

Geopolymer-based conductive concretes

Geopolymer-based concretes are produced using binders obtained through the alkali activation of aluminosilicate sources. These concretes are known for their low carbon emissions and high thermal resistance. Electrical conductivity is incorporated into these concretes to endow them with functional properties, particularly for applications such as energy transmission and heating systems. In one study, the electrical conductivity of a geopolymer concrete developed using fly ash was enhanced by modifying it with carbon fibers. This modification not only improved the electrical conductivity of the concrete but also enhanced its mechanical properties. Such modifications have emerged as an effective method for enhancing the functional performance of geopolymer-based concretes (Gao et al., 2024).

In another study, the addition of graphite to geopolymer concrete was investigated in terms of its effect on electrical conductivity. It was found that graphite significantly increased the concrete's electrical conductivity and influenced its percolation behavior. These findings highlight the importance of additives in improving the electrical conductivity characteristics of geopolymer-based concretes. The conductivity of such materials varies depending on the type and ratio of additives used in the mixture. Therefore, to achieve the optimal level of conductivity for a specific application, detailed mix design and experimental analysis are required.

Experimental studies on geopolymer-based conductive concretes demonstrate that these materials offer significant advantages over traditional concretes in terms of both electrical conductivity and mechanical durability. In the initial study, researchers prepared geopolymer concrete samples using different activator concentrations and mix ratios. After a 28-day curing period, these samples were subjected to tests for electrical conductivity, compressive strength, and tensile strength. The test results revealed a notable increase in electrical conductivity with higher activator concentrations. This improvement is attributed to the formation of a denser and more continuous conductive network within the geopolymer matrix as a result of the increased activator

content. In mechanical tests, the compressive and tensile strengths of geopolymer concrete were found to be comparable to or even superior to those of traditional Portland cement-based concrete with equivalent mix ratios. This indicates that geopolymer concretes not only

support environmental sustainability but also offer strong structural performance. Furthermore, their lower carbon footprint positions geopolymer concretes as an eco-friendly alternative in the construction industry (Zhang et al., 2020).

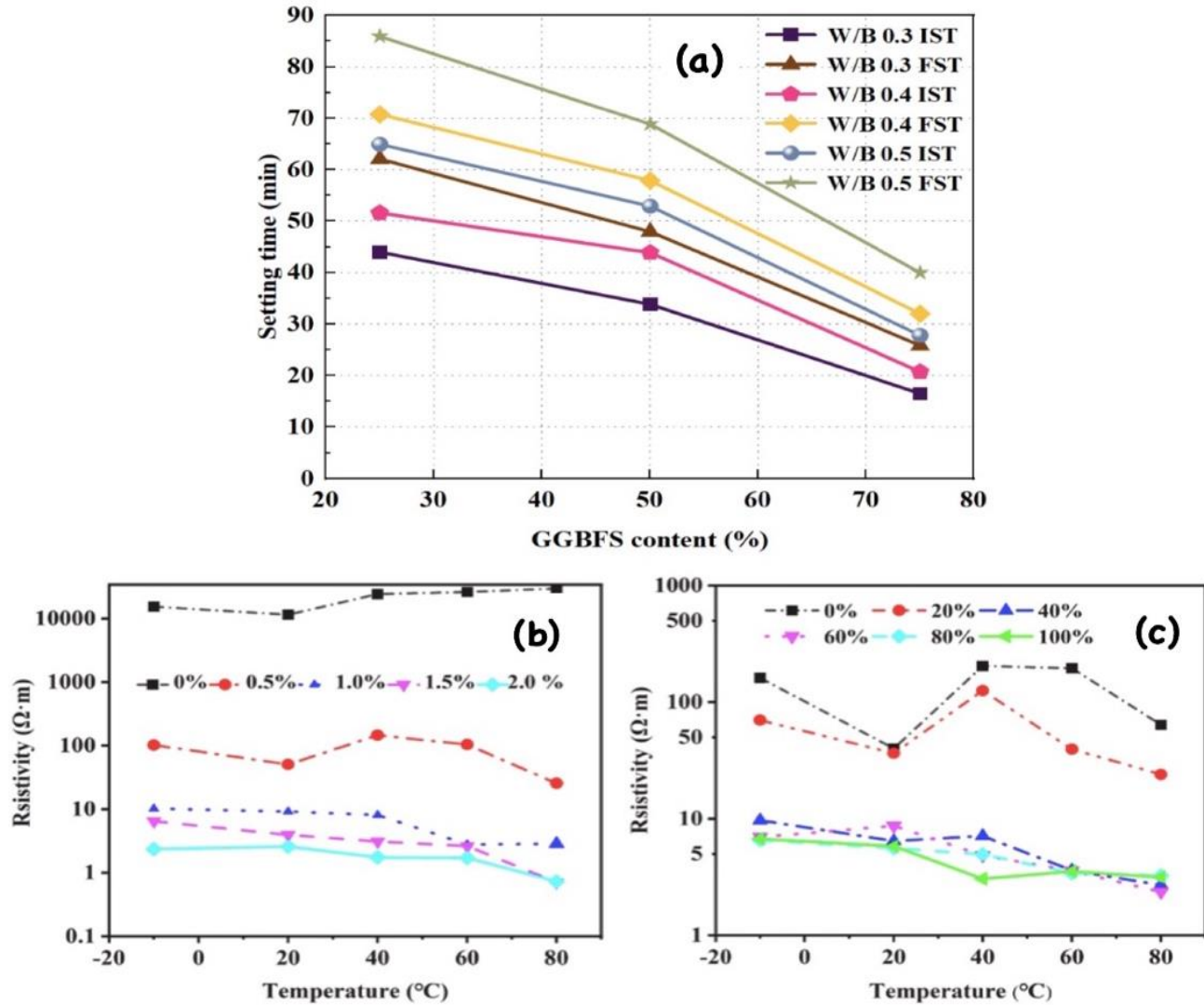


Figure 2. a) Effects of GGBFS content on the setting time (Zhang et al., 2020) and Effect of temperature on GP resistivity; b) Different CFI content; c) Different FA content (Gao et al., 2024)

The figure 2(a) presented in the study by Zhang et al. (2020) illustrates the effect of GGBFS (ground granulated blast furnace slag) content on the initial and final setting times in mixtures with varying water-to-binder ratios (W/B = 0.3, 0.4, 0.5). The findings reveal that as the GGBFS content increases, both the Initial Setting Time (IST) and Final Setting Time (FST) decrease significantly. Particularly at 70–80% GGBFS content, up to a 50% reduction in setting times was observed. This behavior is

attributed to the Ca^{2+} ions in GGBFS, which act as nucleation sites and accelerate the reaction rate. Moreover, samples with lower water-to-binder ratios (W/B = 0.3) exhibited the shortest setting times, confirming the decisive influence of water content on the setting process.

The figure 2(b) and 2(c) presented by Gao et al. (2024), on the other hand, investigates the influence of temperature variations on the electrical resistivity of geopolymers. Figure 6a shows the effect of temperature on

resistivity under different CF1 additive percentages (0–2%), while Figure 6b illustrates how varying fly ash (FA) contents (0–100%) influence this relationship. In both graphs, electrical resistivity is observed to decrease with increasing temperature. Specifically, at higher CF1 and FA contents, the increase in temperature enhances ionic conductivity, resulting in lower resistivity values. For instance, in samples with 2% CF1 content, resistivity decreased to around $10 \Omega \cdot \text{m}$ within the 20–80 °C temperature range.

Both studies examine the influence of additive dosage on the performance of geopolymer systems, demonstrating that increasing the dosage significantly alters system behavior. Both figures use additive ratio (GGBFS or CF1/FA) as an independent variable and present its effect on reaction kinetics in terms of either setting time or electrical resistivity. It was concluded in both studies that more reactive additives enhance both the chemical (setting behavior) and physical (conductivity) properties of the system. The study by [Zhang et al. \(2020\)](#) focuses more on mechanical and setting time aspects, whereas Gao et al. (2024) emphasizes conductivity and electrical performance. Zhang's graphs display a linear decreasing trend, while Gao's figures exhibit more complex, temperature-dependent behavior. Additionally, Zhang's study uses a time scale in minutes, whereas Gao's employs a logarithmic scale with $\Omega \cdot \text{m}$ units, affecting the way data is visualized.

In the second study, the resistance of geopolymer concretes to high temperatures was examined in detail ([Kumar et al., 2022](#)). The researchers exposed concrete samples, produced using various mix designs, to temperatures ranging from 100°C to 1000°C. While the effects of high temperatures on the mechanical performance of the concrete were investigated, a noticeable reduction in compressive strength was observed. However, it is noteworthy that these reductions were less significant compared to those in traditional concretes. Geopolymer concrete demonstrated superior resistance to elevated temperatures, thereby increasing its potential for use in fire-safe structures and components exposed to high heat. This study also emphasized the need to optimize the mix proportions and the types of activators used in order to enhance the thermal stability of geopolymer concrete ([Kumar et al., 2022](#)).

Both studies demonstrate that geopolymer-based conductive concretes can be optimized to become sustainable and high-performance construction materials in terms of both electrical conductivity and mechanical durability. It has been clearly shown that the concentration

of the activator and the mix design directly influence the electrical and mechanical performance of the concrete. Additionally, taking high-temperature conditions into account plays a critical role in enhancing material durability. These findings provide a strong scientific and technical foundation for the widespread future use of geopolymer-based conductive concretes in structural applications that require electrical conductivity and are exposed to harsh environmental conditions.

MATERIAL COMPONENTS AND THEIR EFFECTS ON CONDUCTIVITY

Binder systems

In electrically conductive concretes, binder systems are fundamental elements that determine both the mechanical and electrical properties of the material. The type, content, and admixtures of the binder system directly affect the conductivity of concrete. For instance, conventional binders such as Portland cement exhibit high electrical resistance; however, when modified with carbon-based additives, they can gain conductive properties ([Rahman et al., 2022](#)). The type of binder and the binder-to-aggregate ratio may have limited impact on the electrical properties of conductive asphalt-based concretes. However, since asphalt itself is a non-conductive material, the type, dispersion, and dosage of conductive additives play a decisive role in the performance of the concrete ([Lu et al., 2023](#)). Conductive concrete can be formed by incorporating specific conductive phase elements. Such concretes can be used in applications like de-icing and snow melting on road surfaces. For these applications, the electrical resistivity of the concrete should fall within the range of 10^2 to $10^5 \Omega \cdot \text{cm}$ ([Jiang et al., 2025](#)).

