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Trash to treasure: A review on integrating nanomaterial and industrial waste for sustainable electromagnetic interference shielding composites

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ABSTRACT

The integration of nanomaterials and industrial waste into electromagnetic interference (EMI) shielding composites represents a promising pathway towards sustainable and efficient solutions for modern infrastructure challenges. This paper discusses how these materials are improving, focusing on the nanoparticles and recycled industrial waste that enable them to improve the EMI shielding. Furthermore, the critical applications of EMI shielding composites such as telecommunications, defence, and electronics are elaborated. The mechanical and microstructure properties of cement concrete and mortar based EMI composites are explained in detail. The paper also examines the challenges of producing these materials on a bigger scale and at a reduced cost, as well as the possibilities for future developments. Eventually, this work contributes to the development of high-performing EMI composites that is developed using ecologically friendly materials by minimizing waste which supports sustainable construction.

Keywords: electromagnetic interference shielding; cementitious composites; carbon nanomaterials; industrial waste; sustainable construction materials.

INTRODUCTION

Electromagnetic interference (EMI) shielding has become critical in modern technology due to the widespread use of electronic devices in industrial, commercial, and residential settings [1]. With the rise of wireless communication systems, advanced electronics, and 5G networks, protecting sensitive equipment from EMI has gained significant importance. Traditional shielding materials like metals, while effective, present challenges such as heavy weight, high cost, and corrosion, driving the need for innovative alternatives [2–4].

Recent advancements have focused on developing EMI shielding composites that integrate nanomaterials and recycled industrial waste [5, 6]. Nanomaterials, including graphene, carbon nanotubes, and MXenes, [7] have revolutionized shielding technologies with their exceptional electrical conductivity, lightweight nature, and ability to shield across broad frequency ranges [8, 9]. These materials not only enhance shielding performance but also improve the mechanical strength and durability of composites, making them suitable for applications in aerospace, defence, and telecommunications [10, 11].

Recycled industrial by-products, such as steel slag, fly ash, and copper slag, further contribute to the development of sustainable EMI shielding materials [12, 13]. These waste materials contain conductive or magnetic properties, boosting shielding efficiency while promoting environmental benefits by reducing landfill waste and supporting resource recycling [14–16]. Combining nanomaterials with industrial waste creates multifunctional composites that offer superior performance, reduced environmental impact, and cost efficiency [17, 18].

This review explores the synergistic effects of nanomaterials and industrial waste in EMI shielding composites, highlighting their ability to address modern challenges in electronics, telecommunications, and construction [19, 20].

By providing sustainable, high-performance solutions, these composites not only ensure the reliable operation of electronic systems but also contribute to global efforts toward reducing environmental impact and promoting eco-friendly infrastructure [21, 22]. The advancements discussed lay the foundation for future innovations in EMI shielding, emphasizing the need for further research to optimize material properties and expand their applications.

Sources of electromagnetic radiation

Modern high-tech electronic devices designed to improve our quality of life are the main contributors to electromagnetic (EM) radiation [23]. Devices such as wireless computers, smartphones, wearable tech, televisions, microwave ovens, radios, GPS systems, and radar systems serve as key sources of this radiation [24]. Additionally, power supply lines, overhead electrical cables, satellites, and vehicles also emit EM radiation [25]. Sources of radiation shown in Figure 1.

Impact of electromagnetic radiation

Electromagnetic radiation can disrupt the proper operation of electronic devices, often resulting in malfunction or data loss. For instance, electromagnetic interference (EMI) might appear as color distortions on the edges of a television screen under specific circumstances. Due to such interference, electronic devices capable of transmitting or receiving EM waves are restricted in places like airplanes and hospital ICUs. In some cases, EM wave coupling has been linked to critical aviation accidents [26].

EMI also poses significant challenges for both military and civilian applications [27, 28]. Beyond its technical effects, EM radiation adversely impacts human health, causing damage to tissues and disturbing normal bodily functions [29]. Symptoms like headaches and dizziness are common. Studies suggest that prolonged exposure can lead to serious health problems, including depression, suicidal tendencies, hyperactivity in children, and neuropsychiatric disorders. Additionally, carrying a mobile phone in a pocket near the testicles has been found to reduce male fertility and impair sperm production [30, 31].

Chronic exposure to EM radiation may lead to DNA mutations, which can compromise the body's overall functionality [32, 33]. Research continues to highlight these risks, underscoring the importance of understanding and mitigating EM radiation's long-term effects [34–36]. Harmful effects of EM radiation shown in Figure 2.

The electromagnetic interference shielding mechanism plays a crucial role through reflection, absorption, and multiple internal reflections [37]. Basically, electromagnetic waves bounce off since some free electrons interact within the wave, when the materials involved are conductive, like metals or carbon-based materials. Absorption refers to how

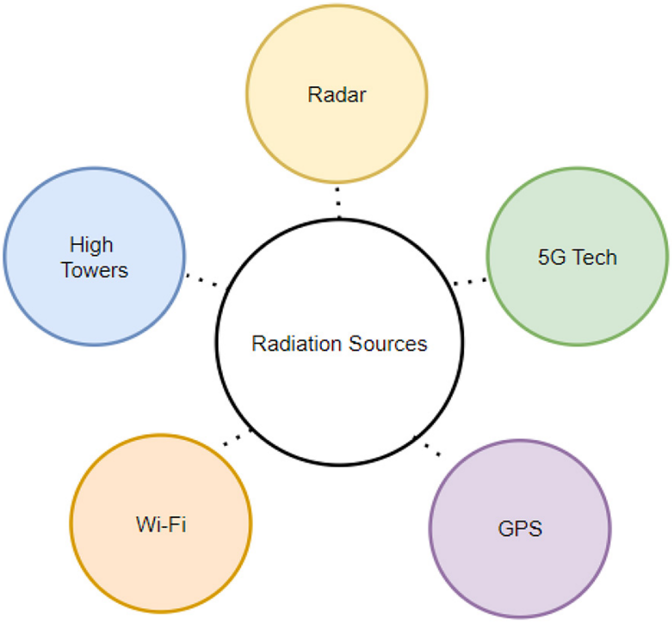

Figure 1. Sources of radiation

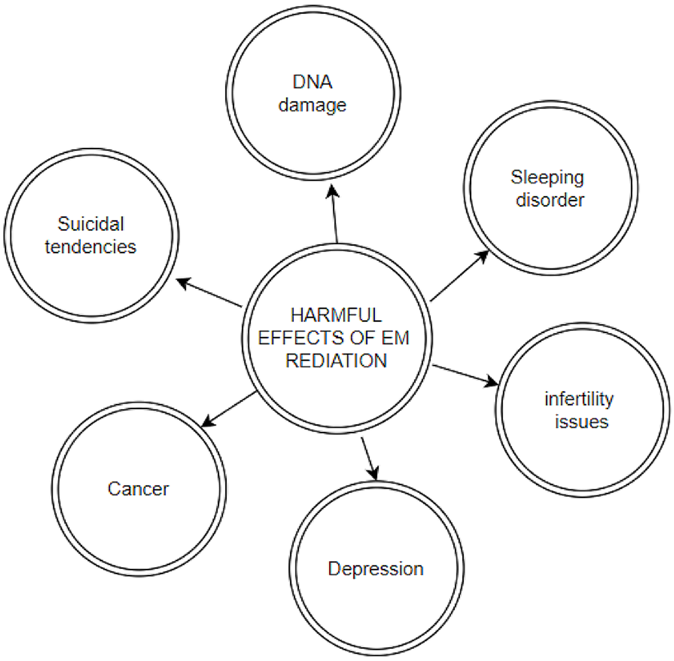

Figure 2. Harmful effects of EM radiation

wave energy dissipates as heat within a material, while increased properties such as electrical conductivity, magnetic permeability, and thickness improve this process [38]. Some magnetic materials, ferrites, for instance, and nanostructures such as graphene or MXenes are quite effective at energy absorption. Within porous or layered structures, the wave undergoes multiple internal reflections, which again attenuate it as it bounces between surfaces. Materials of high conductivity and magnetic properties in well-optimized structure enhance SE measured in decibels (dB). Schematic illustration of mechanism of shielding shown in Figure 3.

Importance of EMI shielding in modern infrastructure

In today's highly connected world, EMI shielding is needed for efficient working of electronic systems and electronic devices. Advanced technologies in the field of telecommunications, aircraft, healthcare, and smart infrastructure have increased the threat that EMI will disrupt sensitive equipment [37]. Effective shielding reduces the interference of signals, loss of data, and a collapse in crucial parts that ensures operating efficiency and safety. In addition to functionality, it enhances the

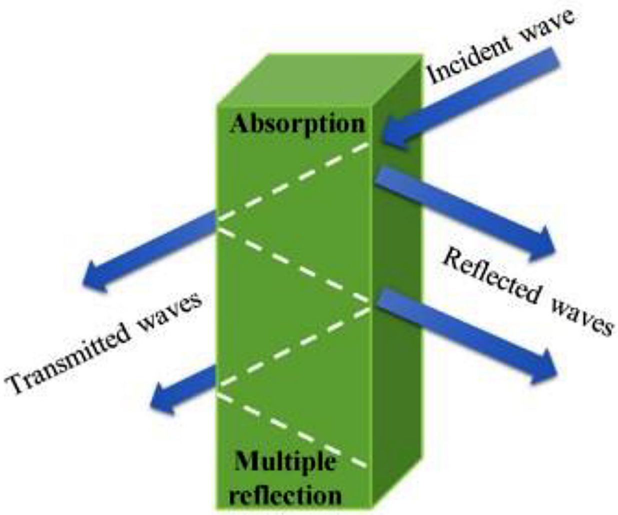

Figure 3. Schematic illustration of mechanism of shielding [37]

construction of sustainable infrastructure through eco-friendly materials, reduction of electromagnetic pollution, and conservation of the environment towards the betterment of the world [39]. Comparison between traditional and modern EMI shielding methods as shown in Table 1

Advantages of modern EMI shielding over traditional methods

Modern EMI shielding improves on older methods by providing lightweight, flexible materials for devices such as cellphones, drones, and foldable electronics. Innovations such as transparent silver nanowire films suit these requirements [41].

