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Advances in Smart Concrete: A Comparative Review of Self-Sensing and Self-Healing Systems

William Lam
williamkennethlam@gmail.com

ABSTRACT

Concrete production is a substantial contributor to global carbon emissions. Because of this, there have been many efforts to develop advanced construction materials that improve durability, reduce maintenance requirements, and extend the service life of infrastructure. Smart concrete has become a potentially promising alternative to conventional concrete. This new type of concrete possesses self-sensing and self-healing capabilities. This review synthesizes current research on smart concrete technologies, specifically focusing on the materials, mechanisms, benefits, and limitations of smart concrete. Self-sensing approaches, including the addition of carbon fibers, carbon nanotubes, graphene-based materials, and steel fibers into the concrete mix, are evaluated with respect to sensing performance, mechanical enhancement, manufacturability, and cost. Self-healing strategies of smart concrete, which include autogenous healing, calcium carbonate mineralization, fiber-assisted healing, supplementary cementitious materials, superabsorbent polymers, encapsulated healing agents, and bacteria-based systems, are also thoroughly examined. Additionally, the review identifies key barriers that are currently limiting the widespread adoption of smart concrete at scale, including high material costs, manufacturing complexity, lack of standardized testing frameworks, regulatory uncertainty, and challenges associated with data integration and long-term monitoring. Considerations surrounding sustainability are also assessed, including embodied carbon, ecological risks associated with nanomaterials and biological systems, and end-of-life recycling limitations. While smart concrete currently possesses substantial potential to improve infrastructure resilience and reduce lifecycle maintenance demands, significant technical, economic, and regulatory challenges remain. In order for smart concrete to be adopted at scale, there will have to be improvements in the standardization of evaluation methods, expansion of long-term field validation, and development of manufacturing approaches that prioritize the balance of performance, scalability, and environmental sustainability.

1. INTRODUCTION

Anthropogenic carbon dioxide emissions are a key driver of global warming. Concrete, one of the world's most widely used materials, contributes significantly to global carbon emissions, with the cement industry alone estimated to account for roughly 8% of global anthropogenic emissions (Andrew, 2018; Coffetti et al., 2022). The production of concrete continues to rise each year. Therefore, in order to counteract the issue of the environmental impact of concrete production, alternative types of concrete are becoming

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increasingly popular worldwide. One such promising alternative is smart, sustainable concrete, which is a type of concrete that is more durable and self-sustainable than traditional concrete, with a wide range of unique abilities. Smart concrete can monitor its own conditions, self-heal, and sense changes in stress, strain, and temperature. Additionally, it is able to adapt accordingly to these environmental changes. Smart concrete presents a promising opportunity to improve structural monitoring and maintenance across the construction industry. While the cost of purchasing smart concrete may be greater than that of traditional concrete up front, its reduced maintenance costs and environmental benefits in the long term are establishing smart concrete as a promising alternative material within the construction industry.

There are a number of key challenges that will require unique solutions which are not yet fully understood, therefore limiting the current adoption of smart concrete. This paper analyzes the current literature on smart concrete, establishes the implications of its widespread adoption, and examines the biggest challenges to adoption. As interest in smart concrete grows, so do its suggested applications, compositional variations, and manufacturing approaches. In addition to synthesizing the existing literature on smart concrete, this paper also suggests possible solutions for the most prevalent challenges facing smart concrete's application and adoption.

Several broad surveys of smart concrete already exist, most notably Tian et al. (2024), which this review draws on frequently. This paper organizes the field as a direct, side-by-side comparison: each self-sensing material and each self-healing mechanism is measured against the same set of dimensions: sensing sensitivity, mechanical benefit, cost, manufacturability, technology readiness, and sustainability. Summary tables are included so that these trade-offs can be compared at a glance, and the discussion is deliberately weighted toward the barriers that continue to keep smart concrete out of routine construction. The goal is to give readers a clearer sense not only of what smart concrete can do, but also of which approaches are closest to practical adoption and why.