To optimize the mix design of electrically conductive concretes, a carbon fiber volume ratio between 0.4% and 0.8% is recommended. This ratio can enhance the electrical conductivity while maintaining the mechanical properties of the concrete ([Oumer et al., 2024](#)). Additionally, it is suggested to add conductive admixtures at a rate of 0.3% to 1.2% by weight of the binder to improve the electrical and mechanical properties of cementitious composites. These additives not only increase electrical conductivity but may also positively affect mechanical strength ([Ou et al., 2024](#)). Experimental studies investigating the impact of binder systems on electrically conductive concretes demonstrate that carbon-based additives significantly enhance the electrical properties of the concrete. In a study conducted by [Zhao et](#)

al. (2023), concrete mixes containing various ratios of carbon fiber were prepared and their electrical conductivity performances were evaluated. The experiment showed that the homogeneous dispersion of carbon fibers within the concrete matrix directly affects electrical conductivity. Non-uniformly dispersed fibers create localized resistance zones, which may hinder the consistent transmission of electrical current. Furthermore, it was noted that carbon fibers may increase the porosity of the concrete and affect its water absorption capacity; however, when used at appropriate dosages, both the electrical and mechanical performance of the concrete improved. It was particularly observed that maintaining the carbon fiber ratio within the 0.4% to 0.8% range resulted in achieving desirable electrical conductivity values.

In addition to these findings, another study conducted by Liu et al. (2025) investigated the use of waste iron tailings in conductive concretes alongside carbon fiber. In this experimental study, the carbon fiber ratio was kept at 1%, and it was found that this proportion resulted in electrical resistivity values ranging from 400 to 1800 $\Omega \cdot \text{cm}$. These values were deemed consistent with the required resistivity range of 10^2 - $10^5 \Omega \cdot \text{cm}$ for heating applications such as snow and ice melting on road surfaces. Furthermore, iron tailings were found not only to enhance conductivity but also to contribute to environmental sustainability and improve the strength properties of the concrete. Both studies concluded that carbon-based additives, when used in appropriate ratios and with proper dispersion, can optimize both the functional and mechanical aspects of concrete (Zhao et al., 2023; Liu et al., 2025).

Dehghanpour conducted a study that proposes a more efficient method for producing heatable, radiation-shielding, and smart-sensing cementitious materials, contrasting with the conventional approach of directly incorporating conductive fillers into the cement matrix. Instead, the research introduces a technique in which a thin, electrically conductive coating is applied to the surface of non-conductive glass fiber reinforced concrete (GRC). Single-walled carbon nanotubes (SWCNTs) and carbon fibers (CFs) were utilized as conductive additives in the coating mixtures. SWCNTs were incorporated at dosages of 0.1%, 0.2%, and 0.3% by weight, while CFs were used at 0.2%, 0.4%, 0.6%, 0.8%, and 1% by volume, resulting in the production of 15 different conductive cement coatings. White Portland cement and fine silica sand were employed as binder and filler materials, respectively. The approximately 3 mm-thick conductive

cement-based coatings exhibited strong adhesion and integration with the GRC substrate, as they were cast simultaneously in the mold. To characterize the electrical, thermal, and microstructural performance of the coatings, resistivity, impedance, electrothermal response, TGA-DTA, and microstructural analyses were performed. The results indicated that the CF-containing composite coatings exhibited superior impedance and resistance performance compared to other formulations. TGA/DTA analyses revealed that varying the CF content had a minimal effect on thermal weight loss. Notably, the lowest resistivity values were recorded as 20 and 80 $\Omega \cdot \text{cm}$ for CF1.0 and CF0.8 samples, respectively. Electrothermal testing demonstrated that these coatings achieved temperature increases from 23 °C to 45.5 °C and 28 °C, respectively, within one hour under a 24 V voltage application, with power densities of 750 W/m² and 232 W/m² (Dehghanpour, 2023). The electrothermal results obtained from this study are shown in Fig. 3.

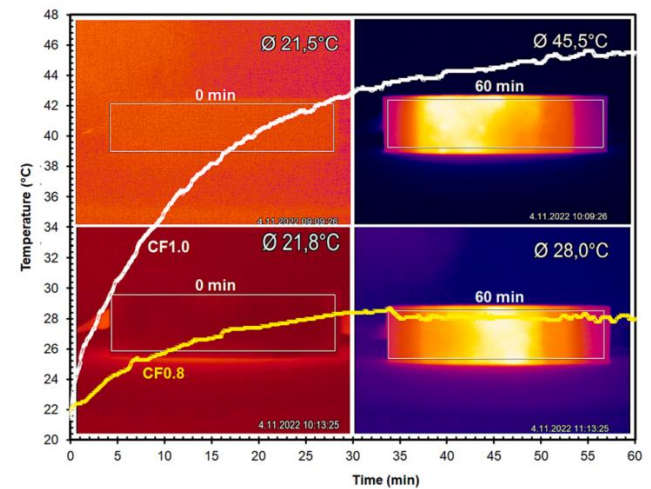


Figure 3. Temperature behavior of CF0.8 and CF1.0 specimens in 60 min with 24 V potential difference.

Conductive fillers

In the production of cementitious materials, chemical, mineral or fiber additives are used to improve the hardness, density, electrical conductivity, water permeability and thermal resistance properties of the material (Doğan & Dehghanpour, 2021). Carbon fibers are effective additives used to enhance the electrical conductivity of concrete. These fibers, with diameters in the micrometer range and lengths of 3–15 mm, form conductive paths within the concrete matrix, facilitating electron movement. Due to these properties, carbon fiber-reinforced concretes are especially preferred in

applications such as de-icing and electromagnetic shielding (El-Dieb, 2018). Moreover, the use of carbon fibers improves the mechanical performance and durability of concrete. The industrial-scale production of recycled carbon fibers also offers environmental and economic advantages (Wang et al., 2019).

Steel fibers are another type of additive used to increase the electrical conductivity of concrete. The addition of steel fibers reduces the electrical resistivity of the concrete, making it suitable for heating applications. However, steel fibers are susceptible to corrosion, which can negatively affect the long-term durability of the concrete (Behbahani, 2011; Bae & Pyo, 2020). Additionally, using high dosages of steel fibers can make the concrete less workable. The orientation of the fibers is also important: fibers aligned in parallel improve electrical conductivity, while randomly dispersed fibers may reduce efficiency (Bae & Pyo, 2020). Carbon nanotubes and carbon nanofibers are nano-sized additives used to enhance the electrical conductivity of concrete. These materials create conductive networks within the concrete matrix, thereby increasing electrical conductivity. They also improve EMI (electromagnetic interference) shielding performance (Konsta-Gdoutos, 2019). However, achieving a homogeneous dispersion of these additives is challenging and requires special dispersion techniques. These applications involve high costs and are generally limited to specialized projects (Oumer et al., 2024).

ELECTRICAL PROPERTY MEASUREMENT

Resistance and conductivity measurement techniques

In the characterization of electrically conductive concrete, resistance and conductivity measurement techniques are critically important for evaluating both the functional and structural performance of the concrete. One of the most commonly used methods for measuring the electrical properties of concrete is the *Wenner four-point probe method*. In this method, four electrodes are placed on the concrete surface: the outer two supply current, while the inner two measure the potential difference. Based on the measured values, surface electrical resistivity is calculated (Liu & Li, 2024). When used for reinforced concrete, this method may require calibration to minimize the influence of reinforcement bars on the measurement results (Liu & Li, 2024). Another method, the *embedded electrode technique*, allows for more precise measurement of the internal electrical properties of concrete. In this technique, copper electrodes are embedded into the

concrete to directly obtain internal resistance data (Zhang et al., 2022). This method is particularly effective in analyzing conductivity distribution in heterogeneous concrete structures (Zhang et al., 2022). The *Van der Pauw method* is used for measuring surface resistance in irregularly shaped or thin concrete slabs. In this method, four electrodes are placed around the perimeter of the concrete specimen, and various current-voltage combinations are applied to determine the average surface resistance. This method yields highly accurate results, especially for anisotropic materials (Ramadan et al., 1994).

In field applications, various electrode configurations are used. Arrays such as Wenner, Schlumberger, and dipole-dipole are particularly suitable for conducting electrical analyses on large concrete surfaces. These techniques allow for a broader assessment of the concrete's homogeneity, internal structure, and conductivity levels (Mirzaei et al., 2021). Another widely used technique in laboratory settings is the *two-electrode method*. In this approach, electrodes are attached to both ends of the sample, and resistance is measured directly. However, the major limitation of this method is that the contact resistance between the electrodes and the concrete may reduce measurement accuracy (Dehghanpour and Yilmaz, 2020). The choice of method depends on the geometry of the concrete specimen, the types of conductive additives used, and the depth at which conductivity is to be measured. Each method has its own advantages and limitations, but when applied correctly, these techniques enable reliable analysis of the electrical behavior of concrete (Liu & Li, 2024; Zhang et al., 2022).

In an experimental study conducted by Zhang et al. (2022), an embedded electrode system was used to measure the electrical resistance distribution of concrete and to simulate this distribution through modeling. In the study, four different cement-based mixtures were prepared, with parameters such as water/cement ratio, aggregate content, and type of additive systematically varied. During the casting process, four copper wire electrodes were symmetrically embedded in each specimen. Through these electrodes, electrical resistance values at specific points of the specimens were measured and their changes over time were monitored. During the experiments, the concrete samples were cured under standard temperature and humidity conditions, and measurements were taken on days 1, 3, 7, and 28. From the measurement data, the changes in electrical resistance throughout the hydration process were analyzed in detail. The results showed that as hydration progressed, the

microstructural densification within the concrete led to a significant increase in electrical resistance. Furthermore, samples with carbon additives exhibited lower initial resistance, and electrical conductivity was found to vary significantly depending on the type of additive used (Zhang et al., 2022). This study also supported the experimental findings through numerical modeling; the distribution of the electric field within the concrete was simulated using the finite element method. The high correlation between the simulation data and the experimental results confirmed the accuracy and effectiveness of the embedded electrode technique. In this context, the study not only contributed to the measurement of electrical properties of concrete but also provided important insights into how these measurements evolve over time.