Sustainable manufacturing employs recycled materials such as carbon fibres, which reduces environmental effect. New shielding materials are designed to block a wide frequency spectrum, allowing 5G and radar systems to function. Economical approaches, including as 3-D printing and paint deposition, provide cost-effective drone and medical device applications. Conductive polymers and nanocomposites are resistant to corrosion and severe temperatures, making them suitable for aerospace and coastal applications [3].

METHODOLOGY

The methodology for this review paper focuses on systematically exploring the techniques, materials, and performance characteristics of electromagnetic shielding concrete. Two primary methods, the Additive Method and the Coating Method, are analyzed in detail. The Additive Method involves incorporating specific materials into the concrete matrix, such as waste materials for cost-effective solutions, carbon nanomaterials for enhanced electromagnetic absorption, and mineral admixtures and fibres to improve shielding and mechanical properties. The coating method, on the other hand, examines the application of metallic coatings on concrete surfaces to enhance electromagnetic wave attenuation. The performance of these approaches is evaluated based on three key aspects: mechanical properties, including compressive, tensile, and flexural strengths; electromagnetic shielding effectiveness across different frequencies; and microstructural analysis to understand the internal structure's impact on performance. This integrated methodology ensures a comprehensive understanding of the optimization and application of electromagnetic shielding concrete. Methodology as shown in Figure 4.

ADDITIVE METHOD

Nanomaterials

Role of nanomaterials

Nanomaterials with strong conductivity, such as CNTs, graphene, and MXenes, improve EMI shielding by creating networks that reflect and absorb electromagnetic waves [42]. They shield a broad frequency range, making them ideal for radar and 5G networks. These materials minimize

Table 1. Comparison between traditional and modern EMI shielding methods [40]

Aspect	Traditional EMI shielding	Modern EMI shielding
Materials used	Metals (aluminum, copper, steel), wire meshes, metallic foils, conductive paints/coatings.	Nanomaterials (carbon nanotubes, graphene), conductive polymers, hybrid composites.
Weight	Heavy due to the use of solid metals.	Lightweight owing to the use of polymers, composites, and nanomaterials.
Flexibility	Limited flexibility; metals and rigid structures dominate.	High flexibility; conductive polymers and thin films enable versatile applications.
Corrosion resistance	Metals prone to corrosion unless coated or treated.	Corrosion-resistant materials such as composites and conductive polymers. [39]
Cost and scalability	High material costs and limited adaptability to modern production techniques.	Cost-effective with scalable techniques like printing, spray coatings, and composite molding.
Environmental impact	Use of non-renewable resources; potential for heavy environmental footprint.	Promotes sustainability through recycled waste materials and eco-friendly nanocomposites.
Frequency range	Effective primarily for low- to mid-frequency EMI.	Tunable shielding across a broader frequency range with advanced materials and designs.
Applications	Traditional electronic enclosures, shielding rooms, and simple assemblies.	Advanced use in wearable electronics, flexible displays, aerospace, and transparent shields.
Energy efficiency	Reflective materials lead to secondary interference and energy wastage.	Absorptive materials dissipate EMI as heat, minimizing secondary interference.

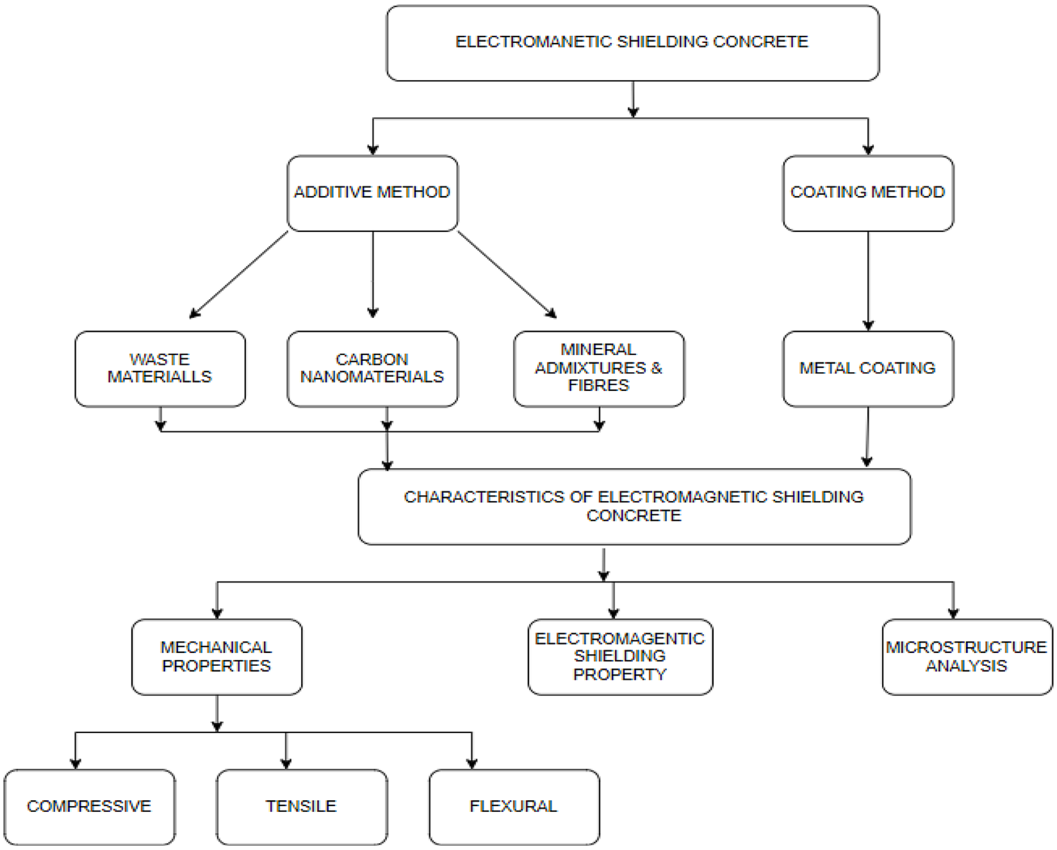

Figure 4. Classification and evaluation of methods for electromagnetic shielding concrete

shielding weight while preserving efficacy, making them excellent for use in aircraft, automobiles, and portable electronics. They enhance tensile strength, impact resistance, and durability. Nanomaterials are adaptable and can be used as coatings, thin films, bulk composites, making them necessary for future EMI shielding technology.

Challenges of integrating nanomaterials and dispersion techniques

Uniform dispersion of nanoparticles in cementitious composites is critical for their optimal use. Nanomaterials, such as CNTs or graphene, tend to aggregate, reducing mechanical strength and EMI shielding. Inadequate dispersion causes faults that reduce performance [43]. Traditional approaches have failed, so advanced procedures such as shear mixing, chemical functionalization, and ultrasonic treatment are required. High production costs and scaling limitations prevent widespread adoption, particularly in cost-sensitive businesses. Nanomaterials also present health and safety issues [3].

Improving dispersion through procedures such as ultrasonic treatment and chemical functionalization increases compatibility while decreasing agglomeration. Hybrid approaches provide superior results. Maintaining the optimal nanomaterial-to-matrix ratio minimizes performance degradation. Addressing these difficulties will allow nanomaterials to reach their full potential as high-performance EMI shielding composites [20].

Potential obstacles and recommendations in addition of nanomaterials

Nanoparticles minimize porosity, provide a denser microstructure, and reduce water and ion absorption, resulting in increased durability. By finely tuning the microstructure, they speed up hydration, improve workability, and boost strength (tensile, compressive, and flexural). Nanomaterials provide increased toughness, crack resistance, ductility, and fatigue resistance. Conductive nanoparticles, such as CNTs and graphene, increase electrical conductivity, allowing self-sensing concrete to detect strain or cracks [13].

Carbon nanomaterials

Recent studies on carbon nanomaterial-based electrical and conductive cement concrete highlight methods to improve its mechanical and electrical properties by incorporating various nanomaterials and treatment techniques. A summary of relevant works is provided below.

Electrically conductive and strain-sensitive materials

Lu et al. [44] reviewed materials with high electrical conductivity and strain sensitivity, highlighting their use in snow melting and structural health monitoring (SHM). They emphasized the need for further research to improve ECCC performance through better composition and processing techniques.

Enhanced performance through nanomaterial impregnation

Ren et al. [45] studied the impregnation of nano-graphite (NG) and magnetite into ECC composites, achieving compressive strength of 46.75 MPa, flexural strength of 6.92 MPa, and electrical resistivity of 3430 Ω·cm with 6 wt% NG and 60 wt% magnetite. They highlighted the importance of modification treatments like alkali excitation and ultrasonic vibration for even filler distribution and high performance, emphasizing the need for nanomaterial treatment techniques to optimize electrically conductive cement concrete.

Cost-effective and green choices

Ren et al. [45] highlighted copper slag's utility as an economical resource in composites, achieving 8180 Ω·cm electrical resistance and 44.55 MPa compressive strength with 3 wt% NG and 60 wt% copper slag, promoting sustainable waste use.Li et al. [46] studied micro and nano Fe_3O_4 in composites, achieving 50 MPa compressive strength and excellent magnetic wave absorption, demonstrating cost savings and environmental sustainability through industrial by-product integration.

Advancements in ultra-high-performance concrete (UHPC)

Yoo et al. [47] found that optimal nanomaterial dosages can reduce UHPC porosity by up to 30%, improving durability. These findings highlight nanomaterials' potential to enhance UHPC performance and lifespan in construction. In summary, carbon nanomaterials show promise for ECCC, but ongoing optimization is needed for their full potential. High-performance composites can be achieved through treatment modifications, careful composition, and sustainable resource use.[48, 49, 50]. Various types and structures of EMI shielding materials as shown in Figure 5.