2. REVIEW APPROACH

This paper is a narrative literature review rather than a systematic meta-analysis. Sources for this review were gathered using Google Scholar, ScienceDirect, and the MDPI and Springer databases. Search terms paired a functional keyword (such as "smart concrete," "self-sensing concrete," "self-healing concrete," "piezoresistive cement," or "bacterial concrete") with a material or mechanism keyword (such as "carbon fiber," "carbon nanotube," "graphene oxide," "steel fiber," "superabsorbent polymer," "supplementary cementitious material," or "microcapsule"). Priority was given to peer-reviewed journal articles and review papers published between roughly 2010 and 2024, though a small number of older but frequently cited works were included because they remain foundational to the field.

Studies were included if they reported on the materials, mechanisms, performance, cost, or sustainability of self-sensing or self-healing concrete, and were set aside if they dealt only with conventional concrete, were not available in English, or did not connect their findings to structural or sustainability outcomes. The criteria used are summarized in Table 1. Because this review draws on a limited and largely English-language source base, it is meant to describe the current direction of the field rather than to provide an exhaustive account of every published study.

Table 1. Inclusion and exclusion criteria used to select sources

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles and review papers	Studies limited to conventional concrete with no smart function
Focus on self-sensing or self-healing concrete	Sources not available in English
Reports on materials, mechanism, performance, cost, or sustainability	Work not tied to structural or sustainability outcomes
Published roughly 2010–2024 (plus a few foundational older works)	Non-scholarly or unverifiable sources

3. OVERVIEW OF SMART CONCRETE

Smart concrete is formed by combining traditional concrete with smart tools that aid in self-healing, self-sensing, and self-adjusting techniques. This traditional concrete alternative is an advanced construction material that integrates traditional concrete's mechanical advantages (such as robustness) with the mentioned capabilities. These properties mainly come from adding different materials, each with special properties, including carbon fibers, carbon nanotubes (CNTs), graphene-based materials, and steel fibers. Such fillers can create conductive networks within the cement, which enable the concrete to detect changes in strain, stress, temperature, or moisture and facilitate real-time structural health monitoring. The use of such sensing functions can help to identify deterioration before visible damage, ensuring quick maintenance and extending the life cycle of the concrete, thereby providing economic savings. Smart concrete can also repair small cracks using bacteria that produce calcium carbonate ($CaCO_3$) or capsules filled with healing agents that activate when cracks form. This can also extend the lifespan of structures, as well as lower the environmental impact of concrete production by decreasing the need for replacement. These properties all contribute towards improved sustainability in infrastructure.

Smart concrete is composed of many diverse materials used to achieve its desired self-sensing and self-healing attributes. The use of different materials in a piece of smart concrete presents significant enhancements or trade-offs, depending on the smart additives used. A successful mix of CNTs and graphene oxide (GO) can improve compressive and flexural strength, increase toughness, and make the concrete conductive (Tian et al., 2024). However, problems like particle clumping and high production costs make the mixing process more difficult. Alternative binder systems and the use of supplementary cementitious materials (SCMs), such as fly ash, slag, calcined clays, and lime, enable the reduction of Portland cement clinker content, resulting in lower carbon emissions while maintaining its advantages. Integrating recycled materials, such as concrete aggregate or even recycled cement paste through innovative technologies (Dunant et al., 2024), also offers reduced environmental impact.

Today, smart concrete is used in structures ranging from buildings to roads, where it can monitor cracks, stress, and temperature changes. This helps to identify damage early on and allows for optimized and proactive maintenance that helps lower the cost of maintenance. Due to its self-adjusting heating abilities, some versions of smart concrete can help melt ice on pavements or warm up surfaces, which improves safety, particularly in areas with colder climates. Overall, smart concrete is primarily used to keep track of the health of structures and lower the cost of maintenance, but it also shows promise in other practical uses, such as de-icing and damage detection. While its use is still not widespread, an increasing number of construction projects are testing smart concrete to help monitor infrastructure, reducing the need for recurring inspections. The means by which smart concrete achieves its unique abilities lie in the materials from which it is made and the respective accompanying systems.