Test methodologies and standards

1) Percolation threshold test

One of the fundamental criteria in determining the electrical performance of electrically conductive concrete is the *Percolation Threshold Test*, which is used to understand how conductivity changes based on the proportion of conductive additives incorporated into the concrete mix. This test defines the minimum amount of additive required to form a conductive network within the concrete matrix—this critical point is known as the *percolation threshold*. Below this threshold, the additives are dispersed randomly and do not create a continuous conductive path; however, once the threshold is exceeded, the additives begin to make contact with each other, forming continuous pathways through which electric current can flow. Experimental studies have shown that this threshold value varies depending on factors such as the type, size, shape, surface properties, and distribution of the additive within the concrete matrix. For instance, in an experimental study conducted by Xu et al. (2018) on carbon fiber-reinforced concrete, it was found that a carbon fiber volume ratio of 0.25–0.5% was sufficient to form a conductive network within the concrete, and that a sudden increase in conductivity occurred beyond this range—indicating the percolation threshold. It was also observed that concrete behaved as a high-resistance, insulating material when the additive ratio remained below this threshold.

Similarly, Li et al. (2022) reported that in tests performed on cement composites with expanded graphite additives, the graphite particles were able to form conductive networks even at lower content levels. Consequently, the percolation threshold was found to be

lower compared to carbon fiber mixtures. This is attributed to the higher specific surface area and plate-like structure of graphite, which allows it to disperse more effectively throughout the concrete matrix. As a result, high conductivity was achieved even with small amounts of additive. On the other hand, in a study conducted by Kim et al. (1993) on steel fiber-reinforced concrete, it was demonstrated that percolation behavior depends not only on the amount of additive but also on the orientation and spatial distribution of the fibers within the concrete. Non-uniform distribution or misalignment of steel fibers can hinder the formation of a continuous conductive path, raising the percolation threshold or preventing the desired level of conductivity from being achieved.

All these studies indicate that in the production of conductive concrete, achieving the desired electrical performance depends not only on the quantity of conductive additives used but also on their physical characteristics, distribution within the concrete, and the production method. Accurate determination of the percolation threshold is especially important for engineering applications that require specific electrical performance, such as heated surfaces, electromagnetic shielding systems, and smart infrastructure solutions. Therefore, percolation threshold tests are indispensable in the design and performance prediction of conductive concrete.

Surface Temperature test, conducted to evaluate the heating performance of electrically conductive concrete, involves applying a specific voltage to a concrete specimen, allowing current to flow through it, and measuring the surface temperature over time. This method is used to assess the suitability of the concrete for electrical heating applications. The Surface Temperature Test is a commonly used experimental method to determine the heating performance of electrically conductive concrete. In this method, an electric voltage is applied to concrete samples, and the resulting surface temperature increase caused by the flowing current is measured over time. The primary purpose of this test is to evaluate whether the concrete is suitable for use in electrical heating systems. For example, in a study conducted by Lo et al. (2021), concrete samples with varying graphite content were subjected to a 50 V voltage, and it was reported that the surface temperature of the mixture containing 20% graphite reached approximately 58 °C. This finding demonstrates that graphite enhances the Joule heating effect by forming electrical pathways within the concrete matrix. Similarly, Yang et al. (2023) observed in their study on concrete mixtures containing

steel and carbon fibers that both the fiber content and the applied voltage had a direct impact on surface temperature—higher values of each led to increased heating. This test not only evaluates the material's heat generation capacity but also allows assessment of the uniformity and continuity of the heat distribution.

Additionally, [Abdelrahman and ElGawady \(2021\)](#) emphasized that electrode design and placement play a significant role in heat distribution, highlighting that large-surface electrodes provide more uniform heating. These testing methods offer valuable technical data for evaluating the applicability of conductive concretes in snow-melting systems, heated pavements, and structural health monitoring systems.

In the electrical resistance and conductivity measurements techniques, electrodes are placed on the concrete specimen to measure electrical resistance. The four-probe method minimizes the influence of contact resistance, providing more accurate results. Electrical resistance and conductivity measurements are of critical importance in accurately evaluating the performance of conductive concretes. For this purpose, the two-probe and four-probe techniques are commonly used. Experimental studies have shown that the four-probe method yields more reliable and precise results by reducing contact resistance. However, it has also been demonstrated that two-probe measurements can be used effectively with proper calibration ([ASTM, 2023](#)). Moreover, the geometry and placement of electrodes significantly affect measurement results; different electrode configurations can lead to variations in resistance values ([Sensor et al., 2021](#)). In addition, it has been established that the water content of concrete is a determining factor in these measurements, with increasing moisture saturation resulting in lower electrical resistance ([JACT, 2022](#)). These findings highlight the importance of carefully controlling the measurement method, electrode design, and environmental conditions during conductivity testing. While AC helps reduce polarization effects, DC provides a simpler application. The appropriate type of current is selected depending on the test purpose and specimen characteristics. The application of direct current (DC) and alternating current (AC) in electrically conductive concrete significantly affects measurement outcomes. DC methods are often preferred due to their simplicity; however, polarization effects at the electrode–concrete interface can cause deviations in resistance values. Conversely, AC methods mitigate these polarization effects, offering more stable measurements ([Zhang et al., 2012](#)). In an experimental study conducted by Zhang and

colleagues, resistance values measured under both AC and DC were compared. It was reported that resistance values measured under AC were lower and more consistent than those under DC. Similarly, [Li et al. \(2022\)](#) observed an increase in resistance values over time under DC, indicating that the electrical properties of concrete may change in the long term. Furthermore, [Liu et al. \(2022\)](#) showed that AC methods allow for the evaluation not only of the ohmic properties but also of the capacitive and inductive characteristics of concrete. They noted that this makes the AC method more sensitive in detecting microstructural changes within the concrete matrix. These findings emphasize that the choice of current type in electrical testing should be made carefully, based on the objective of the measurement and the properties of the concrete.

2) Structural health monitoring systems

Electrically conductive concretes stand out with their potential for direct integration into structural health monitoring (SHM) systems, offering advantages over conventional concretes. Through the incorporation of conductive additives such as carbon nanotubes (CNTs), graphene, carbon black, and steel fibers, these concretes acquire piezoresistive properties, allowing them to detect external influences—such as applied loads, crack formation, and temperature fluctuations—via changes in electrical signals. Operating on the principle of resistance variation, these self-sensing systems can continuously monitor the durability and integrity of structures without requiring any external sensors embedded within the concrete ([Chu et al., 2023](#)). For example, [Lu et al. \(2023\)](#) demonstrated that incorporating CNT-polymer nanocomposite-coated aggregates into concrete significantly enhanced its electrical conductivity, enabling the detection of even micro-level cracks. This approach offers significant advantages, particularly in infrastructure requiring constant monitoring, such as bridges, tunnels, and high-rise buildings.

Additionally, in an experimental study conducted by [Zhang et al. \(2012\)](#), electrical resistance changes were analyzed in ultra-high-performance concretes (UHPC) containing CNTs and graphene under applied loads, revealing their strain-sensing potential. The study showed that resistance variation ratios were strongly correlated with the amount of deformation, indicating the effectiveness of these concretes in identifying the location and magnitude of damage. Furthermore, [Chu et al. \(2023\)](#), in their research on self-sensing concretes with carbon black additives, noted that these materials demonstrated

sensitivity to both short-term impact loads and long-term loading scenarios. This enables the monitoring of not only sudden stress events but also progressive fatigue-related damage over time. The use of such conductive concretes in structural health monitoring systems not only enhances structural safety but also contributes to reduced maintenance costs and enables earlier intervention. Additionally, the sensitivity of electrically conductive concrete to changes in temperature and humidity makes it a valuable component of multi-parameter monitoring systems. In this respect, by continuously tracking electrical signals in real time, it becomes possible to predict and prevent structural deterioration even before it occurs.

3) Self-Heating concretes (anti-icing)

Self-heating concretes are among the innovative construction materials developed to enhance infrastructure safety and improve energy efficiency, particularly in cold climates. These concretes fall under the category of electrically conductive cement-based composites (ECCC) and are capable of generating heat through Joule heating when an electric current is applied, thanks to conductive additives embedded in their matrix. The heat generated via resistive heating is dispersed throughout the surrounding concrete. As an alternative to traditional de-icing methods such as salting or mechanical removal, this technology effectively melts snow and ice on the surfaces of roads, bridges, and airport runways, thereby enhancing traffic safety and reducing maintenance costs. It can also be used as an “electrical curing” technique to accelerate the setting of fresh concrete under cold weather conditions (Zhao et al., 2024).

In the production of self-heating concretes, carbon-based additives (such as carbon fibers, carbon nanotubes, graphene, and carbon black) and metal-based conductive materials (e.g., steel fibers, stainless steel wires) are commonly utilized. These materials are embedded into the concrete matrix to enable the flow of electric current. The proportion, distribution, and bonding mechanism of these conductive materials within the concrete directly influence both its heating capacity and mechanical strength (Zhao et al., 2024). For instance, if the additive ratio is too low, a conductive percolation network cannot form and the system fails to heat; if too high, it may compromise workability and mechanical properties. Additionally, factors such as moisture content, internal temperature, and environmental conditions significantly affect the heating performance.