Waste materials

This in turn has resulted in recent advances in nanomaterials and recycling of industrial waste, significantly enhancing the designs of cementitious composites, primarily through improved electromagnetic interference (EMI) shielding properties [51]. Some investigations made it clear that using waste materials in composites in construction is also important by emphasizing the improvement in mechanical strength, electrical properties, and sustainability. Gülmez et al. (2022) [52] studied the inclusion of waste steel

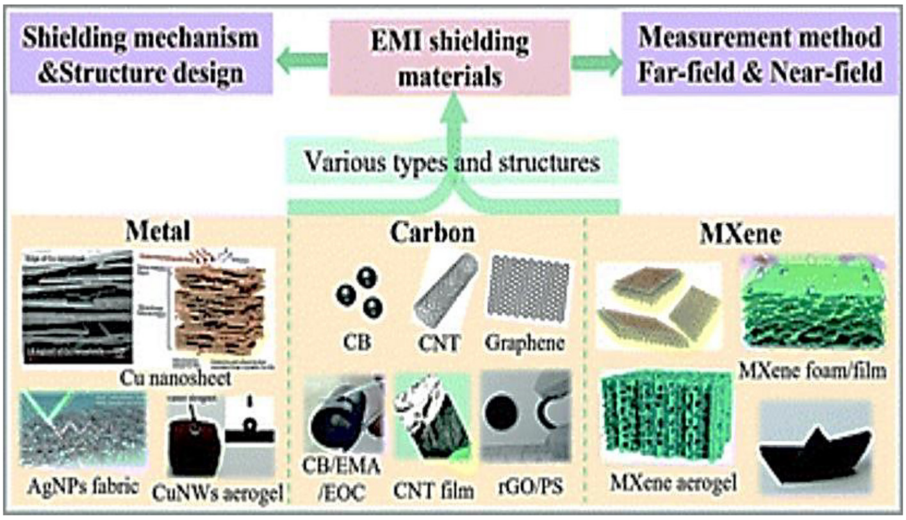

Figure 5. Various types and structures of EMI shielding materials [37]

and iron powders in geopolymer tiles; these materials showed a significantly improved EMI shielding effectiveness. Shielding effectiveness reached up to 26.1 dB using 10% addition of steel particles. The inclusion of waste material would not only optimize the electromagnetic performance of building materials but also minimize waste disposal problems [53]. For instance, Yang, Yao [54], and Zhuge (2022) demonstrated that the addition of copper swarf waste into cement composites at high percentage levels is associated with good mechanical properties and electrical conductivity and, therefore, has excellent potential for usage in EMI shielding. The increase in complex permittivity and decrease in resistivity of copper swarf led to the generation of eddy currents, therefore enhancing the EMI shielding properties. Saleem et al. (2022) [55] investigated the incorporation of furnace slag in fibre-reinforced concrete and have shown that, when together, the inclusion of slag along with carbon fibres also enhanced the mechanical shielding properties.

A carbon fibre-slag composite outperformed the steel fibres with higher reflectivity and total shielding effectiveness and thus is a potential candidate for EMI protection in concrete applications. Ozturk et al. (2020) [56] researched the use of mill scale waste from the iron-steel industry in mortar. They concluded that, for an addition of 15% mill scale, the mechanical properties matched those of control mortars, but EMI shielding performance was significantly improved. The cubic crystal structure of the mill scale particles made the enhanced performance due to better electromagnetic shielding. Han et al. (2023) [57] presented the incorporation of aluminium alloy perforated sheets (ALS) as reinforcement in mortar. Their findings indicated that ALS-reinforced samples reached tensile strength up to 2.6 times, along with enhanced EMI shielding performance up to 3.6 times that of an unreinforced sample, of which the results demonstrate the immense potential of ALS to boost the mechanical and electromagnetic characteristics of structural materials simultaneously. More recently, Logesh et al. (2023) [58] research focused on lightweight composites filled with carbon fibres and fly ash for microwave absorption and EMI shielding. Their results demonstrated a total shielding effectiveness of 42.29 dB at a minimum thickness that verified the appropriateness of these composites for high performance EMI shielding in lightweight construction materials. Last, Ren et al. (2022) [38] introduced copper slag and nanographite into electrically conductive cementitious composites (ECCC). This optimized dispersion process, obtained from chemical alkali excitation and ultrasonic vibration, improved mechanical and electrical properties. The best samples attained compressive strength as high as 44.55 MPa and electrical resistance at 8180 ohm.cm, with applications in snow melting, EMI shielding, and structural health monitoring. In conclusion, these studies prove that cementitious composites integrating recycled industrial waste and nanomaterials can be developed to transform into a better aspect for applications. Improvement in EMI shielding, mechanical strength, and sustainability leads toward the bright prospects of eco-friendly and high-performance construction materials.

Potential obstacles and recommendations in addition of waste materials

Material costs and environmental effect can be decreased by using industrial waste such as steel slag, copper slag, and fly ash into EMI shielding composites. These byproducts enhance electromagnetic wave attenuation and nanomaterial efficacy [59]. It encourages trash management and green building. Using industrial waste in cementitious composites decreases prices, landfill waste, and the requirement for raw materials. It lowers greenhouse gas emissions by replacing ordinary cement. Waste enhances mechanical qualities, making composites suitable for building [51]. Combining nanoparticles with industrial waste minimizes nanomaterial constraints while promoting sustainability. Using waste in composites improves strength and EMI shielding, making them high-performance and eco-friendly. This reduces dependency on traditional cement production and supports CO_2 reduction initiatives [17].

Mineral additives and fibres

There has been massive interest and concern in the use of cement-based materials as electromagnetic shielding over the past few years owing to enhanced use of electronic devices with interference arising from electromagnetic interference. Hence, this review integrates findings from various studies based on multiple examinations of electrogalvanic properties of cementitious composites, particularly with supplementary cementitious materials that include fly ash, slag, and carbon fibres. Li et al. (2023) [60] carried an investigation concerning the mechanical and electromagnetic shielding effectiveness of cement paste with varied contents of fly ash and slag. The finding indicated that strength decreased with an increase in the percentage of fly ash and slag, but dry resistance increased with an increase in the percentage of fly ash and slag, directly influencing reflection loss, which is indeed one of the significant factors for shielding effectiveness. The electromagnetic shielding performance increased with the increase in metallic elements content, such as iron (Fe), and changes in mesopores under 100 nm, associated with higher multiple reflection losses. Wanasinghe et al. (2020) [61] based their work on the optimization of the water-to-cement ratio and additive content to fly ash (FA) and ground granulated blast furnace slag (GGBFS) for better shielding effectiveness. At a frequency of 1.5 GHz, maximum EM shielding effectiveness for FA and GGBFS mixes was achieved at 3.38 dB and 5.06 dB, respectively. The optimum water-cement ratio for maximum shielding 1.89 dB was determined at 0.3. Das et al. (2022) [48, 62] investigated the EMI shielding properties of conductive concrete incorporating magnetite, graphite aggregates, and steel fibres. The greatest SE for conductive concrete was achieved at 36 dB, which was much greater than for normal concrete. This gain can be associated with the higher conductivity of magnetite and graphite, which was further improved by the reinforcement of steel fibres [63]. Logesh et al. [58] prepared lightweight composites comprising carbon fibre and fly ash incorporated with ground granulated blast furnace slag. The study reported a reflection loss of -41.24 dB and total shielding effectiveness of 42.29 dB in the X-band. Carbon fibre-fly ash composites could be helpful for the application of electromagnetic wave absorption and shielding. Yuan et al. [47] explored the impact of steel slag and steel fibres added to high-strength concrete for electromagnetic shielding. The research found that when the HSC had 20% of SS replaced, shielding improved, but its strength reduced. Conversely, however, the system of HSC with steel fibres exhibited remarkably improved resistance to shielding and strength. The most sensitive factor, which influenced the effectiveness of shielding, was electrical resistivity. In terms of increase percentage in this frequency range - 600-1,000 MHz, for the steel fibre-reinforced HSC, it was 23.5–75.6. Musial et al. [62] presented a study about using admixtures, including steel fibres [63], carbon black, and graphite flakes, within cementitious composites for HPM pulse shielding. The highest mechanical and shielding properties were achieved with the highest amount of steel fibre. The study proposed a balance between the electromagnetic shielding effectiveness and the structural integrity. In summary, the inclusion of SCMs such as fly ash, slag, and carbon fibres introduces significant enhancements in the electromagnetic shielding properties of cementitious composites. With optimal mixes of materials along with changes in water-to-cement ratios and admixture treatments, high EMI shielding effectiveness can be achieved that makes them promising for EMI shielding applications. Future research should focus on the improvement of the dispersion of nanoscale admixtures and on cost-effectiveness of such advanced material to enable thorough practical applicability [64].

Cement-based ceramic pellets with varying concentrations of manganese oxide (MnO_2) [65] were developed for electromagnetic interference (EMI) shielding applications. Composed of Portland cement with up to 10 wt% MnO_2, the pellets were sintered at 850 °C for 5 hours and then polished for further analysis. Characterization revealed a high dielectric constant (around 300) and low dielectric loss (<0.3), both of which improved with higher MnO_2 content. EMI shielding effectiveness (SE) values ranged between 2 dB and 9 dB in the 8–13 GHz frequency range, with the 10 wt% MnO_2 sample achieving up to 9 dB. Overall, pellets with higher MnO_2 concentrations consistently demonstrated SE values above 7 dB. Advantage and Disadvantage of each type of materials as shown in Table 2.

Metals are widely available with excellent conductivity but are heavy and costly. Carbon-based materials are lightweight with high conductivity but less available. Ceramics handle heat well but are brittle. Conductive polymers are versatile but less conductive. Cement is infrastructure-friendly but requires modifications.