4. MATERIALS IN SMART CONCRETE

4.1 Materials for Self-Sensing

4.1.1 Carbon Fibers

Unlike normal concrete, which barely conducts electricity, carbon fiber concrete can carry small electrical signals because the fibers form conductive paths inside the cement, allowing for electrical signals. Once stress starts building or tiny cracks begin forming, the fibers shift slightly against each other, changing the electrical resistance. Those changes can be measured and used to tell when the material is being strained or damaged. This piezoresistive effect is one of the main reasons carbon fibers are studied in self-sensing concrete systems. One way researchers quantify this effect is the gauge factor, which describes how strongly electrical resistance responds to strain. Lee et al. (2017), for example, reported a gauge factor of roughly 405 for cement composites containing about 0.5% carbon fibers by volume, far above the near-zero response of plain cement. The fibers also help from a structural standpoint by slowing crack spread and making the concrete tougher after cracking begins (Tian et al., 2024). The efficacy of the sensing depends a lot on how evenly the fibers are spread through the mix. If they are not evenly distributed, the conductive network becomes patchy and less dependable. Carbon fibers are therefore useful not just for reinforcement, but also because they give the concrete a way to react to what is happening internally.

There are a few reasons carbon fibers are appealing in concrete applications. They are strong for their weight, resist corrosion, and can help delay long-term structural wear (Tian et al., 2024). Since the electrical resistance shifts as stress changes inside the material, engineers may be able to identify problems earlier instead of waiting until visible damage appears. This could result in fewer repairs and less material wasted over the life cycle of the structure. Longer-lasting infrastructure also tends to reduce the amount of reconstruction needed later on, which may lower overall resource use and emissions tied to maintenance work (Coffetti et al., 2022).

At the same time, there are still several practical problems surrounding carbon fibers and concrete. Carbon fibers take a large amount of energy to manufacture, so they remain more environmentally expensive than many standard construction materials. In most cases, carbon fiber concrete is still too expensive for ordinary construction projects and is used more often in specialized settings, such as bridge strengthening and seismic retrofitting (Akeed et al., 2022). Mixing also poses several problems. The fibers sometimes bunch together in parts of the concrete instead of spreading evenly through the mix, and when that happens, both the sensing response and structural performance can drop off. Preventing this usually requires extra treatment steps or more complicated mixing methods, which pushes production costs even higher (Tian et al., 2024).

Manufacturing methods have a significant effect on performance. Researchers have experimented with ultrasonic mixing, chemical dispersants, and surface treatments to help the fibers spread more consistently throughout the cement paste (Coffetti et al., 2022; Tian et al., 2024). Better dispersion improves both conductivity and crack resistance while also improving the strength of the material. There are many research efforts aimed at lowering the energy cost of production and making carbon fiber concrete more realistic for larger-scale construction use. The amount of carbon fiber added plays a key role in its efficacy. Small amounts may not form a stable sensing network, but very high amounts can increase costs quickly without changing performance all that much. Although the material has shown strong potential in laboratory studies, it is rarely used in real-world applications. Much of the current research is focused on making the material simpler and cheaper to produce while still maintaining reliable sensing behavior (Coffetti et al., 2022; Tian et al., 2024).

4.1.2 Carbon Nanotubes

Carbon nanotubes (CNTs) share lots of similarities with carbon fibers and are typically studied for many of the same reasons in self-sensing concrete systems. Both materials create conductive electrical networks within the concrete that allow for tiny changes in electrical resistance to be observed and measured as damage develops. However, CNTs are much smaller than carbon fibers, and because of this, CNTs interact with the cement matrix in distinct ways that carbon fibers cannot. While carbon fibers primarily reinforce concrete by bridging larger visible cracks and improving post-cracking behavior, CNTs can influence the material at the nanoscale by interacting with non-visible microcracks and the products formed during cement hydration (Tian et al., 2024; Lushnikova et al., 2023).