Experimental studies in the literature highlight both the technical and practical aspects of self-heating

concretes. In a comprehensive review published by Zhao et al. (2024) in the journal *Construction and Building Materials*, concrete samples containing various additives were subjected to a 20V direct current (DC) to evaluate their Joule heating performance. The experiments showed that samples with 0.5–1.0% carbon fiber content could reach temperatures between 45–50 °C from ambient conditions within approximately 10–15 minutes. Surface temperatures were measured using thermocouples placed on the samples, and differences in performance were observed depending on the distribution of electrical conductivity within the concrete. This study demonstrated that self-heating concretes are highly effective for snow and ice melting applications and could potentially replace traditional methods (Zhao et al., 2024). Similarly, in another study by Wang et al. (2021), the self-heating ability of ultra-high-performance concrete (UHPC) was enhanced by integrating stainless steel wires into the mix. When subjected to a 30V electrical current, the ice placed on the concrete surface melted completely within approximately 30 minutes. The results suggest that such concretes offer an environmentally friendly and durable solution for transportation infrastructure, particularly in strategic areas like airport runways, tunnel entrances, and bridge decks (Wang et al., 2021). Moreover, these concretes can be integrated into smart systems and activated only when necessary, thereby promoting energy efficiency. In conclusion, self-heating concretes offer a promising solution to the construction industry's demand for sustainable and high-performance materials. Although existing experimental studies have proven the practicality and effectiveness of this technology, further research is needed on topics such as long-term performance, energy consumption, environmental impacts, and cost-effectiveness. Critical factors for large-scale adoption include the homogeneous distribution of additives, material compatibility, and the concrete's ability to retain its electrical properties throughout its service life (Zhao et al., 2024; Wang et al., 2021).

4) Electromagnetic shielding applications

Today, electromagnetic interference (EMI) poses a significant threat to the safety and functionality of electronic devices. Therefore, developing construction materials capable of providing electromagnetic shielding has become increasingly important. Electrically conductive concretes stand out in this context as hybrid materials with the potential to offer EMI protection. The ability of concrete to absorb or reflect electromagnetic waves depends on the type of conductive additives it

contains and the geometry of its surface. In a study conducted by Li et al. (2024), the electromagnetic wave absorption capacity of cement-based mortars modified with carbon black (CB) was investigated. Specifically, samples produced with a pyramidal surface design were evaluated in the frequency range of 1.1–18 GHz. Due to its high surface area and conductive structure, carbon black formed numerous conductive pathways within the mortar's microstructure, facilitating the penetration and absorption of electromagnetic waves. The pyramidal surface design promoted multiple internal reflections of the incoming waves, increasing energy dissipation, and achieving a reflection loss of up to -30 dB. This level of performance indicates that sufficient electromagnetic shielding was achieved for both military and industrial applications. Furthermore, these samples absorbed a significant portion of the incoming wave energy, minimizing reflection.

In another study, Wang et al. (2024) developed cement-based electromagnetic absorbing composites using industrial graphite waste (GT) and steel fibers (SF). While GT, with its high carbon content, enhanced electrical conductivity, the steel fibers not only improved structural strength but also contributed to the scattering of electromagnetic waves within the material, thereby enhancing absorption capacity. Experimental results showed that when the GT content was increased to 6% and the SF content to 1%, an effective electromagnetic absorption performance with a reflection loss of -23 dB was achieved. Moreover, the compressive strength of these composites remained within an acceptable range. These findings demonstrate that such materials not only provide electromagnetic shielding but also retain mechanical integrity, making them viable for use in the construction industry. When both studies are considered together, it becomes evident that cement-based materials modified with conductive additives can be functional in terms of both mechanical and electromagnetic performance. These materials, which offer EMI shielding without compromising structural properties, have significant application potential in environments sensitive to electromagnetic radiation, such as smart buildings, data centers, military facilities, and hospitals.

5) Grounding and insulation systems

Unlike traditional concrete, which is typically an electrical insulator, electrically conductive concretes are composite materials enhanced with conductive additives that enable the transmission of electrical current and allow interaction with electromagnetic fields. These unique

properties make conductive concrete a valuable alternative in applications requiring grounding systems and thermal-electrical insulation. While conventional metal electrodes used in grounding systems tend to corrode over time and suffer performance degradation, conductive concretes offer more stable performance due to their long service life and large surface contact area (Zhao et al., 2017). In an experimental study conducted by Zhao et al. (2017), a cement-based concrete mixture modified with carbon fibers and carbon black was investigated for its potential use as an alternative grounding electrode for power transmission towers. The samples used in the study contained 0.1% carbon fibers and 0.1% carbon black, which significantly improved the electrical conductivity of the concrete. After a 28-day curing period, the electrical resistivity of the concrete was measured at approximately $530 \Omega \cdot \text{cm}$. Furthermore, the samples were tested within a temperature range of -40°C to 50°C , and conductivity remained stable despite the thermal variations. In terms of mechanical performance, the samples exhibited a compressive strength of 35.8 MPa and a flexural strength of 6.3 MPa, indicating that they could meet both electrical and structural requirements. Compared to conventional metal rods, these concrete electrodes provided lower grounding resistance and demonstrated greater resistance to corrosion (Zhao et al., 2017).

In another study, the effect of electrode embedding depth on the electrical and thermal performance of conductive concrete was examined (Yu et al., 2024). In this study, electrodes were embedded at various depths within the concrete specimens, and surface temperature distributions and energy consumption were measured under applied voltage. Results showed that deeper electrode placement led to slower but more uniform surface temperature increases. Additionally, when the applied voltage exceeded a certain threshold, resistance fluctuations and instabilities were observed within the internal structure of the concrete. This finding highlights the importance of carefully determining optimal voltage levels and electrode embedding depths to maintain long-term electrical stability. The researchers emphasized that for concrete systems exposed to external environmental conditions, careful optimization of these parameters is crucial for maintaining energy efficiency and system reliability (Yu et al., 2024). Together, these two experimental studies demonstrate that electrically conductive concretes can be effectively used not only for electromagnetic shielding but also for grounding systems and surface heating applications. Their advantages—such as long service life, low maintenance requirements, high

structural strength, and environmental stability—make them increasingly attractive for advanced engineering applications.

6) Smart infrastructure and energy systems

Electrically conductive concretes offer significantly more functional features compared to traditional concrete materials, making them especially prominent in smart infrastructure and energy systems. Thanks to the inclusion of conductive additives such as carbon fibers, steel fibers, graphite powder, carbon black, and carbon nanotubes, this type of concrete can conduct electricity. The addition of electrical conductivity enables the use of such concrete in applications like self-heating, structural health monitoring, and energy management (Ağdaşlı et al., 2020). In particular, the use of these concretes in cold climate regions—such as airport runways, sidewalks, and bridge surfaces—is of great importance for preventing icing. Through their heating capabilities, snow and ice can be rapidly melted from surfaces, thereby increasing safety and reducing environmental impacts. For example, in one study, 36 different concrete mixtures were prepared using nano carbon black derived from waste tires and wire erosion waste. These mixtures were tested for both mechanical and electrical performance. The best-performing mixture (N6C1S0) provided a heat output ranging from 180 to 1315 W/m² during electrothermal tests conducted at −10 °C, effectively demonstrating deicing performance (Ağdaşlı et al., 2020). Similarly, in another study, deicing was achieved using carbon fiber-reinforced concretes without the need for salt, and it was emphasized that this system is more environmentally sustainable compared to conventional salting methods (Kheradmand et al., 2019). These types of applications enable electrically conductive concretes to go beyond being mere construction materials and become active components of infrastructure.

Additionally, the heating performance and flexural strength of mortars reinforced with carbon and steel fibers have been tested under laboratory conditions. When a voltage of 30 V was applied, the surface temperature reached up to 50 °C, and with a fiber content of 1.25%, the flexural strength increased to 5.2 MPa (Jang et al., 2023). Furthermore, another study conducted on mortars enriched with carbon nanotubes and carbon nanofibers revealed that these materials significantly enhanced the electrical resistance and strain-sensing capabilities of the composite. This makes it possible to monitor the structural health of buildings in real time and detect potential damages at an early stage (Zhang et al., 2022). In conclusion, electrically

conductive concretes contribute significantly to energy efficiency, environmental sustainability, and infrastructure safety. Especially in smart city applications, the widespread use of these materials holds the potential to make infrastructure systems more secure, durable, and efficient.

ADVANTAGES AND LIMITATIONS

Performance Advantages

Electrically conductive concrete (ECC) can be used not only as a structural material but also as part of smart systems with active functionality. One of the most notable performance advantages of ECC is its ability to generate heat when electrical current is applied, thereby melting snow and ice on its surface. This feature offers an environmentally friendly alternative to methods involving the use of salt and chemicals, which are harmful to the environment, especially for deicing infrastructure elements like roads, bridges, and airport runways in cold climates. The study conducted by Kheradmand et al. (2019) investigates the effectiveness of carbon fiber-reinforced electrically conductive concretes (ECON) in snow and ice melting applications without the use of salt. This research aims to reduce the environmental harm caused by traditional deicing methods and to offer more sustainable infrastructure solutions.

The study extensively examines how the inclusion of carbon fibers in the concrete mix affects its electrical and thermal properties. The researchers identified the percolation threshold of carbon fibers within the concrete to determine the optimal fiber dosage. This threshold refers to the point at which a continuous conductive network is formed within the concrete. The percolation thresholds were determined as 0.25–1% (by volume) for cement paste, 0.6–1% for mortar, and 0.5–0.75% for concrete. These values indicate the minimum amount of carbon fibers required to enhance the concrete's conductivity. Experimental results showed that the concrete mixture containing 0.75% carbon fiber reached an electrical conductivity of 1.86×10^{-2} S/cm after a 28-day curing period. This value decreased to 1.22×10^{-2} S/cm after 460 days, indicating a reduction in conductivity over time, although the concrete still maintained adequate conductivity. Additionally, the efficiency of converting electrical energy into thermal energy was recorded as 66% on day 28, decreasing to 50% on day 460. These findings are important for assessing the system's long-term performance. Furthermore, the design of the developed ECON system was evaluated using finite element (FE)

modeling, and its snow/ice melting capacity was analyzed. The results demonstrated that with appropriate mix ratios and system configurations, ECON could be an effective deicing solution for infrastructure elements such as highways and airport runways. This study shows that carbon fiber-reinforced electrically conductive concretes can be used as an environmentally friendly and energy-efficient alternative. However, further research is needed on the sustainability of long-term performance and the optimization of system design.