COATING METHOD

Metal coatings

Jong-Min Jang et al. [71] researched how different metallic coatings help block electromagnetic interference (EMI), which can disrupt electronic equipment in places like buildings, hospitals, and

Table 2. Advantage and disadvantage of each type of materials

Material	Advantage	Disadvantage
Metals	- High electrical conductivity,providing effective shielding[66] - Wide availability and familiarity in the industry[66] - Can attenuate both magnetic and electrical waves[66]	- Heavy weight, which can be a concern in certain applications[67] - High cost compared to other materials[67] - Poor corrosion resistance in some cases[67]
Carbon-based materials	- High electrical conductivity, making them effective for shielding[67][59] - Lightweight and flexible, allowing for versatile applications[67][68] - Can be used in composites to improve shielding effectiveness[67]	- May require additional processing steps for incorporation into materials [69] - Limited availability and higher cost compared to traditional materials [69]
Ceramics	- High thermal stability, suitable for high-temperature applications[70] - Can provide effective shielding in certain frequency ranges[70]	- Generally lower electrical conductivity compared to metals[70] - Limited flexibility and may be brittle[70]
Conductive polymers	- Lightweight and flexible, allowing for versatile applications[70] [68] - Can be easily processed and molded into various shapes[70] - Can provide effective shielding in certain frequency ranges[70]	- Lower electrical conductivity compared to metals[70] - Limited availability and higher cost compared to traditional materials[70]
Cement-based materials	- Widely used in construction, providing an opportunity for integration into existing infrastructure[70] - Can be tailored with additives to improve electromagnetic shielding properties[70]	- Limited electrical conductivity compared to metals and carbon-based materials[70] - May require additional processing steps for incorporation into materials[70]

military bases. They tested three types of coatings – copper (Cu), copper-zinc (Cu-Zn), and copper-nickel (Cu-Ni) – using a process called arc thermal spraying to apply them in various thicknesses. The study focused on how the coatings' structure, conductivity, and ability to shield against EMI changed with thickness. Results showed that thinner coatings (100 µm) had more defects, making them less effective, while thicker coatings (500 µm) showed fewer flaws and higher conductivity, leading to better EMI protection. Of the three, the Cu-Zn coating was the most effective, blocking 80 dB of EMI at 1 GHz with a 100 µm layer, compared to 68 dB for Cu and only 12 dB for Cu-Ni at the same thickness. The study concluded that increasing the coating thickness improves EMI shielding. Cu-Zn stood out as a good choice for shielding, providing strong protection even in thinner layers, while Cu and Cu-Ni required greater thickness to achieve similar effectiveness. Coating and thickness shown in Table 3.

Recent studies have made significant advancements in the field of electromagnetic shielding for various applications, particularly in ordnance store protection and construction materials. Pan et al. [72] explored the shielding performance of ammunition warehouse walls using different protective coatings. Through FEKO software

Table 3. Experimental variables (coating and thickness) [71]

Coating	For deposition of coating		Thickness (µm) of coating
	Wire-1	Wire-2	
Cu	Cu	Cu	100
			200
			500
Cu-Zn	Cu	Zn	100
			200
			500
Cu-Ni	Cu	Zn	100
			200
			500

simulations, they demonstrated that adding conductive materials like carbon powder and steel fibres to concrete improved high-frequency electromagnetic shielding. However, low-frequency fields showed minimal improvements. Metal coatings with low conductivity showed increased effectiveness at higher frequencies, while the presence of seam holes reduced shielding, particularly at resonant frequencies of 0.7 to 0.8 GHz. Park et al. [73] investigated electromagnetic field penetration through slits on metal plates coated with ferrite sheets. Using Fourier transforms and mode-matching techniques, they found that electric and magnetic shielding characteristics differ in the near-field region, especially at low frequencies. The number of slits and the presence of ferrite sheets had a significant influence on shielding performance. Non-periodic slits were also found to reduce effectiveness, with results validated against commercial solvers. Ren et al. [45] focused on electrically conductive cementitious composites (ECCC) incorporating nano-graphite and magnetite. Their study demonstrated that a combination of alkali excitation and ultrasonic vibration treatments led to optimal mechanical and electrical properties. A composite with 6 wt% nano-graphite and 60 wt% magnetite achieved a compressive strength of 46.75 MPa, flexural strength of 6.92 MPa, and an electrical resistance of 3430 Ω·cm. This highlights the potential of ECCC in electromagnetic shielding and structural health monitoring applications.These studies emphasize the role of material composition, coatings, and structural design in enhancing electromagnetic shielding, offering valuable insights for future developments in high-performance shielding materials.

Conductive metals like copper, aluminum, nickel, silver, and graphene are key materials for EMI shielding [54]. Copper offers excellent conductivity, low surface resistance, and anticorrosion, ensuring efficient and durable performance. Aluminum, lightweight and cost-effective, provides reliable shielding and resists oxidation. Nickel's high magnetic permeability is ideal for low-frequency shielding. Silver, highly conductive but costly, suits high-end applications [74].

Graphene, with its high conductivity, durability, and flexibility, is an exciting material for lightweight, compact EMI shielding. Effective shielding involves materials that can conduct, absorb, and reflect electromagnetic radiation, with denser shields performing better [23].

Nanomaterials improve thermal conductivity for heat dissipation in fire-resistant constructions while also adding EMI shielding to cementitious composites, which is crucial for sensitive areas such as communication hubs. Nanoparticles make composites stronger, making them perfect for sophisticated infrastructure and construction [75].

CHARACTERISTICS OF ELECTROMAGNETIC SHIELDING PROPERTIES

Mechanical properties for electromagnetic shielding concrete

Researches on the inclusion of CNTs in UHPC as well as boron-based additives in the conventional concrete have been very interestingly considered because such inclusions of the above types significantly enhance the mechanical properties and efficiency of the electromagnetic shielding. Discussion on dispersion, mechanical properties, and EMI shielding of CNTs incorporated in to the UHPC has been done by Jung et al. [43] in the year 2023. The contents concentration ranged from 0 to 2.0 wt%, and sonication and shear mixing were used for maximizing flowability during experiments. In this regard, it can be noted that improvements in compressive strength and elastic modulus were observed with the incorporation of CNTs at lower concentrations for optimal pore filling, bridging effects, and denser structures of the C–S–H paste. Indeed, compressive strength of a reference UHPC is 178.6 MPa while compressive strength was improved by 5.5% and elastic modulus was improved by 12.0% at the CNT0.5. specimen preparation process shown in Figure 6.

But mechanical properties were adversely influenced due to agglomeration at higher level of CNT content, while the inclusion concentration almost reached or surpassed the critical inclusion concentration, in addition to initiating some voids and thus influences hydration (Jung et al., 2023). In another evidence-generating study, Ozturk et al. [76] investigated the mechanical and electromagnetic properties of concretes doped by boron wastes and by-products. The samples were made up of 5% compressive strength added approximately 23% through control samples prepared solely using Portland cement. In this case, improvement resulted from having a more compact

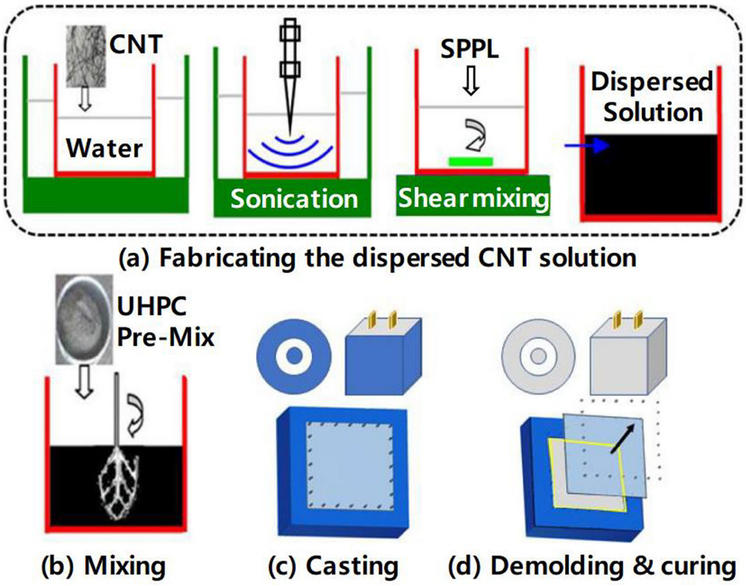

Figure 6. Specimen preparation process [43]

microstructure obtained by the formation of ettringite thereby improving structural characteristics of concrete. The investigation further reported that with the inclusion of boron-containing materials, SE was obtained up to a range of 3.16 to 100 times that of regular concrete. Which, if anything, would be said to provide quite substantial improvements in EMI shielding without compromising on the strength parameters. The obtained compressive strength results by Ozturk et al. (2023) had earlier indicated that 5% borogypsum was associated with an increase of about 15% in the compressive strength. Established composition showed its effectiveness in developing denser microstructures in this case. Values of tensile splitting strength were almost the same for all samples. Nonetheless, tensile strength reached maximum values only for samples with colemanite, which indicates that interaction during hydration between potassium borates and calcium hydroxide can significantly affect strength. The major attention is also paid to a tremendous potential of nanomaterials and additives based on boron for further increasing the level of mechanical and electromagnetic properties of concrete, as is reported for both studies.