When dispersed throughout the cement, CNTs form multiple conductive pathways that allow electrical current to pass through the concrete, much like carbon fibers. As stress develops or microcracks begin to form, the arrangement and contact between nanotubes change, producing measurable shifts in electrical resistance, allowing for improved monitoring compared to traditional concrete (Lushnikova et al., 2023; Tian et al., 2024). Lushnikova et al. (2023) observed this directly, measuring a steady rise in electrical sensitivity in cement mortar as the carbon nanotube content increased from 0 to only about 0.018% by weight of cement, and the researchers' molecular-dynamics modeling showed the stiffness and tensile strength of the calcium-silicate-hydrate matrix improving as more nanotubes were added. Because these conductive networks are on a much smaller scale than those formed by carbon fibers, CNT-based systems are used for detecting very small deformations that carbon fibers would not be able to detect. This high sensitivity has made CNTs one of the most widely studied materials for self-sensing concrete applications and an incredibly promising additive.

A key advantage of CNTs is their ability to modify the cement matrix itself. Their extremely large surface-area-to-volume ratio allows them to both interact with hydration products and also influence the development of the concrete microstructure (Lushnikova et al., 2023). Researchers have shown that properly dispersed CNTs can not only reduce porosity but also improve bonding between cement phases and increase compressive strength, flexural strength, and fracture toughness (Lushnikova et al., 2023; Tian et al., 2024). This combination of mechanical enhancement and very sensitive damage detection allows for the monitoring of structures continuously rather than relying solely on the much more financially inefficient periodic inspections. Earlier identification of deterioration may also allow repairs to occur before severe damage develops, which would help to extend service life, thereby reducing the environmental costs associated with reconstruction and maintenance (Coffetti et al., 2022).

Despite these advantages, CNT concrete still faces several significant challenges preventing widespread adoption in today's economy. Producing high-quality CNTs, in a similar way to producing carbon fibers, requires energy-intensive manufacturing processes and remains substantially more expensive than the standard concrete additives (Lushnikova et al., 2023; Tian et al., 2024). Dispersion is also particularly difficult because nanotubes attract one another and are susceptible to forming bundles or agglomerations during the mixing process. This clustering often limits both the mechanical benefits and sensing capabilities of the material by disrupting the network of conductivity (Lushnikova et al., 2023; Tian et al., 2024). Researchers typically rely on ultrasonication, surfactants, and chemical functionalization techniques, which allow them to prevent the nanotubes from clumping and distribute them more evenly throughout the cement. There are also key ongoing concerns regarding both the environmental and the occupational health impacts of nanoparticle production and nanoparticle handling (Tian et al., 2024).

One important concept in CNT concrete is the idea of the percolation threshold, which is the minimum CNT concentration needed to create a continuous conductive network throughout the concrete. If the concrete is below the threshold, conductivity and sensing performance decrease very sharply because electrical pathways are not connected. If the concrete is above the threshold, conductivity noticeably improves, although excessive CNT concentrations will increase costs and promote agglomeration without providing sufficient performance gains. This helps explain why the very small additions studied by Lushnikova et al. (2023) still sit below the level needed for a robust network, whereas self-sensing studies aiming for a strong, stable piezoresistive response often use higher dosages closer to 0.5–1.0% by volume (Lee et al., 2017). As a result, much of the current research surrounding CNT concrete focuses on identifying optimal concentrations and manufacturing methods that factor in cost and scalability while still optimizing performance (Coffetti et al., 2022; Lushnikova et al., 2023; Tian et al., 2024). Although laboratory studies have continuously shown strong potential, challenges involving manufacturing consistency, economic feasibility, and long-term field performance strongly limit widespread adoption. Current efforts are aimed at making CNT concrete more practical for real-world smart infrastructure applications while preserving the sensing capabilities that distinguish it from conventional concrete systems (Coffetti et al., 2022; Tian et al., 2024).