In addition to its heating capabilities, electrically conductive concrete (ECC) holds significant potential for use in structural health monitoring systems. Conductive fiber additives endow the concrete with piezoresistive properties—meaning that the material exhibits changes in electrical resistance under stress or deformation, allowing for the real-time detection of crack formation or structural deterioration. A study conducted by Ağdaşlı et al., (2020) examined the piezoresistive properties of electrically conductive concretes. This property, which refers to changes in the electrical resistance of concrete under mechanical stress, is a crucial parameter for structural health monitoring systems. In the study, concrete mixtures with varying carbon fiber contents were prepared, and their electrical conductivity and mechanical properties were tested. Experimental results showed that increasing the proportion of carbon fibers led to a significant improvement in the electrical conductivity of the concrete. Furthermore, changes in electrical resistance were monitored during the application of mechanical stress, and it was found that these changes were sensitive to the deformation of the concrete. These findings demonstrate that carbon fiber-reinforced electrically conductive concretes can be used as sensors in structural health monitoring systems. This enables the real-time monitoring of concrete structures and the early detection of potential damage. The study reveals that electrically conductive concretes are not only suitable for heating applications but also for advanced uses such as structural health monitoring. However, further research is needed in this area, especially to evaluate long-term performance.

Electrically conductive concretes (ECC) offer significant advantages not only in heating functionality but also in terms of energy efficiency and mechanical strength when compared to traditional systems. In ECC systems, electrical energy is directly transferred into the concrete, eliminating the need for external heating systems and minimizing energy losses. This feature provides an environmentally friendly and energy-saving solution for deicing and heating infrastructure components in cold

climates. In a study conducted by Jang et al. (2023), self-heating concrete systems reinforced with carbon and steel fibers were investigated. Different concrete mixes were prepared with varying ratios of carbon fiber (CF) and steel fiber (SF), and their heating performance and flexural strength were tested. As a result, a concrete sample containing 1.25% carbon fiber reached a surface temperature of up to 145.1 °C under 30 V of applied voltage. Additionally, the flexural strength of this mix was measured at 5.2 MPa. These results indicate that ECC not only provides functional performance but also maintains sufficient mechanical strength.

This study highlights the potential of ECC in terms of energy efficiency and mechanical strength. The conductive fiber network within the concrete allows for effective conversion of electrical energy into heat. At the same time, with appropriate fiber content, the mechanical properties of the concrete can be preserved or even enhanced. These characteristics show that ECC is an effective solution for dealing with snow and ice in winter conditions and contributes to the development of sustainable infrastructure systems. The use of recycled materials in the production of electrically conductive concrete (ECC) offers significant benefits in terms of both environmental sustainability and technical performance. The inclusion of industrial by-products such as graphite, steel slag (SS), and ground granulated blast furnace slag (GGBS) in concrete mixtures increases electrical conductivity and helps optimize mechanical strength.

In a study conducted by Li et al. (2022), 27 different concrete mixes containing graphite powder, steel slag, and GGBS were prepared and analyzed for their mechanical and electrical properties. One particular mix, containing 4% graphite powder, 15% GGBS, and 20% steel slag, achieved 3.4 MPa in flexural strength, 36 MPa in compressive strength, and 7.779 $\Omega \cdot \text{cm}$ in electrical resistivity. These results demonstrate that, with the appropriate proportions, recycled materials can meet both the structural and functional requirements of ECC. The study also noted that while graphite improves conductivity, it may reduce mechanical strength, whereas steel slag and GGBS enhance mechanical properties but have a limited effect on conductivity. Therefore, a balanced combination of these materials is recommended to achieve optimal performance.

These findings show that ECC can be developed using sustainable materials and offer an effective solution for environmentally friendly infrastructure applications.

One of the key advantages of electrically conductive concrete (ECC) systems is their adaptability in terms of

system design and performance to meet user needs. This flexibility is particularly important regarding the effects of electrode size and placement on the electrical and thermal performance of the concrete. A study by [Malakooti et al. \(2021\)](#) investigated the impact of different electrode sizes and configurations on the heating performance of ECC. Various types of stainless steel electrodes were used to prepare prototype concrete slabs measuring 24 inches $\times$ 24 inches (610 mm $\times$ 610 mm). In all slabs, the distance between the electrodes was fixed at 18 inches (460 mm), and an AC voltage of 60 V was applied. Experimental results showed that increasing electrode diameter enabled faster and higher surface temperature rise. For instance, electrodes with a 1-inch (25 mm) diameter increased the surface temperature by 7.4°C within 2 hours, while smaller 0.75-inch (19 mm) electrodes achieved a lower temperature rise. This indicates that larger electrodes provide more efficient heating. However, smaller electrodes are more cost-effective and can still offer satisfactory energy efficiency. These findings indicate that the performance of ECC systems can be optimized according to application requirements. Specifically, careful design of electrode size and placement enhances energy efficiency while reducing costs. Therefore, in ECC system design, it is crucial to develop customized solutions tailored to the needs of the application area and environmental conditions. [Dehghanpour & Yilmaz, \(2020\)](#) investigated the potential of electrically conductive concrete (ECC) for snow and ice mitigation applications, an area of increasing interest in recent years. Recognizing that the long-term conductivity of ECC incorporating steel fibers diminishes due to corrosion, they proposed the development of steel fiber-free conductive concrete alternatives. In this study, their primary objective was to examine the behavior of rebars embedded in ECC that does not contain steel fibers. To this end, ECC slab specimens measuring 45 $\times$ 45 $\times$ 5 cm were produced, both with and without Φ 10 steel rebars. Carbon fiber was employed as the sole conductive fiber type in all mixtures. The heating performance and thermal behavior of the slabs were evaluated in a controlled cooling environment at approximately -10°C . According to their findings, in rebar-reinforced specimens, temperature increase initiated near the electrode regions and gradually progressed toward the center of the slabs. In contrast, in specimens without rebars, the temperature rise appeared to initiate from random locations across the surface ([Dehghanpour & Yilmaz, 2020](#)).

Fig. 4 shows the schematic of the electrical conductor mixing procedure and molding.

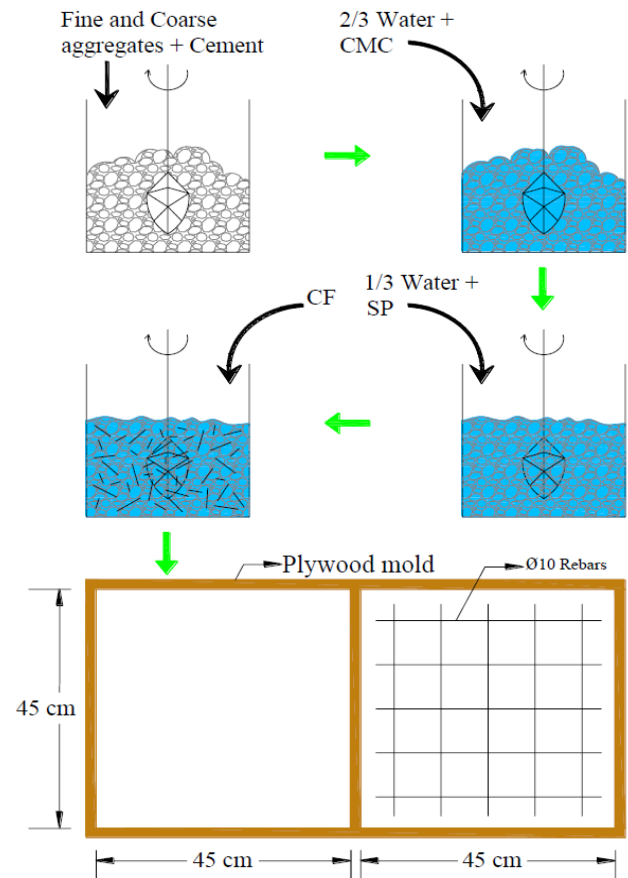


Fig. 4. Schematic view of electrical conductive mixing procedure and molding.

7.2. Mechanical–Electrical Balance

Electrically conductive concretes (ECC) combine both electrical and mechanical properties, making them suitable for various engineering applications. These concretes are enhanced with conductive additives such as carbon fibers, steel fibers, graphite powder, and graphene to achieve electrical conductivity. In terms of mechanical balance, these additives can affect the concrete's strength, crack behavior, and deformation characteristics. The mechanical balance of ECCs is directly related to the amount and distribution of the conductive additives. For example, while the addition of graphite powder and steel fibers can improve the electrical conductivity of concrete, excessive use of these additives may adversely affect mechanical strength. Therefore, it is necessary to establish a balance between electrical conductivity and mechanical performance. Additionally, ECCs can be used for deicing applications during winter months due to their self-heating capabilities. Such applications require the optimization of both electrical conductivity and mechanical strength of the concrete ([Oumer et al., 2018](#)). Several experimental studies have investigated the mechanical and electrical balance in electrically conductive concretes. These studies examine how different types and amounts of additives influence both the mechanical strength and the electrical

conductivity of concrete. In a study involving conductive concrete containing iron particles and nano-graphite, an industrial by-product called ING (iron nano-graphite) was used. Experiments on concrete samples with different ING ratios showed a significant increase in electrical conductivity depending on the additive ratio. However, particularly with a 5% additive ratio, a slight decrease in mechanical strength was observed. This result indicates that additives which enhance electrical performance can negatively affect mechanical properties when used beyond a certain threshold (Dong et al., 2021). Another study aimed at simultaneously optimizing mechanical strength and electrical conductivity tested the performance of cement composites using various additives (carbon fiber, steel fiber, graphite powder, and carbon black). The findings revealed that each additive had a different impact on the mechanical and electrical properties of the concrete. For instance, carbon black provided high conductivity but did not significantly contribute to mechanical strength. The most successful results were obtained from mixtures that combined carbon fiber and graphite powder. This highlights the importance of carefully selecting the type and proportion of additives when developing multifunctional concretes (Abbas & Alsaif, 2025). In another study examining the effect of carbon fiber on heating capacity, concrete samples containing 0.1% to 0.5% carbon fiber were prepared, and their electrical conductivity as well as electromagnetic heating performance were evaluated. Experimental results showed that increasing the carbon fiber content improved not only electrical conductivity but also heating performance. In particular, samples containing 0.5% carbon fiber exhibited a rapid temperature increase in the concrete when voltage was applied. This demonstrates the potential of carbon fiber-reinforced concrete for heated pavement applications aimed at melting snow and ice (Ji et al., 2023). Scanning Electron Microscopy (SEM) images play a crucial role in examining the microstructural properties of electrically conductive concretes. In this study, SEM images from two different articles were compared: carbon fiber-reinforced conductive concrete (Ji et al., 2023) and conductive cement composites containing carbon black and carbon fiber (Gwon et al., 2023).