Jung et al. (2023) pointed out that fine dispersion of CNTs is highly crucial for acquiring their full mechanical performance; meanwhile, Ozturk et al. [76] mentioned that the strength improvement by means of boron additives is accompanied not only by enhanced strength but also by high EMI shielding. With these research findings, new paths open for the development of advanced concrete materials that give priority to demands in modern construction in terms of structural integrity as well as electromagnetic protection. As multifunctional construction materials continue to rise in demand, further research will be necessary to optimize formulations and processes in effectively achieving such enhancements. It encompasses different researches related to the addition of materials such as steel slag (SS), steel fibres, perforated aluminum alloy sheets (ALS) [57], and carbon fibres in order to enhance the electromagnetic (EM) shielding strength and mechanical strengths of high-strength concrete (HSC). Yuan et al. [47] made some studies related to the influence of SS and steel fibres on HSC. They found that 20% replacement by SS exhibited minimal EM shielding enhancement and a loss in both compressive and flexural strength. In contrast, high steel content significantly increased EM shielding, reduced electrical resistivity, and strengthened and toughened the composite. Higher fibre content improved these properties, and electrical resistivity and EM shielding are related. HSC reinforced with rebar also showed a rise in shielding effectiveness from 23.5 to 75.6% in the 600–1000 MHz frequency band. Han et al. studied the possibility of ALS as a reinforcing material in mortar composites. Their work demonstrated that ALS raised the tensile strength to 2.6 times and EM shielding 3.6 times. The study established that re-melting absent, ALS could improve both the mechanical performances as well as the shielding. Yoo et al. [46] discussed chemically treated carbon fibres in ultra-high-performance fibre-reinforced concrete. At a concentration of 0.1% by weight, the carbon fibres treated with nitric acid produced the highest shielding effectiveness, 49 dB at 1 GHz. Both steel and carbon fibres showed enhancements in shielding, but chemically treated fibres had the largest increases to tensile strength and conductivity. A combination of fibres and reinforcement materials, especially steel fibres, ALS, and chemically treated carbon fibres, was found in all these studies to considerably enhance both the EM shielding and mechanical properties of high-performance concretes. Study on the mechanical and electromagnetic characteristics of NS and SF added self-compacted geopolymer concretes SCGC [77] . From the results, it has been interpreted that apart from slight improvement in compressive strength value, NS has no significant effect, but compressive strength and modulus of elasticity with an increase in the content of SF as well as its aspect ratio. NS improved the transmission resonance characteristics electromagnetically, whereas SF solely decreased these characteristics. Exceptionally, sample C7 shows the highest electromagnetic absorption, and it is 1% SF as well as 2% NS. This experiment showed how the introduction of recyclate carbon fibre and wet-grinded steel slag enhanced hydration and distributed rCF in cementitious composites. The addition of rCF/WSS promoted mechanical strength while minimizing electrical resistivity. It was shown that the addition of WSS would favor the electromagnetic interference shielding due to overall shielding effects dominated by losses due to absorption. High compressive strength at early ages for fly ash and slag mixtures of different percentages declined significantly with a further increase in percentage slag [78], but rose significantly by 28 days through further hydration. Even though fly ash does contribute to pore filling, it weakens the mechanical strength at higher percentages. Optimum strength and carbon emission reduction benefits were obtained with a balanced mix of 20% fly ash and 30% slag [60]. In a nutshell, the incorporation of steel fibres along with nanosilica, recycled carbon fibre, and steel slag serves to bring improvement in the mechanical and electromagnetic properties of the cementitious material towards EMI shield applications [75].

Yi Cao et al. [79] reinforcement of carbon foam composites by CNTs and MMT for much improvement in compressive, tensile, and flexural strength. CNTs show high strength in tension and stiffness. Contrary to this, MMT also increased the scattering of stresses and improved the interfacial adhesion so their compressive, tensile, and flexural resistance improved. The tensile strength (6.2 MPa) and flexural modulus (1250 MPa) of the tensile along samples have been more uniform without any apparent relation to samples. Soonho Kim et al.[80] have studied tensile strength properties of HPFRCCs: carbon fibres at 0.2% tensile strength gain occurred to the extent of 7.8% as compared with that without carbon fibres. Introducing carbon fibres improves not only the bridging of crack widths with steel fibres, but they also improve the ultimate capacity to carry load. There appears to be a residual crack width as large as 0.1–0.2 mm required for retention of tensile strength and other overall mechanical properties. The paper by Se-Hee Hong et al. [80, 81] notably elaborates an extensive investigation of lightweight aggregate concrete reinforced with steel fibres, showing the main result to be heavily reliant on the effect of improvement in compressive and flexural strength deterioration by steel fibres. The chief weakness of lightweight aggregates is due to porosity, but steel fibres uphold their mechanical integrity and distinctly raise resistance to cracking. Together, these results show that CNTs, MMT, and fibre reinforcements have such strength based on mechanical and electromagnetic properties, opening possibilities toward new material composite usage in construction and other types of structures.

Mechanical properties for electromagnetic shielding mortar

Seunghyeon Han et al. [57] study mortar composites containing ALS. They reported the following enhancements: ALS additions enhance the compressive strength from 11.4 MPa to 13.4 MPa; tensile strength has been improved 2.6 times by ALS 3. The researchers suggested that such enhancements are because ALS resists the transverse deformation and attaches well with mortar, de-laying fracture and spalling. Flexural strength also similarly enhanced, and it shows the effectiveness of ALS in reinforcing a mortar under tension. Murat Ozturk [56] et al. evaluate the possibility of waste mill scales use in mortar. The study indicates that mill scale added improves tensile and compressive strengths, but the maximum compressive strength achieved is 23.12%

at a substitution ratio of 15%. Strength decreases when mill scale exceeds 30% because the workability decreases due to irregular structures and decreases with bonding with the cement paste. Mechanical properties of Mill scale – compressive strength, flexural strength as shown in Figure 7.

Haoran Liu et al. [82] present an alkali-activated mortar based on magnesium slag, blast-furnace slag, and silica fume, with ultra-high molecular weight polyethylene (UHMWPE) reinforcement. The best mechanical properties of this mixture are obtained with a sodium silicate modulus 1.2, yielding the highest compressive and flexural strengths. In this research, UHMWPE reinforcement does not affect the mechanical properties strongly up to 0.5 wt%, but further concentrations led to a progressive decrease. These studies are more likely to depict the possible potential of innovative reinforcements such as ALS, mill scales and UHMWPE in improving mortar composites and their extensive applications in mechanisms as well as electromagnetic shielding.

In their research on MXene films [83], Soyeon Kim et al. placed their emphasis on the improvement of the mechanical properties of dicatechol-crosslinked (DC) MXene films for EMI shielding [41]. The incorporation of DC into MXene films added a tensile strength, modulus, and toughness enhancement, as compared in the stress-strain curves presented by them. Importantly, tensile strengths up to 39.2 MPa, 6.2 GPa moduli, and 40.02 kJ·m^{-3} toughness were achieved in MX@DC-2 films compared with the pure MXene films with a 2.5-fold, 8.5-fold, and 5.1-fold improvement, respectively. Such enhancement is likely due to the strong H-bonds between hydroxyl groups on the DC molecules and the MXene sheets. However, films of MX@DC-10 with higher DC content showed a reduction in the value of Young's modulus down to 1.47 GPa but nearly doubled breaking strain and increased toughness by 6.7 times. In the paper by Zhenxing Wang [84] et al., superior mechanical performances of d-Ti_3C_2Tx/wood-derived (DW) composites have been reported, including flexural strength up to 288 MPa and stiffness of 8.6 GPa, mainly attributed to the mechanical interlocking between the nanosheets of d-Ti_3C_2Tx and cellulose nanofibrils, combined with hydrogen bonding and reduced structural defects, and such material properties make composites highly appropriate for EMI shielding and next-generation building material application. Dimuthu Wanasinghe [61] et al. have studied the mechanical properties of cement mortars with different water-to-cement ratios, fly ash (FA), and slag content. They found that higher water content and FA results in lesser compressive and flexural strength due to increased porosity. Although addition of slag resulted in an early pozzolanic reaction, high amounts of slag showed a decrease in strength due to less formation of calcium silicate hydrate. Yue Li et al. [60] studied the influence of changing the fly ash and slag content on cement paste (CP). The addition of more fly ash decreased the compressive strength while increasing the proportion of slag showed to have a positive effect on long-term strength; however, this was due to the reaction between volcanic ash and slag. The combination of 20% fly ash and 30% slag gave the best balance of mechanical performance as well as carbon emission reduction. Orhan Kaya et al. [85] conducted an experimental investigation on the mechanical and volumetric properties of asphalt concrete where different ratios of graphite powder are added as a filler

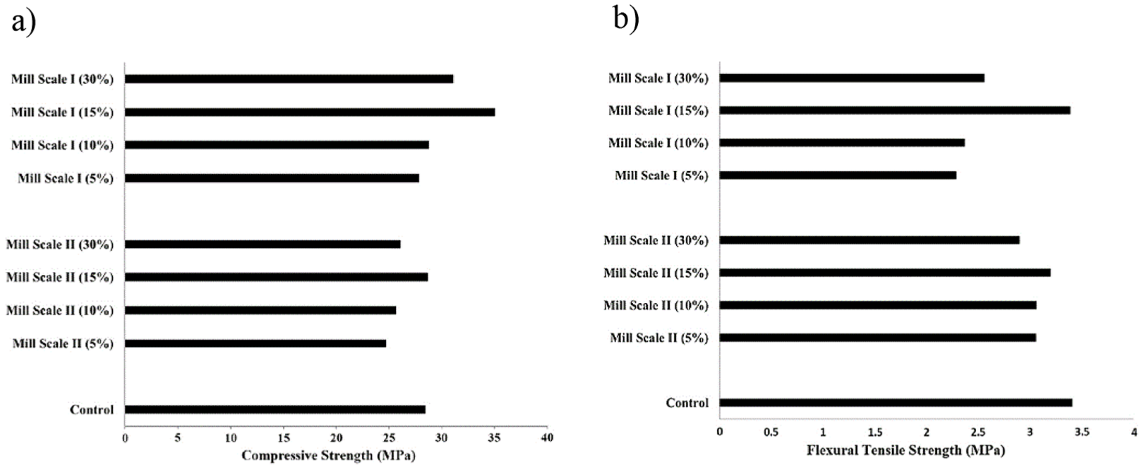

Figure 7. Mechanical properties – mill scale: a) compressive strength, b) flexural strength [56]

material. Based on the results, an increase in graphite ratios decreases Marshall stability (MS), flow, voids filled with asphalt (VFA), and unit weight, but air content and VMA increases. An increase in the graphite powder ratio from 0% to 100% leads to a significant decrease by 32% in MS. This could have resulted from graphite having a lower specific gravity in bulk in addition to having a sheet-like structure that weakens inter-layer bonding. The inclusion of graphite in the mix caused asphalt binder absorption, leading to the mix becoming drier and the effective binder content reducing in it, thus reducing the overall durability. This would imply that a lower graphite content could provide better mechanical performance and stability for smaller graphite powder ratios. The authors concluded that a graphite content that is relatively low may provide the balance of durability with performance in asphalt concrete mixes. Ozturk et al. [86] investigated the mechanical and electromagnetic properties of mortar containing EAFS as a replacement material. In that research, they observed an increase in flexural tensile and compressive strengths up to a 40% content of EAFS replacement but showed a gradual decline at higher replacement percentage. Adding EAFS as aggregates enhanced the overall mechanical strength in cement-based materials, meaning they had potential as a positive replacement material in construction materials.