4.1.3 Graphene-based Materials

Graphene-based materials (GBMs), including graphene oxide (GO) and graphene nanoplatelets (GNPs), are some of the most promising nanomaterials currently being studied for self-sensing concrete systems. Like carbon fibers and carbon nanotubes (CNTs), graphene derivatives also create conductive networks within the otherwise electrically insulating cement matrix, allowing changes in electrical resistance to be used to assess strain and damage (Lushnikova et al., 2023; Tian et al., 2024). However, graphene-based materials are different from the other two additives in that they consist of multiple atomically thin two-dimensional sheets rather than just fibers or tubes. This sheet structure provides a very large surface area for the interaction of cement particles and hydration products. When stress or microcracking occurs within the concrete, changes in contact between the graphene sheets and disruptions in electron transport chains produce observable and measurable variations in electrical resistance, allowing for the real-time monitoring of structural behavior (Lushnikova et al., 2023; Tian et al., 2024). Graphene oxide and graphene nanoplatelets are used for distinct roles within these systems. GO is used for its ability to more effectively disperse in cement. It is also used for its influence on hydration processes. Alternatively, GNPs are frequently used to maximize electrical conductivity and mechanical reinforcement.

Graphene-based materials stand out for their ability to modify the cement microstructure. Researchers have repeatedly shown that GO can act as a nucleation site for cement hydration products, essentially allowing the formation of a denser and more uniform microstructure (Lushnikova et al., 2023). This refinement of the pore structure helps to reduce permeability and enhance resistance to environmental degradation. Graphene sheets can also help limit nanoscale cracks and prevent water and aggressive chemicals from entering the concrete. In addition to these durability benefits, GBMs have been heavily associated with improvements in compressive and flexural strength, as well as fracture toughness and sensing sensitivity (Lushnikova et al., 2023; Tian et al., 2024). Because graphene possesses the ability for strong electrical conductivity, these improvements can often be achieved with very small material additions compared to traditional reinforcing materials. The combination of enhanced durability and highly sensitive structural health monitoring positions GBMs as a very promising tool for not only extending infrastructure service life but also reducing maintenance-related resource consumption (Coffetti et al., 2022).

However, despite the potential of graphene-based materials, they are not yet mainstream in the industry. Producing graphene derivatives often requires ultra-complex manufacturing and chemical processing steps that consume significant amounts of energy and financial resources (Coffetti et al., 2022; Dunant et al., 2024; Tian et al., 2024). This means that cost remains significantly higher than that of conventional concrete additives. Like the previously mentioned additives, dispersion also presents a major challenge. Because graphene sheets tend to attract one another, they can form agglomerations during mixing that reduce conductivity, which creates inconsistencies in sensing performance (Lushnikova et al., 2023; Tian et al., 2024). Researchers use a variety of methods including ultrasonication, chemical functionalization, and polymer-based dispersants to improve graphene distribution throughout the cement. There are also concerns regarding the environmental and occupational health impacts associated with the production, handling, and disposal of nano-scale materials (Tian et al., 2024). These limitations prevent graphene-based materials from widespread use today.

Manufacturing methods play a crucial role in determining both the performance and sustainability of graphene-based self-sensing concrete. Effective dispersion strategies are a key part of achieving uniform conductive networks and thereby maximizing the mechanical benefits. Researchers have spent significant effort on lower-energy synthesis methods and greener production routes for GO and GNPs in an effort to reduce both cost and environmental impact (Coffetti et al., 2022; Dunant et al., 2024). Optimizing graphene dosage is another crucial consideration. Small additions may be insufficient to establish reliable sensing behavior, while excessive amounts can increase costs and promote agglomeration without providing proportional performance gains. Additional challenges involve the standardization of graphene quality, as well as scaling production to industrial levels while ensuring consistent long-term performance in field conditions. Consequently, current research is focused not only on improving sensing capabilities but also on developing practical methods that can support the adoption of graphene-enabled smart concrete systems (Coffetti et al., 2022; Tian et al., 2024).