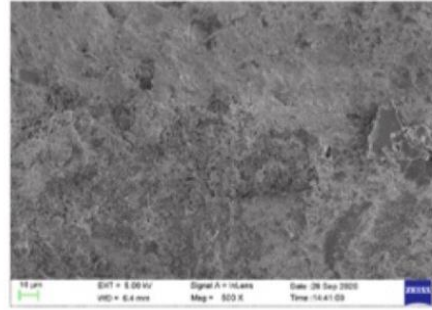
In the study by Ji et al. (2023), the SEM images show the distribution and bonding state of carbon fibers uniformly dispersed in the concrete matrix. The images clearly display the fiber network within the concrete; the fibers contact each other, forming a percolation network that ensures electrical conductivity. Moreover, the fibers are tightly bonded with the cement paste, which positively contributes to both mechanical strength and conductivity performance. The diameter and length of the fibers are described in detail in the SEM images, and a homogeneous distribution within the matrix is reported. Fig. 5. Shows the Microstructure of specimens with different carbon fiber content at 14 days and SEM images of carbon black: (f) 20,000 × , (g) 100,000 ×

The SEM images presented in the study by Gwon et al. (2023) detail the distribution of conductive particles (carbon black and carbon fiber) within the cement matrix and their interactions. It was observed that the carbon black particles, although small in size, were distributed somewhat irregularly, while the carbon fibers played a critical role in bridging these particles, thus forming an electrically conductive network. In the images, regions with agglomerated carbon black particles were also identified, which could lead to local heterogeneities in conductivity. Furthermore, some voids were detected between the cement paste and the particles, potentially affecting the microstructural strength of the composite. Both articles emphasize the critical role of carbon fibers in forming conductive networks. In the study by Ji et al. (2023), carbon fibers were found to be more evenly and uniformly dispersed within the matrix, resulting in a lower percolation threshold and the formation of a more effective conductive network. In contrast, in the study by Gwon et al. (2023), the irregular and agglomerated structure of carbon black particles hindered uniform conductivity and led to increased local electrical resistance. SEM images further reveal that fiber-matrix bonding, which directly influences mechanical strength, was more successful in the study by Ji et al. In contrast, voids and particle agglomerations observed in the study by Gwon et al. (2023), were linked to reduced mechanical properties of the composite. In conclusion, SEM analyses demonstrate that the distribution of carbon fibers within electrically conductive concrete and cement composites is a decisive factor in determining both electrical conductivity and mechanical strength. The homogeneous and efficient fiber network presented in Article 1 offers superior performance compared to the more heterogeneous particle distribution in Article 2. In a study focused on electrically conductive concrete with carbon fiber additives, the effects of varying carbon fiber dosages on electrical conductivity and mechanical strength were thoroughly investigated. Specimens were prepared with carbon fiber contents ranging from 0.25% to 1.0%, and their electrical and mechanical performances were tested. The results showed a significant improvement in electrical conductivity with increasing carbon fiber content, along with a notable enhancement in mechanical strength. This indicates that carbon fibers not only form conductive pathways to boost electrical performance but also limit crack propagation, thereby strengthening the mechanical properties of the concrete (Sassani et al., 2018).

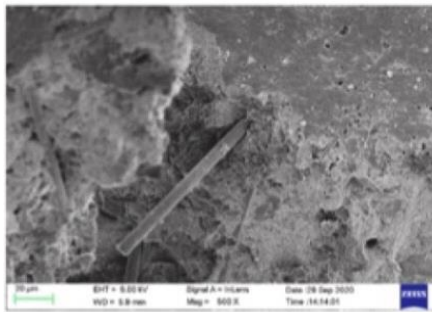
In another study involving the use of steel slag aggregates, concrete mixtures were prepared by replacing natural aggregates with various proportions of steel slag, and the electrical conductivity and mechanical strength of these specimens were evaluated. Up to 50% steel slag replacement led to improvements in both conductivity and compressive strength. However, at 75% replacement, a decline in mechanical strength was observed due to an increase in internal porosity. The study concluded that

using industrial by-products like steel slag in appropriate proportions can enable the production of environmentally

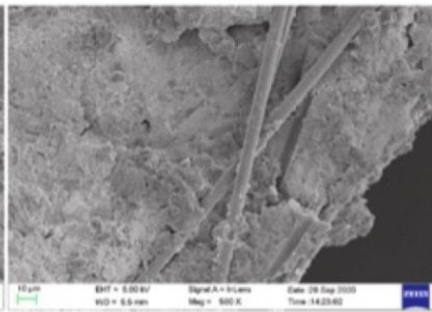
and technically beneficial conductive concrete (Santillán et al., 2022).



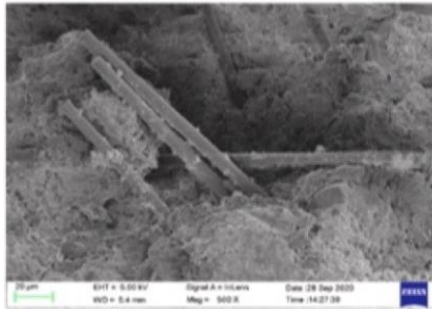
(a) 0 % (C-1)



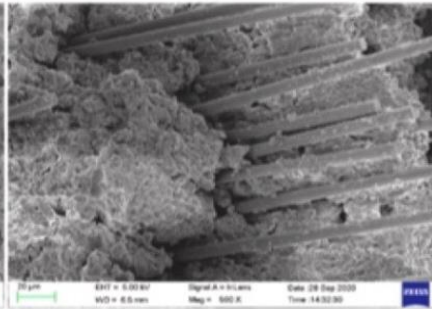
(b) 0.38 % (C-2)



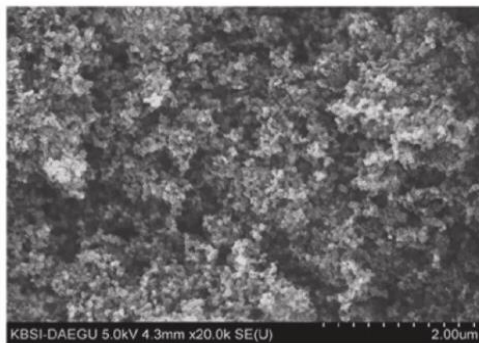
(c) 0.75 % (C-3)



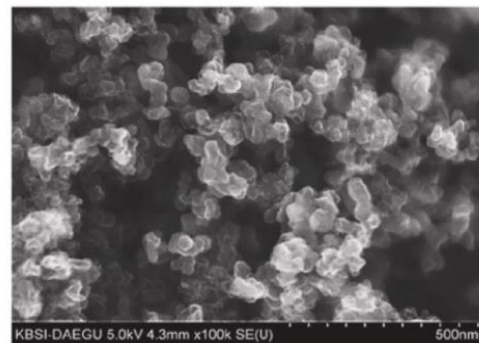
(d) 1.13% (C-4)



(e) 1.50 % (C-5)



(f)



(g)

Fig. 5. Microstructure of specimens with different carbon fiber content at 14 d. Ji et al., (2023) and SEM images of carbon black: (f) 20,000 ×, (G) 100,000 ×