A comparison of both the studies reveals that these alternative fillers, namely graphite powder and EAFS, have the potential to alter the mechanical properties of materials-an area approached by optimizing the ratio for maximum durability and performance in practical applications. Mechanical properties of modified cementitious composites as shown in Table 4.

Table 4 shows CNT-modified cement with high compressive strength (180 MPa) and low resistivity (2500 Ω·cm), suitable for structural and electrical applications. Copper slag-nano graphite provides balanced characteristics (44.55 MPa, 6.92 MPa, 3430 Ω·cm) and is a sustainable alternative. Aluminum alloy mortar increases flexural strength but has a lower compressive strength (13.4 MPa).

Table 4. Mechanical properties of modified cementitious composites

Composite	Compressive strength (MPa)	Flexural strength (MPa)	Electrical resistivity (Ω·cm)	Reference
CNT-modified cement	180	5.5	2500	[43]
Copper slag and nano-graphite mix	44.55	6.92	3430	[45]
Aluminium alloy reinforced mortar	13.4	2.6x Baseline	–	[57]

ENHANCEMENT IN ELECTROMAGNETIC SHIELDING EFFECTIVENESS IN CONCRETE

Ozturk et al. [76] also examined the SE of concrete with boron by-products and wastes. SE is described as the ratio of electric field strength without and with the sample, expressed in decibels (dB). The testing was conducted in accordance with IEEE Std 299–2013, over a frequency of 2–18 GHz. The highest SE was exhibited by borogypsum, reaching 30 dB at 10.96 GHz, while the values over 10 dB were observed across most of the spectrum. The experiments pointed out that specimens prepared using material content containing boron exhibited SE values that were, at least, 3.16 to 100 times higher than those based on ordinary Portland cement. Due to the higher density of boron materials, their massive application and characteristics were suggested. The authors also pointed out that the neutron absorption capacity of boron in concrete may be used in building structures in microwave shielding applications. Shielding effectiveness of the concrete sample as shown in Figure 8.

Lee et al. [87] investigated the electromagnetic shielding effectiveness (SE) of high-strength concrete reinforced with amorphous metallic fibres. The PP0.15AM0.5 specimen had a SE value of 51.7 dB at 100 mm thickness; it was thereby an order greater than the 34.1 dB obtained in the case of steel fibre-reinforced concrete. The increase in thickness to 200 mm also increased SE. The results demonstrate that even at lower contents, amorphous metallic fibres greatly enhance SE. At higher contents, the formation of a conductive network will increase the efficiency of SE. Better performance of SE with increased thickness and content indicates positive correlation with electric conductivity.

Yuan et al. [47] investigated the uses of steel slag and steel fibres to improve the electromagnetic shielding effectiveness of HSC. The addition of the steel fibres enhanced SE, especially when

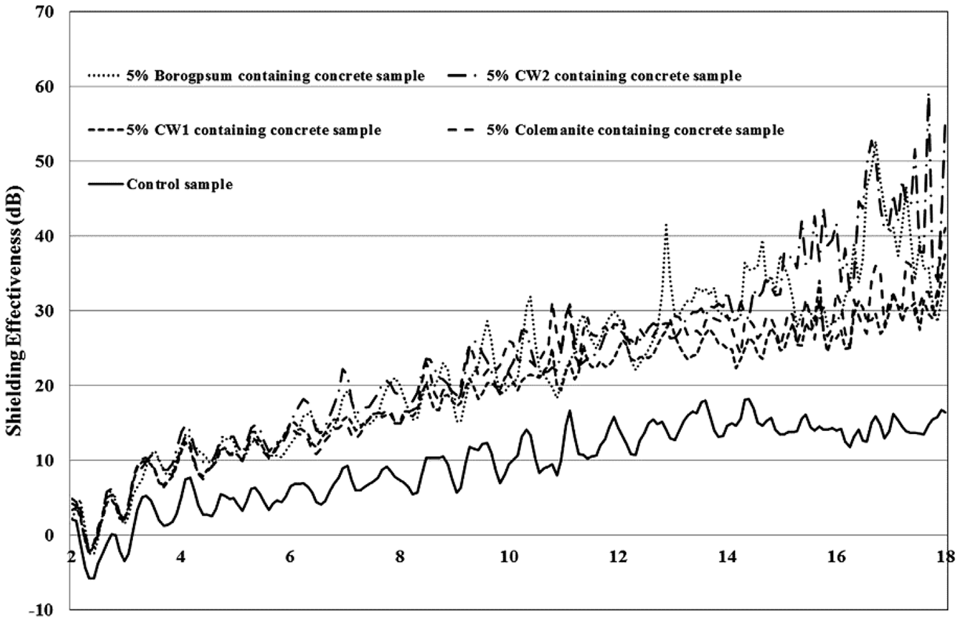

Figure 8. Shielding effectiveness of the concrete sample [76]

applied with steel rebar grids. At 50 mm spacing of the rebar, the improvement of SE on HSC compared with that of non-reinforced concrete within the range of 600–1000 MHz was up to 75.6%. Further additions of the fibre density and reduction of rebar spacing significantly enhanced SE, although more than the low-frequency regime.

Saleem et al. [55] investigated the electromagnetic shielding ability of fibre reinforced concrete incorporating furnace slag. The conclusion drawn was that, carbon fibre showed higher reflectivity and SE as compared to steel fibres, where SE values ranging between 1–6 GHz were higher for carbon fibre reinforced concrete than that of steel fibre reinforced concrete. The electrical conductivity-rich mixture, mixture 4 exhibited the highest SE, thus, demonstrating that electrical conductivity was directly related to electromagnetic shielding capability.

Jung et al. [43] studied the electrical conductivity and EMI SE of UHPC reinforced with CNTs. It is noticed that the electrical conductivity escalated with the increase of the CNT content, especially beyond 0.5 wt% indicated generation of conductive pathways. In tandem with this, the SE further escalates with an increase in the content of CNT and frequency. ASTM-D4935-18 test exposed significant SE enhancement with CNT concentrations of more than 0.5 wt%, and the SE was insensitive to perceived differences between specimens with 1.0 and 2.0 wt% CNTs due to comparable conductivities.

In experiments on IEEE-STD-299, UHPC-CNT composites show higher SE values at lower frequencies (<1 GHz) while it started to decrease once the frequency crossed the 30 MHz mark. This is in contrast with ASTM results. Results under ASTM depict that SE is variable according to the experiment method used but CNT content was an indispensable contributor to enhance SE.

Yoo et al. [46] also investigated UHPC reinforced with chemically treated carbon fibres (CFs), and it was found that CFs treated with nitric acid (n-C) proved to be the best and revealed maximum SE ~49 dB at 1 GHz with 0.1 wt %, while plain CFs proved to possess higher SE ~48.4 dB at 0.3 wt %. Even though the contents of conductive materials in these composites are lower compared to polymeric composites, UHPC-CF composite revealed competitive SE for EMI shielding applications like telecommunication and electrical power facilities.

Chen et al. [78] investigated the electromagnetic interference (EMI) shielding effectiveness (SE) of steel slag-recycled carbon fibre cementitious composites. According to electromagnetic theory, total EMI SE (SET) is composed of reflection loss (SER), absorption loss (SEA), and multiple reflection loss (SEM). For steel slag-recycled carbon fibre composites, SEA dominated the SET, with an increase in steel slag dosage leading to a rise in SET from 43.0 dB to 49.0 dB as slag content increased from 5 to 15 wt%. This increase in SE is primarily attributed to enhanced conductivity and interfacial polarization caused by FeO and Fe_2O_3 in the slag. The dielectric and magnetic losses contributed significantly to the absorption loss (SEA), which increased from 37.1 dB to 42.6 dB with added steel slag. Wet-grinding further refined particle size, boosting SET to 53.0 dB due to improved conductivity and additional interfaces for electromagnetic wave scattering.

Similarly, Hong et al. [81] examined lightweight aggregate concrete reinforced with steel fibres and steel slag, finding a significant improvement in SE with steel slag content. Shielding effectiveness improved from 4 to 17 dB in the 0.4–1.4 GHz frequency range when slag was incorporated. The addition of steel fibres further increased SE, with NC-SS15F showing a maximum of 50.3 dB at 1.3 GHz and LC-SS15F reaching up to 59.8 dB at 1.2 GHz, highlighting the superior performance of steel fibre in enhancing SE. The incorporation of both slag and steel fibres provided enhanced conductivity, contributing to improved SE across the tested frequency ranges [63 , 88]. Various types of bio-wastes, their composites, and shielding effectiveness values as shown in Table 5.

Table highlights waste materials for EMI shielding: Leather waste offers high SE (-55 to -90 dB), straw-based composites achieve up to -70 dB, and bagasse fibre composites reach -37.72 dB. Cow dung treated with KOH/H_2SO_4 provides 26 dB SE, showcasing sustainable shielding potential.

ENHANCEMENT IN ELECTROMAGNETIC SHIELDING EFFECTIVENESS IN CEMENT MORTAR

Yin et al. [96] produced nanocellulose fibres (CNF) combined with silver nanoparticles (AgNPs); they showed the possibility of having a very good SE of EMI. The SE of the CNF/AgNP composite films increases impressively with an increase in the content of AgNP up to 80.07 dB across a wide frequency range of 0.03–3000 MHz. This is due to the dense conductive networks that the nanoparticles provide and the mortar/brick structure peculiar to the composite, thus facilitating greater electromagnetic wave reflection and absorption, which in turn causes high attenuation of EM waves through ohmic loss and interfacial polarization relaxation. Electromagnetic shielding mechanism of composite films as shown in Figure 9.