4.1.4 Steel Fibers

Steel fibers are some of the most widely used reinforcement materials in the production of modern concrete. Interestingly, they were originally developed to improve mechanical performance and were not considered as a way of providing sensing capabilities. When incorporated into concrete, steel fibers physically bridge the cracks and transfer the loads across the damaged regions, increasing toughness, ductility, and resistance to crack propagation (Tian et al., 2024). While steel fibers do possess certain conductive properties, their sensing ability is significantly less sensitive than other nanomaterials like CNTs or graphene derivatives. This gap is visible in direct comparisons: where nanotube-based composites reach gauge factors on the order of 160 or more, steel-fiber systems respond far more weakly to strain (Lee et al., 2017). The material does, however, offer the advantage of combining proven structural reinforcement with self-sensing functionality in a single material system.

The main benefit of steel fiber-reinforced concrete is its ability to improve the durability and structural performance of concrete. By bridging cracks and limiting their growth, steel fibers help concrete withstand repeated loading and reduce the likelihood of sudden brittle failure (Coffetti et al., 2022; Tian et al., 2024). These improvements often extend service life and reduce the frequency of need for repair and replacement activities, thereby saving financial resources. From a sustainability perspective, steel fibers offer several advantages over the previously discussed advanced nanomaterials. They are less expensive than CNTs or graphene-based additives and often are produced from recycled steel waste streams, including industrial by-products and recovered steel materials (Coffetti et al., 2022; Dunant et al., 2024). Incorporating recycled content supports principles of a circular economy while also reducing the hefty environmental burden associated with raw material extraction. Unlike many self-sensing nanomaterials that remain largely confined to laboratory research, steel fiber-reinforced concrete has already achieved widespread commercial use in many applications including industrial floors, tunnels, pavements, precast elements, and shotcrete systems.

Even so, the steel fibers are quite dense, so their use increases the weight of the concrete mixture compared to carbon-based additives. This increases transportation-related environmental impacts. Workability is also an issue at higher fiber concentrations, as fibers may cluster together during mixing and form "fiber balls" that reduce not only sensing reliability but also mechanical performance (Tian et al., 2024). Corrosion presents another concern; although steel fibers are generally protected by the alkaline environment of concrete, aggressive conditions including exposure to chloride or severe cracking can lead to significant corrosion over time. This results in reduced durability and negatively affects the stability of the conductive sensing network (Ebead et al., 2022). These limitations can make steel fibers less suitable than carbon-based nanomaterials for certain applications requiring extremely sensitive sensing performance.

Like all concrete additives, manufacturing and processing methods play a crucial role in determining the effectiveness of steel fiber-reinforced self-sensing concrete. Uniform fiber distribution through proper mixing procedures is essential for maximizing both crack-bridging performance and electrical conductivity (Coffetti et al., 2022; Tian et al., 2024). Researchers have also investigated surface treatments and protective coatings that improve fiber bonding and corrosion resistance, helping maintain long-term durability and sensing performance (Tian et al., 2024). The use of recycled steel fibers remains an area of particular interest because it offers an opportunity to improve sustainability while maintaining mechanical benefits. Optimizing fiber dosage is also important, as insufficient amounts may fail to establish reliable conductive pathways while excessive amounts can increase cost, reduce workability, and complicate construction. Although challenges involving quality control, corrosion management, and sensing standardization remain, steel fibers are currently among the most practical and commercially viable self-sensing concrete additives available. Ongoing research is focused on improving sensing accuracy while preserving the durability, affordability, and scalability that have already enabled widespread real-world adoption (Coffetti et al., 2022; Tian et al., 2024).