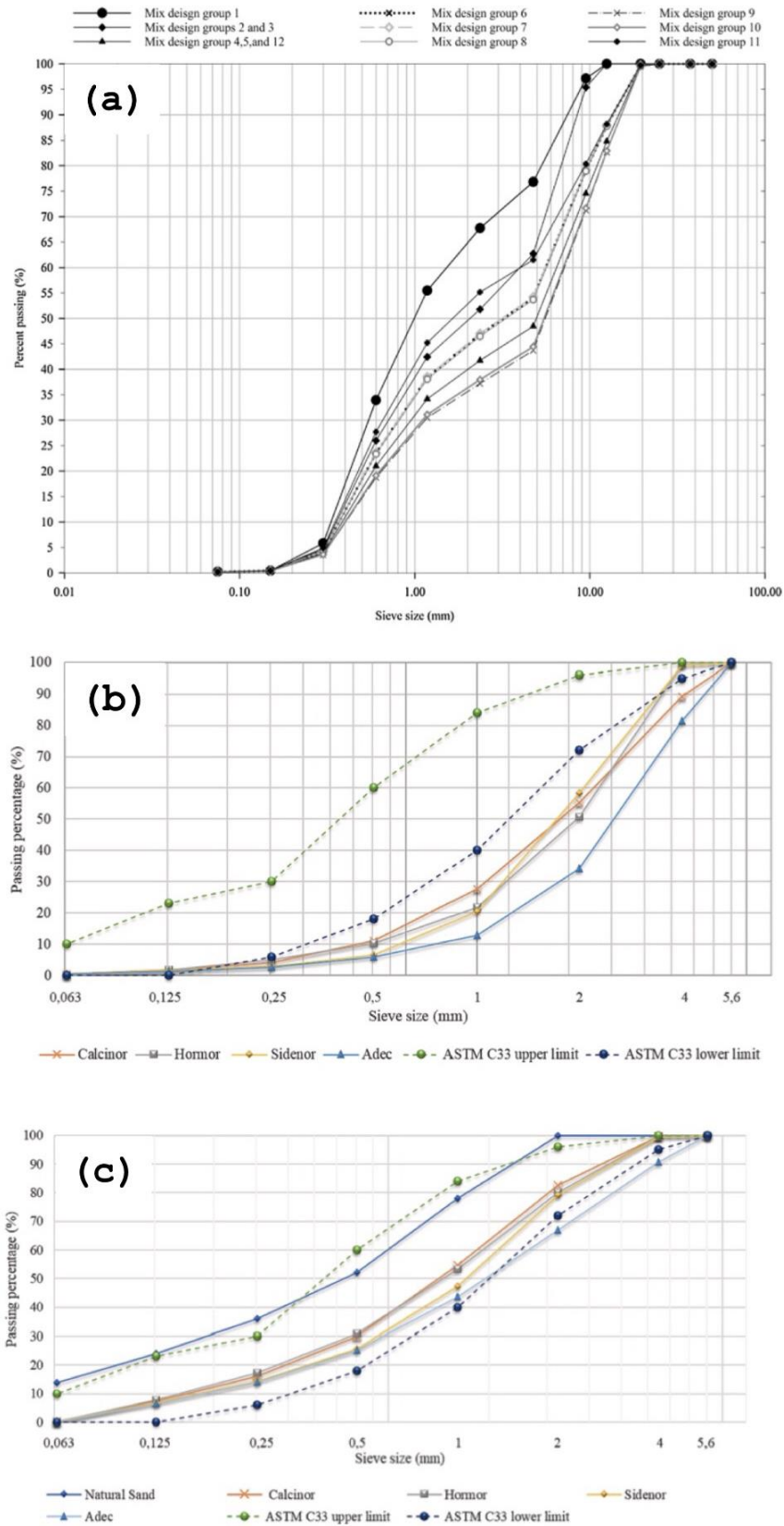


Fig. 6. Microstructure of specimens with different carbon fiber content at 14 d. Ji et al., (2023) and SEM images of carbon black: (f) 20,000 ×, (G) 100,000 ×

The particle size distributions of various aggregates used in the graphs above have been comparatively evaluated using three different graphs from the literature. These graphs are significant in demonstrating the potential of both natural and alternative aggregates—particularly steel slag—in concrete mix designs. The gradation curves presented by [Sassani et al. \(2018\)](#) illustrated the particle size distribution of aggregate systems across 11 different mixture design groups. The sieve sizes range from 0.01 mm to 100 mm and are plotted on a logarithmic scale, allowing for a detailed analysis of both fine and coarse aggregate distributions. The resulting curves reveal clear differences among the mixture groups. Notably, Group 1 displays a finer gradation, while Groups 4, 5, and 12 are dominated by coarser aggregates. This variation suggests that the concrete mixtures were specifically tailored to meet different strength and workability requirements. The gradation curves presented by [Santillán et al. \(2022\)](#) show the particle size distributions of fine aggregates obtained from four different steel slag sources (Calcínor, Hormor, Sidenor, Adec). These distributions are compared against the upper and lower limits defined by ASTM C33 standards. According to the results, the slag from the Adec source appears to have a coarser texture and falls outside the ASTM limits. In contrast, slags from the other sources mostly remain within the ASTM C33 boundaries, suggesting that these slags are suitable for use in concrete production. These findings indicate that steel slag with acceptable gradation characteristics can be obtained from specific suppliers.

Another set of gradation curves from [Santillán et al. \(2022\)](#) evaluates the effect of gradation corrections on steel slag and compares these materials with natural sand. Slags from Calcínor, Hormor, Sidenor, and Adec were analyzed alongside a natural sand sample. It was observed that natural sand exhibited higher passing percentages, indicating a finer overall texture. After gradation adjustments, the steel slag samples were brought within ASTM C33 limits and displayed particle size distributions quite similar to that of natural sand. This outcome significantly enhances the feasibility of replacing natural sand with steel slag, offering a valuable advantage in terms of sustainable material management. When all three graphs are collectively assessed, it becomes evident that the gradation characteristics of aggregate systems directly influence both mix performance and material suitability. While the study by [Sassani et al. \(2018\)](#) revealed the variation in aggregate blend designs, the other two graphs assess the compliance of steel slag with standards and its

comparative performance with natural sand. The fact that corrected steel slag falls within ASTM C33 limits and performs similarly to natural sand underscores its potential as a viable alternative material for sustainable construction applications. All these studies collectively emphasize that the performance of electrically conductive concretes depends not only on the type of conductive additive used but also on its dosage, combination, and distribution within the concrete matrix. Furthermore, since mechanical strength must also be ensured alongside electrical conductivity, comprehensive and multi-dimensional optimization studies are essential. Fig. 6(a) shows the gradation curves of aggregate systems used in the mix design groups. Fig. 6(b) presents the grain size distribution of fine steel slag aggregates, while Fig. 6(c) illustrates the grain size distribution of corrected steel slag aggregates.

7.3. Long-Term Durability

The long-term durability of electrically conductive concrete is of great importance in terms of how well the material can maintain both its electrical performance and mechanical properties against environmental influences. These types of concrete, particularly used for melting snow and ice under winter conditions, must retain their electrical conductivity and mechanical strength when exposed to harsh environmental conditions such as sulfate attack and freeze-thaw cycles. In one study, long-term sulfate exposure tests were conducted on electrically conductive sand concrete. The results showed a fluctuation of about 15% in mechanical strength, while a continuous increase in electrical conductivity was observed ([Gordina et al., 2022](#)). This suggests that sulfate ions chemically interact with the conductive additives within the concrete, altering the electrical network structure, though these changes have a relatively limited impact on mechanical properties. Additionally, experiments on electrically conductive concrete containing graphene oxide revealed that adding 0.09% graphene oxide improved both mechanical strength and electrical conductivity. However, considering the permeability characteristics of the concrete, it was reported that in pervious concrete, both mechanical and electrical performance declined ([Wang et al., 2023](#)). This indicates a critical balance issue caused by the interaction between the structural characteristics of pervious concrete and conductive additives.

In another study on electrically conductive concrete containing steel fibers and graphite powder, it was found that graphite powder significantly increased electrical conductivity but caused a noticeable decrease in

mechanical strength (Silva et al., 2022). This study emphasizes the trade-off between electrical conductivity and mechanical strength and the necessity of optimizing both properties. It is particularly important to consider that excessive use of additives such as graphite may weaken the structural integrity of the concrete. Table 2 shows the comparison of studies by Wang et al. (2023) and Silva et al. (2022) on electrically conductive concrete.

In general, to ensure long-term performance in the design of electrically conductive concrete, a careful balance must be established between electrical conductivity and mechanical strength. Optimized mixtures should be developed by considering the type and amount of conductive additives as well as the structural properties of the concrete. In this way, the durability of the concrete against environmental effects can be enhanced without compromising its electrical performance.

Table 2. Comparison of Studies by Wang and Silva on electrically conductive concrete

Feature	Wang et al. (2023)	Silva et al. (2022)
Main Additives	RGO, Carbon fiber, Steel fiber	Steel fiber, Graphite powder
Mechanical Performance	Increase (20% in compressive, 15% in flexural strength)	Decrease (as graphite increases)
Electrical Conductivity	Increase	Increase (as graphite increases)
Microstructure Analysis	SEM images	SEM images
Long-Term Durability	Tests against sulfate solutions	Tests not specified

7.4. Cost and Applicability

Electrically conductive concrete (ECON) presents a promising alternative, particularly in cold climate regions, for removing ice and snow accumulation on road surfaces. However, the large-scale applicability and economic sustainability of this technology vary depending on the type and proportion of conductive additives used as well as the production methods. The cost-effectiveness of electrically conductive concrete is largely influenced by the type and quantity of conductive materials incorporated into the mix. In the development of electrically conductive concrete, cost-efficiency and sustainability have become increasingly important considerations. In this context, a study conducted by Dehghanpour et al. (2019) comprehensively evaluated the economic and environmental contributions of materials obtained from secondary sources—such as recycled nano carbon black (RNCB) and waste wire erosion particles (WWE)—when added to concrete mixtures. The study analyzed the cost of three different mixes with similar levels of electrical conductivity. The mix containing only 1% by volume of carbon fiber (CF) was calculated to cost \$914.95. In comparison, a mix with 6% RNCB and 0.5% CF cost \$517.38, while a third mix containing 6% RNCB, 0.2% CF, and 1.5% WWE cost \$576.93. This analysis demonstrated that appropriate combinations of waste materials can yield cost savings of between 37% and 43% (Dehghanpour et al., 2019).

From a sustainability standpoint, all the additives used in the study were derived from industrial waste and are reusable materials that pose no harm to the environment. RNCB was recovered from end-of-life vehicle tires, and

WWE was obtained from waste generated during wire erosion processes. As a result, the study not only contributes to effective waste management but also offers economical and environmentally friendly alternatives to traditional, more expensive, and ecologically harmful carbon-based additives. Additionally, the concrete produced with these additives not only enhanced electrical conductivity but also showed improvements in mechanical properties such as impact and flexural strength. Therefore, the study presents environmentally conscious, long-lasting, and cost-effective concrete solutions for sustainable urbanization and infrastructure systems (Dehghanpour et al., 2019).

8. CURRENT RESEARCH AND EMERGING TECHNOLOGIES

8.1. Next-generation conductive materials

Electrically conductive concrete (ECCC) is an advanced engineering material that extends beyond the structural load-bearing properties of conventional concrete, offering smart functionalities. These types of concrete are developed for a wide range of engineering applications such as self-heating, strain sensing, electromagnetic interference shielding, and energy harvesting. These functionalities are achieved by incorporating high-conductivity additives into the cementitious matrix (Zhou et al., 2024). Next-generation conductive materials enable the creation of multifunctional concrete structures and offer sustainable, energy-efficient solutions. Additives such as carbon nanotubes, graphene oxide, and carbon fibers provide significant improvements in both conductivity and mechanical performance. However, future research must focus on optimizing

additive dosages, improving dispersion techniques, and evaluating long-term durability.

Carbon-based additive materials such as CNT and CF increase electrical conductivity and also exhibit positive contributions micromechanically. CBRC analysis by Dehghanpour et al. (2022) showed that incorporating CNT, Al_2O_3 and CF significantly reduces the indentation depth, indicating increased hardness and strength. The CNT0.04A4CF0.4 sample exhibited the lowest depth (1323 nm), suggesting the highest resistance to crack propagation. Improvements are attributed to enhanced interface adhesion and stiffness. CNTs were more effective than CF alone, and Al_2O_3 contributed to crack inhibition. Overall, reinforcing elements increased compressive and flexural strength by improving micromechanical performance and reducing brittleness (Dehghanpour et al., 2022). Curves summarizing these results are shown in Fig 6.