Han et al. [57] studied mortar composites reinforced with perforated aluminum alloy sheets (ALS) for their shielding effectiveness. The SE grew directly proportional to the layers of ALS doped in the mortar. ALS 3, with three layers, achieved a SE value of 41.68 dB. This reinforcement created conductive pathways that enhanced the conversion of electromagnetic energy to thermal energy, thus enhancing wave absorption. It was in addition to the fact that the weight ratio of the product design added to its efficiency because it weighed less than any other traditional EMI shielding material.

Waste mill scale was used by Ozturk et al [56] to produce mortar with electromagnetic shielding property. Mill scale II showed good attenuation as it contained a better ferromagnetic feature. Its SE attains 40 dB in the frequency range of 11–18 GHz. Due to its cubic structure and magnetic characteristics, it could absorb electromagnetic waves in an excellent manner accompanied by excellent reflection of electromagnetic waves. This reflects the fact that mill scale can be used as a candidate for the shielding of the wireless communications.

Wang et al. [84] Prepared a very effective EMI shielding composite made from MXene and cellulose obtained from wood. Composites of d-$Ti_3C_2T_x$/DW had great EMI SE higher than 39 dB at 12.4 GHz. The characteristic was mainly absorption-dominated with slight reflection performance. This is primarily attributed to a relatively high conductive value of the MXene layers, as well as multiple internal reflections in

Table 5. Various types of bio-wastes, their composites, and shielding effectiveness values

Type of waste	Composite	SE	Reference
Leather wastes	Leather solid waste	-55 to -90 dB	[89]
Straw	Graphene aerogel Straw carbon Wheat straw	-70 dB -47.58dB RL < -10 dB	[90] [91], [92] [93]
Bagasse fibre	Bagasse fibre Core shell Bagasse fibre/polyaniline composite	-35.73 dB -37.72 dB	[94] [95]
Animal waste	Cowdung/KOH/H_2SO_4	-26 dB	][37]

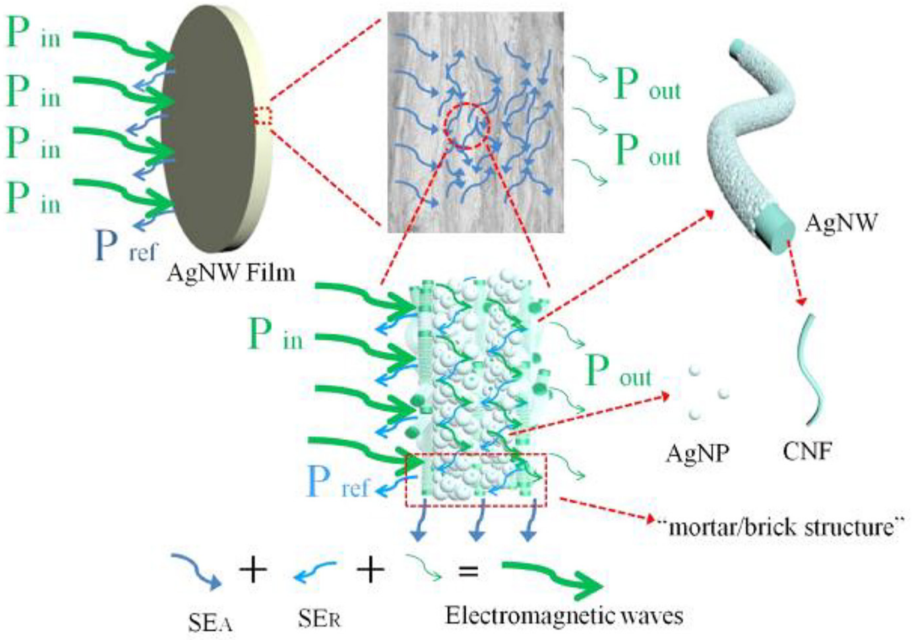

Figure 9. Electromagnetic shielding mechanism of composite films [96]

the structure of composites. Even at such a low thickness of 2 mm, it could demonstrate better performance than many 3 and 4 mm metal-based and carbon-based materials, thereby indicating the feasibility of ultra-lightweight, high-performance EMI shielding.

Liu et al. [82] reported on the effect of UHMWPE powder addition in a magnesium slag-based alkali-activated mortar system. The EM SE was significantly enhanced in the order of 808% at lower frequencies of 0.03–1.5 GHz due to the addition of 0.5 wt% of the UHMWPE. It, therefore, opened doors for further research work incorporating UHMWPE to enhance shielding efficiency of alkali activated material. Such diverse studies thus focus the growing interest in developing sustainable and effective materials for EMI shielding. [96] From nano cellulose composites to waste-derived materials such as mill scales and aluminium alloys, each material brings unique properties that contribute to its effectiveness. Clearly, the choice of material, its conductive properties and structural configuration play a major part in determining the performance of an electromagnetic shield.

Musiał et al. [62] investigated the shielding effectiveness (SE) of cement-based composites for high-power microwave (HPM) pulses, focusing on the material's electromagnetic wave reflection and absorption properties. Using ASTM D4935-10 standards, they measured SE across the 0–6 GHz frequency range. Composites with 10% graphite flakes, graphite powder, and carbon black significantly improved SE, particularly above 1 GHz, while polypropylene and steel fibres showed promising results despite limited prior research. Some materials, such as those incorporating carbon nanotubes, failed to meet expectations. The study highlighted the effectiveness of certain admixtures in enhancing shielding, although the cost and availability of materials could limit practical applications.

Jang et al. [97] explored carbonyl iron powder (CIP)-embedded CFRP composites for electromagnetic interference (EMI) shielding. They observed increased AC conductivity and improved EMI shielding, driven mainly by absorption losses due to the material's conductive and magnetic properties. As CIP content increased, so did the shielding effectiveness, with the C300 specimen achieving 99.7% SE at 8 GHz. The results demonstrated effective EMI shielding across a broad bandwidth, particularly in the high-frequency range.

Kim et al. [83] focused on enhancing MXene films by treating them with dicatechol (DC) molecules, which slightly reduced electrical conductivity but improved EMI shielding performance. The pristine MXene film showed a shielding effectiveness of 61.5 dB, while the MX@DC-5 film increased this to 66.2 dB. The films primarily shielded electromagnetic waves through reflection, with over 62% of incident radiation being reflected. This, along with high absorption levels, made MXene films highly effective for EMI shielding applications

Sun et al. [98] developed MXene-xanthan nanocomposite films with a layered microstructure for effective electromagnetic interference (EMI) shielding and Joule heating. The EMI shielding effectiveness (EMI SE) was measured in the X-band using S-parameters (Sij), revealing that films with higher MXene content exhibited superior shielding. The SE decreased from MXF1 to MXF5 (63.6 to 24.6 dB) as xanthan content increased, reducing electrical conductivity. However, MXF5 still achieved a shielding efficiency of 99.65%, confirming the films' exceptional EMI shielding performance. The shielding mechanism was absorption-dominant, with absorption (SEA) contributing more to total SE than reflection (SER). For example, MXF1 exhibited an SEA of 34.7 dB and SER of 14.1 dB. Transmission coefficients for the nanocomposite films were nearly zero, in contrast to neat xanthan films, which showed no shielding capability. The study also compared specific shielding effectiveness (SSE) and SSE per thickness (SSE/t), finding that the nacre-inspired MXene-xanthan nanocomposite films offered extremely high SSE/t values (up to 40,527.4 dB $cm^2 \cdot g^{-1}$), and outperforming other MXene-, metal-, and carbon-based materials due to their ultrathin structure and high conductivity. The layered structure further enhanced EMI shielding by creating multilevel barriers for electromagnetic waves. [99]. Various types of industrial wastes, their composites, and shielding effectiveness values as shown in Table 6.

The table shows various waste materials used for EMI shielding: cigarette wrappers (-50.79 dB), e-waste metal powders (-48.3 dB), red mud (-51.4 dB), fly ash (-20 to -23 dB), tissue paper (-40 dB), rubber (-22.4 dB), and plastic waste composites with carbon nanotubes (-106.3 dB). EMI Shielding Effectiveness of Various Materials as shown in Table 7.

The table shows that MXene films offer the highest SE of 66.2 dB (0.3–1.2 GHz), while CNTs achieve 48–49 dB at 1 GHz. Copper slag and fly ash with graphite provide SE values of 42.3 dB and 36.1 dB, respectively, offering eco-friendly alternatives for EMI shielding.

MICROSTRUCTURE ANALYSIS OF CONCRETE AND CEMENT MORTAR ON ELECTROMAGNETIC SHIELDING

Ren et al. [45] looked into various activation processes of electrically conductive cementitious composites (ECCC) containing nano-graphite activated magnetite. Results reflected that the samples remained porous without treatment; however, combined activation reduced intermolecular pores and increased the density of cement matrix.

Table 6. Various types of industrial wastes, their composites, and shielding effectiveness values

Type of waste	Composite	SE	Reference
Cigarette wrapper	Cigarette wrapper/Polydimethylsiloxane	-50.79 dB	[100]
Electronic waste	Metal powders	-48.3 dB	[101]
Red mud	Red mud	-51.4	[93]
Fly ash	Poly (vinyl butyral)–polyaniline-Co/Ni composite	-20 Db -23 dB	[102, 103]
Tissue paper	Waste tissue paper	-40 dB	[74, 104]
Rubber	Ground tire rubber	-22.4 dB	[105]
Plastic waste	Carbon nanotube Epoxy Plastic packaging	-35 dB -106.3 dB -44.8 dB	[105] [106] [107]

Table 7. EMI shielding effectiveness of various materials

Material	Shielding effectiveness (dB)	Frequency range (GHz)	Reference
Carbon nanotubes (CNTs)	48–49	1	[80]
Copper slag	42.3	0.03–3	[106]
Fly ash with graphite	36.1	0.1–1.5	[57]
MXene films	66.2	0.3–1.2	[57]

Activated nano-graphite had a more homogeneous distribution and thus resulted in an even lower tendency to form agglomeration of particle, enhancing the mechanical properties. G6M60 improved in compressive and flexural strength as well as conductivity. It is because the combined activation method by nano-graphite and magnetite had resulted in a good conductive network and a denser cement matrix due to interaction, which filled in micro-pores, enhanced load-bearing capacities. Cao et al. [79] studied carbon foam composites containing carbon nanotubes (CNTs) and montmorillonite (MMT).