Table 2. Comparison of self-sensing additives across key dimensions

Material	Sensing sensitivity	Mechanical benefit	Relative cost	Technology readiness
Carbon fibers	High; gauge factor ~405 at 0.5 vol% (Lee et al., 2017)	Bridges larger cracks; adds post-crack toughness	High (energy-intensive)	Mostly lab-scale; niche field use (retrofit, seismic strengthening)
Carbon nanotubes	Very high; detects nanoscale microcracks	Densifies matrix; raises compressive and flexural strength	Very high	Mainly research; dispersion still a barrier
Graphene-based	Very high, even at very low dosage	Refines pore structure; improves durability and strength	Very high	Early research; hard to scale
Steel fibers	Low to moderate	Strong crack-bridging, ductility, fatigue resistance	Low (often recycled)	Widely used commercially

4.2 Materials for Self-Healing

4.2.1 Unhydrated Cement Particles

Unhydrated cement particles are one of the most fundamental self-healing mechanisms in the production of concrete because they rely on materials already present within the cement itself. Unlike synthetically engineered healing systems that require additional additives, encapsulated agents, or biological components, autogenous healing occurs when previously unreacted clinker grains are exposed to water and continue the hydration process (Tian et al., 2024; Van Tittelboom & De Belie, 2013). As new hydration products form, like calcium silicate hydrate (C-S-H), they partially fill the cracks and pores within the concrete, thereby reducing permeability and greatly improving the mechanical performance. Because this mechanism uses the cement particles that were already incorporated during the construction itself, it is often considered the simplest and most naturally occurring form of self-healing in the production of cement.

The main advantage of autogenous healing is the fact that it is able to extend service life without using any additional materials. When cracks remain very small, continued hydration helps to seal the pathways that could otherwise allow water, chlorides, and other harmful substances to penetrate the concrete, weakening its mechanical strength. By slowing the deterioration of the concrete and reducing maintenance requirements, autogenous healing lowers lifecycle costs and decreases the environmental impacts that come with repair, replacement, and material consumption (Coffetti et al., 2022). Since the process relies on resources already used in the production of the concrete, it offers a highly sustainable approach to damage mitigation.

However, the effectiveness of autogenous healing is heavily dependent on exposure to moisture and the presence of sufficient unhydrated cement particles. As the concrete ages, the quantity of remaining unreacted clinker continually decreases, which reduces the material's capacity for further healing. In addition, autogenous healing is generally limited to very small microcracks, typically less than approximately 100 μm in width (Van Tittelboom & De Belie, 2013), making it unsuitable as a standalone solution for any type of larger or structurally significant damage (Ebead et al., 2022). Environmental conditions also play a very important role; healing may be limited in dry environments where water is unavailable to support the continued hydration needed.

Current research seeks to enhance the natural healing capacity of unhydrated cement particles through both improved mix design and curing practices. Researchers have looked for ways to optimize cement particle size distributions, extend the moisture retention, and incorporate supplementary cementitious materials that support ongoing hydration reactions (Coffetti et al., 2022; Tian et al., 2024). Rather than serving as a self-healing solution completely on their own, unhydrated cement particles are increasingly viewed by scientists as a foundational mechanism that can be combined with other healing technologies to improve overall crack repair and long-term durability.

4.2.2 Calcium Carbonate

Calcium carbonate ($CaCO_3$) healing differs from hydration-based self-healing mainly because it relies on the formation of new mineral deposits within cracks as opposed to the continued reaction of existing particles. In systems using calcium carbonate, the carbonate precipitates inside damaged regions through chemical reactions, microbial activity, or other mineralization processes that slowly fill the voids and seal the cracks (Coffetti et al., 2022; Tian et al., 2024). As more and more of these deposits appear, they help to reduce permeability and restore the protective functions originally provided by the concrete. Because calcium carbonate is highly compatible with cement materials, it can integrate well with the surrounding structure and provide a very stable form of crack closure.