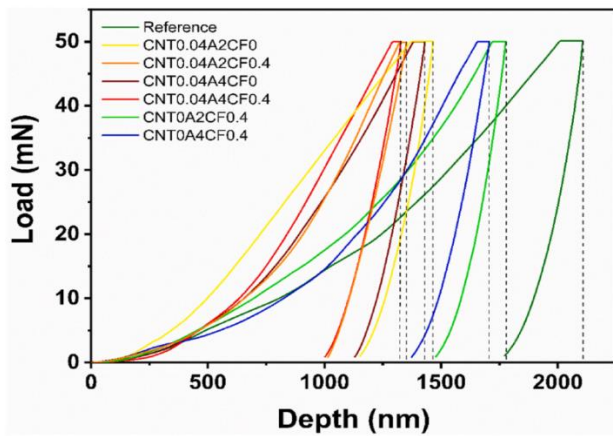


Figure 6. CBRC analysis results of cement mixtures containing alumina, CNT and CF (Dehghanpour et al., 2022).

8.2. Functional material integration

In recent years, sustainability, multifunctionality, and smart material approaches have gained prominence in civil engineering. In this context, electrically conductive concretes (ECCs) have drawn attention not only for their mechanical performance but also for their environmental and technological functionalities. Through the integration of various carbon-based additives—such as carbon fibers, carbon nanotubes, graphene, and biochar—or metallic additives into the concrete matrix, conductivity is achieved. This property enables the use of ECCs in a wide range of advanced applications, including self-monitoring, heating, de-icing, and electromagnetic shielding (Zhang et al., 2018; Al-Attar et al., 2022; Ramos et al., 2022). For instance, an experimental study by Zhang et al. (2018) investigated the potential of carbon fiber-reinforced concrete to prevent surface icing. The incorporation of carbon fibers at rates between 0.5–1.0% improved the electrical conductivity of the concrete while also positively

impacting its mechanical strength. The study demonstrated that with uniform integration, carbon fibers can enable the development of surface-heating concrete elements. Similarly, Al-Attar et al. (2022) compared the electrical properties of concrete samples containing carbon nanofibers (CNFs) produced using conventional casting and 3D printing techniques. Their findings indicated that the 3D printing method facilitated better alignment of CNFs within the matrix, resulting in improved electrical conductivity. Moreover, the moisture content of the concrete significantly affected its conductivity—highlighting an important parameter to consider in material design.

In studies focused on structural health monitoring (SHM), the piezoresistive properties of carbon nanotubes, graphene, and carbon nanofibers have been evaluated (Ramos et al., 2022). These additives enable detection of deformation or crack formation by measuring the changes in electrical resistance under external loading. Graphene, in particular, has shown a proportional and linear resistance change with strain, making it a strong candidate for integration into monitoring systems.

From a sustainability perspective, Li et al. (2022) explored the incorporation of biochar derived from spent coffee grounds that was functionalized with melamine. The results showed that the biochar dispersed homogeneously within the concrete matrix and significantly enhanced its electrical conductivity. This approach also promotes the use of eco-friendly and recycled resources in concrete production.

8.3. AI-assisted material optimization

Artificial intelligence (AI)-assisted material optimization in electrically conductive concretes has emerged as a significant area of research in the field of civil engineering in recent years. This approach enables the use of various admixtures—such as carbon nanotubes, graphene, and steel slag—in optimal proportions and combinations to enhance both the mechanical and electrical properties of concrete. AI and machine learning techniques allow for the efficient and accelerated design and performance prediction of these complex material systems. For example, Dong et al. (2022) employed XGBoost and NSGA-II algorithms to optimize the electrical resistivity and compressive strength of cementitious composites reinforced with graphite-based nanomaterials. Through multi-objective optimization, they were able to identify mixture ratios that provided both high conductivity and sufficient compressive strength (Dong, 2023). Similarly, Sun et al. (2021) conducted experiments on 81 different concrete mixtures containing graphite powder, steel slag, and ground granulated blast furnace slag. Using this dataset, they developed a Random Forest model optimized with the Beetle Antennae Search (BAS) algorithm. The model demonstrated high accuracy in predicting both the compressive strength and electrical resistivity of the concrete mixtures. In another

study, [Zhang et al. \(2024\)](#) developed an artificial neural network (ANN) model optimized via the Particle Swarm Optimization (PSO) algorithm to predict the compressive strength of smart cementitious materials. Compared to conventional methods, this model exhibited higher prediction accuracy and better generalization capability. These studies highlight the effectiveness of AI and machine learning techniques in the design and performance forecasting of electrically conductive concretes. Such approaches contribute to the development of more efficient and sustainable concrete mixtures for both laboratory and real-world applications.

9. FUTURE DIRECTIONS AND RESEARCH GAPS

Electrically conductive concretes hold great potential for sustainable infrastructure systems, structural health monitoring, energy-efficient buildings, and smart city applications. However, studies in this field are still limited, and there is a need for comprehensive and application-oriented research. Future research directions and existing gaps are outlined below:

Functional additives (carbon nanotubes, graphene, biochar, steel fibers, metal oxides, etc.) offer different levels of conductivity, but their distribution within the concrete matrix, interaction with the water/cement ratio, and effects on the microstructure are not yet fully understood. Especially the agglomeration tendency of nanomaterials can hinder the formation of conductive networks ([Ramos et al., 2022](#)). This makes it difficult to strike a balance between electrical conductivity and mechanical performance.

Many experimental studies on electrically conductive concretes focus on short-term results. However, there is a lack of systematic data regarding the long-term behavior

of these materials under external environmental conditions (freeze-thaw, humidity, carbonation, chloride exposure, etc.) ([Li et al., 2022](#)). In the future, comprehensive durability studies are required to evaluate the field performance of such materials. There are significant variations among the methods used for measuring electrical conductivity (e.g., surface resistivity, volume resistivity, 4-point and 2-point methods), which hinders the comparability of results ([Sun et al., 2021](#)). To accelerate progress in the field, the development of standardized test procedures is necessary.

In recent years, some studies have started to use AI-based modeling and optimization techniques ([Dong et al., 2022](#); [Zhang et al., 2024](#)). However, most of the models developed in this field rely on specific experimental datasets and have limited generalization capabilities. Integration of data sharing, large datasets, and techniques such as transfer learning can help make these models more robust. Potential applications of electrically conductive concretes include self-heating surfaces (deicing), electromagnetic interference (EMI) shielding, and energy storage systems. However, in order for these applications to be fully realized, the integration of electrical systems with concrete must be thoroughly optimized in terms of structural, electrical, and safety considerations ([Al-Attar et al., 2022](#)). Most functional additives are costly, raising concerns about economic sustainability in large-scale applications. Therefore, research on the use of waste-based or locally sourced conductive materials (e.g., waste carbon, biochar) should be increased, and environmental impact analyses should be conducted ([Li et al., 2022](#)).

The table 3 summarizes future research directions and existing research gaps in light of recent studies on electrically conductive concretes.

Table 3. Summary of current research, gaps, and future directions in electrically conductive concretes

Research Area	Current Status	Research Gap	Future Direction / Suggestion
Functional Additives	Carbon nanotubes, graphene, steel fibers are used	Homogeneous dispersion issues, agglomeration problems	New dispersion techniques, hybrid additives
Long-Term Durability	Short-term lab tests available	Environmental effects like freeze-thaw, carbonation not well studied	Long-term field tests and accelerated aging studies
Test Standardization	Various methods such as surface and volumetric resistance	Low comparability of results	Development of international standard test methods
AI-Based Modeling	ML algorithms started to be used	Small datasets, poor model generalization	Big data, transfer learning, open data platforms
Energy Applications & System Integration	Deicing and EMI shielding studies	Weak integration with electrical systems	Integrated design protocols between building and electrical systems
Economic and Environmental Sustainability	Additives are expensive, limited applications	Small-scale applications, few LCA studies	Waste-based conductive materials, increase in life cycle analysis

CONCLUSIONS AND GENERAL EVALUATION

This review has systematically evaluated current research on electrically conductive concrete (ECON) technologies, with a particular focus on conductive additives, performance characteristics, and implementation challenges. The findings clearly demonstrate that ECON offers multifunctional potential in the construction sector, combining structural capabilities with additional functionalities such as self-heating, crack sensing, and electromagnetic interference (EMI) shielding.

Carbon-based materials—such as carbon fibers, carbon nanotubes (CNTs), and graphene—as well as metallic additives like steel fibers and powders, have been shown to significantly improve electrical conductivity while also enhancing mechanical strength, crack control, and durability. Among these, CNTs and graphene derivatives exhibit exceptional performance due to their unique microstructural influence and ability to bridge cracks and form continuous conductive pathways.

A critical factor in achieving effective electrical conductivity is surpassing the percolation threshold, which depends on the type, content, and dispersion of the conductive additive. However, challenges such as ensuring homogeneous dispersion, maintaining workability, and optimizing cost-performance ratios continue to hinder large-scale adoption. In addition, inconsistencies between laboratory-scale results and real-world performance, along with the absence of standardized testing protocols and limited long-term monitoring data, present further barriers to practical implementation.

Geopolymer-based conductive concretes have emerged as a promising sustainable alternative, offering reduced carbon emissions, high thermal resistance, and long-term durability. These systems align well with global efforts toward eco-friendly construction and carbon neutrality.

In conclusion, realizing the full potential of electrically conductive concretes in engineering applications requires a multidisciplinary and holistic approach—one that integrates material science, structural design, sustainability principles, and economic considerations. Future research should prioritize the development of cost-effective and scalable mix designs, standardized testing frameworks, and smart optimization techniques, including AI-assisted methodologies. With continued innovation, ECON systems are poised to become a key element in the advancement of smart and resilient infrastructure.

DECLARATIONS

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Supplementary information

The online version does not contain supplementary material available at link or upon request from the corresponding author.

Competing interests

The authors declare no competing interests in this research and publication.

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