SEM analysis performed for their samples revealed that the compressive strength was enhanced by up to 40% with CNT incorporation, while the material showed improved energy absorption and crack propagation resistance. Carbon foam composites containing 5 wt% MMT showed maximum EMI shielding efficiency at 65 dB, which is a 75% improvement in comparison to pure carbon foam. At concentrations beyond 5 wt%, MMT worsened agglomeration and resulted in reduced internal porous cells and thereby reduced shielding effectiveness. CNT took the energy, and MMT reflected electromagnetic waves within and hence boosted the shielding performance.

Li et al. [108] studied the influence of micro (m-Fe_3O_4) and nano-Fe_3O_4 (n-Fe_3O_4) on mortar microstructure. From the SEM images, it seems that an incorporation of m-Fe_3O4 as well as n-Fe3O4 resulted in much denser microstructure rather than that of pure mortar. Texture became denser, holes of the pore space were reduced, therefore, it is already proved that these additives had effectively enhanced the mechanical properties of mortar by providing a denser shape to the structure of mortar [109]. Microscopic images and XRD pattern of nano Fe_3O_4 As illustrated in sem image shown below in Figure 10 represents TEM in section a & b, SEM in section c and micrograph and X-ray diffraction pattern of nano Fe_3O_4 [110].

ENVIRONMENTAL BENEFITS OF SUSTAINABLE EMI SHIELDING COMPOSITES

EMI shielding composites offer environmental benefits by reusing industrial wastes like fly ash, copper slag, and steel slag, reducing landfills and promoting a circular economy [6]. These materials enhance mechanical properties, lower carbon footprints, and cut CO_2 emissions, as seen

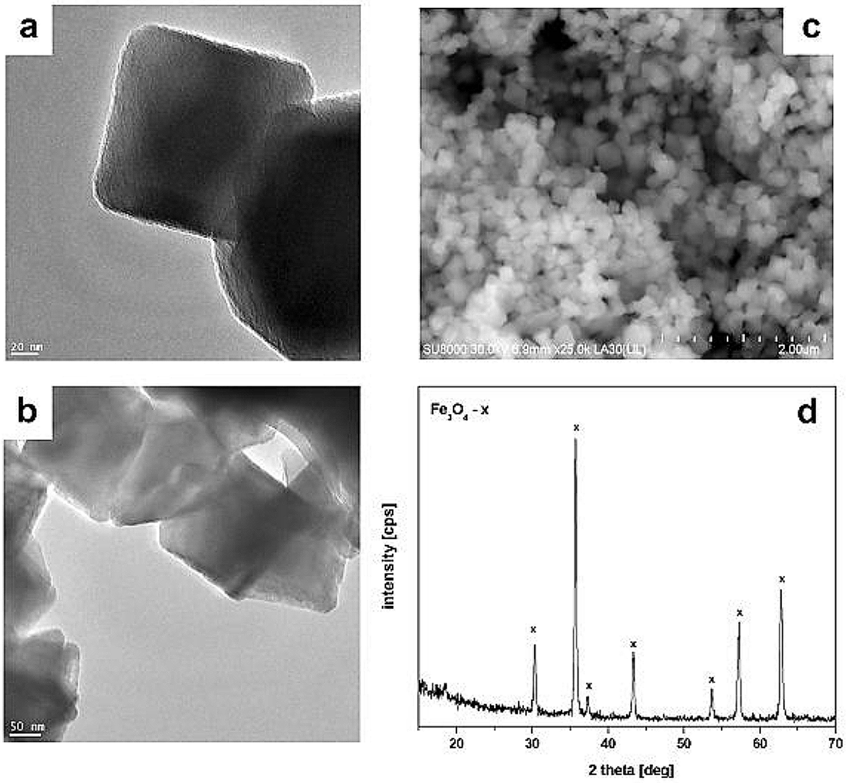

Figure 10. Microscopic images and XRD pattern of nano Fe_3O_4

in fly ash cement reducing clinker use. Lightweight, durable designs reduce energy for transport, installation, and repairs, boosting resource efficiency [93]. Self-repairing composites extend structure lifespans and support eco-friendly certifications like LEED and BREEAM. These composites align performance with sustainability, addressing global infrastructure demands [37].

REAL-TIME APPLICATIONS OF ADVANCED EMI SHIELDING MATERIALS

Smart construction and infrastructure resilience

Electrically conductive cement composite (ECCC) integrates materials that include carbon nanotubes, copper slag, and fly ash, which it is best suited for use in smart building systems. Among its applications are structural health monitoring and shielding electromagnetic waves in critical structures such as hospitals and data centers. For example, ECCC offers structural strength along with being an EMI barrier in critical infrastructure [44].

Perforated aluminum alloy sheets (ALS)

The material shows excellent promise for lightweight construction requirements such as for modular and prefabricated buildings. With high shielding effectiveness, ALS-reinforced mortar finds applications where additional EMI protection is required [57].

Military and aerospace

Advanced nanomaterials (MXenes and carbon nanotubes)

Light weight yet extremely efficient, MXenes and carbon nanotubes have tremendous potential for shielding sensitive electronics in aircraft cockpits and military command centers. They ensure reliable performance even in the harshest environmental conditions- exactly what is needed in aerospace and defense applications [20].

Steel fibre-reinforced concrete (SFRC)

SFRC is also widely used in the construction of bunkers and ammunition storage facilities. It is used to increase EMI shielding performance with structural strength enough to support heavy loads [47, 63]

Telecommunication and electronics

Fly ash and slag composites

Fly ash slag composites can be the ideal material for EMI-shielded enclosures of telecommunication towers, data centers, and server rooms because they can prevent electromagnetic interference from occurring and disturbing sensitive operations [64].

Graphite and carbon fibre composites

Graphite and carbon fibre composites are used in manufacturing antenna radomes and satellite dishes, which are lightweight and strong. These materials have the dual advantage of mechanical strength and effective EMI shielding [111].

CONCLUSIONS

- Nanoparticles like CNTs, nanosilica, and steel slag enhance concrete composites' mechanical and EMI shielding properties. A 0.5 wt% CNT addition improved UHPC compressive strength by 5.5% and elastic modulus by 12%. Copper slag achieved 44.55 MPa strength (30% improvement) with 8180 Ω·cm resistivity, suitable for EMI shielding. Steel slag composites provided 43–49 dB SE, while 100 μm copper-zinc coatings achieved 80 dB SE, outperforming pure copper by 18%, highlighting advancements in multifunctional materials.
- The integration of industrial byproducts such as fly ash (20%) and slag (30%) into cement composites not only mitigates environmental impact but also enhances structural integrity and EMI shielding capabilities. These eco-friendly materials contribute to a circular economy by promoting waste reuse while achieving superior performance metrics compared to traditional materials
- The scalability of advanced nanomaterials like CNTs and graphene is limited by high costs and complex synthesis. Hybrid systems incorporating industrial by-products (e.g., fly ash or slag) with minimal nanomaterial content provide a cost-effective solution, maintaining performance. Scalable methods like roll-to-roll CNT processing, graphene CVD, and 3D printing can reduce costs. Refining dispersion techniques, such as ultra-sonication, ensures property enhancement. Future research should

focus on optimizing formulations, adopting economical manufacturing, and collaborating with industries for real-world implementation.

- Current research lacks comprehensive studies on the long-term durability of these composites under varied environmental conditions, including extreme temperatures and moisture exposure. Implementing protective coatings and hybrid composites with enhanced toughness could significantly improve durability outcomes. Accelerated aging tests alongside thorough environmental exposure assessments are essential to validate the practical utility of these materials
- The absence of international standards for evaluating mechanical and electromagnetic performance limits the market penetration of EMI shielding composites. Establishing standardized testing protocols is vital for facilitating wider adoption in engineering applications
- Enhancements in production workflows, along with strategic collaborations with industry partners, can lead to reduced resource consumption and lower production costs. Utilizing computational techniques such as multi-scale modelling can predict material behaviour effectively, enabling optimized formulations for improved performance
- Advanced composites that integrate structural strength with EMI shielding capabilities offer promising multifunctionality for modern construction needs. By leveraging nanotechnology alongside sustainable materials, there is potential for transformative changes in construction practices that align with sustainability objectives. Addressing durability, scalability, and cost challenges will be pivotal in bridging the gap between innovative research and practical application
- Future developments in concrete and cement composites are intended to improve mechanical strength, durability, and EMI shielding. Optimizing dispersion strategies for additives such as carbon nanotubes, graphene, boron-based compounds, and MXenes can improve their structural and functional properties. Eco-friendly materials, including fly ash and industrial wastes, as well as hybrid fibres and nanosilica, are projected to improve tensile strength, crack resistance, and EMI shielding.
- Self-healing materials, computational modeling, and long-term durability testing will all help to extend the lifespan of concrete and certify its performance. Graphene may be used to replace graphite in concrete, however appropriate quantity and bonding must be determined. Machine learning can help with material design, combining conductive and magnetic layers to improve shielding effectiveness.
- The use of three-dimensional printing allows for accurate filler placement, resulting in personalized qualities. These discoveries address smart city, aerospace, and military applications by developing multipurpose, high-performance materials for modern infrastructure demands.
- The use of biodegradable and recyclable materials in shielding composites decreases e-waste impact, while multifunctional composites meet modern electronic needs such as EMI shielding, thermal control, and adaptability. Telecommunications focuses on materials that safeguard high-frequency signals for 5G, whereas defence seeks lightweight, long-lasting shielding for harsh situations. Consumer electronics require thin, flexible solutions that improve miniaturization and performance. To meet industry demands in the long run, future research should target cost-effective production, dispersion optimization, and standardized testing for durability in severe environments.

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