One of the main advantages of calcium carbonate healing is the fact that it can improve durability by limiting the ingress of water, chlorides, sulfates, and other aggressive substances that contribute to significant concrete deterioration. Unlike autogenous healing, which relies on the presence of unhydrated cement particles, mineral precipitation continues even after the original cement has reacted. By sealing cracks and reducing permeability, calcium carbonate formation is able to extend service life and decrease the need for repair, offering economic upside (Amran et al., 2022).

The effectiveness of calcium carbonate healing depends heavily on various environmental conditions, including moisture availability, carbon dioxide concentration, temperature, and, in some cases, microbial activity (Ebead et al., 2022; Tian et al., 2024). Healing occurs relatively slowly compared to some engineered repair methods, particularly in environments where the conditions necessary for precipitation are not met. In addition, while calcium carbonate deposits can effectively seal small and moderate cracks, the mineralization process alone is not sufficient to fix larger cracks.

Current research focuses on accelerating and enhancing the formation of calcium carbonate to improve healing efficiency and broaden its practical applications. Most research efforts have been focused on admixture formulations, controlled curing conditions, and biologically assisted mineralization strategies, which would allow for faster or more extensive precipitation within cracks (Coffetti et al., 2022; Tian et al., 2024). Because calcium carbonate is often the final healing product in several different self-healing technologies, including bacterial systems, it is viewed as one of the key mechanisms that can be combined with other approaches to improve crack repair, durability, and long-term infrastructure performance (Zhang et al., 2024).

4.2.3 Fibers

Unlike traditional self-healing approaches, fibers do not repair cracks directly once added to the concrete mix. Instead, they contribute self-healing properties by controlling crack growth and maintaining crack widths within ranges that can be healed through the previously discussed healing mechanisms (Snoeck et al., 2014; Tian et al., 2024). Fibers such as polyvinyl alcohol (PVA), polypropylene, and steel fibers help to bridge newly developing cracks and distribute various stresses more evenly throughout the entire concrete matrix. In other words, rather than allowing a few large cracks to form, the fiber reinforcement allows for the development of many microcracks, creating the necessary conditions for natural healing processes. As a result, these fibers are often considered enabling materials that support self-healing rather than healing agents themselves.

One important advantage of fiber reinforcement is the ability to improve durability before any significant damage occurs to the concrete. By limiting the potential width of cracks and reducing crack propagation, fibers increase toughness, fatigue resistance, and resistance to shrinkage-related damage (Coffetti et al., 2022; Tian et al., 2024). Because many fiber systems can be incorporated into conventional concrete production methods with relatively minor modifications, they offer a practical and scalable approach to enhancing long-term durability.

Despite these benefits, fibers' effectiveness depends entirely on the presence of other healing mechanisms capable of sealing cracks on their own, as they themselves do not actively generate healing products. If crack widths become too large, the benefits of the fiber reinforcement can no longer support effective self-healing. The self-healing performance is also influenced strongly by several factors such as fiber type, dosage, aspect ratio, orientation, and distribution throughout the concrete matrix (Tian et al., 2024). Poor dispersion can reduce crack-bridging effectiveness, while excessive fiber content may negatively affect workability and overall concrete quality.

Researchers are addressing these limitations by optimizing fiber geometry, surface properties, and distribution to maximize crack control while minimizing impacts on constructability and cost. They are also actively exploring hybrid systems that combine fibers with supplementary cementitious materials, superabsorbent polymers, encapsulated healing agents, or bacterial healing technologies to create more comprehensive self-healing systems (Tian et al., 2024; Snoeck et al., 2014). Because of this, fibers are viewed as one of the central components of advanced self-healing concrete, providing the crack-control framework necessary for other healing mechanisms to operate effectively.

4.2.4 Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) help to enhance self-healing through ongoing pozzolanic and hydration reactions that persist long after the materials are initially added. Unlike unhydrated cement particles, which rely on the remaining clinker grains that are already present within the concrete, SCMs contribute new reaction products that help to fill cracks and strengthen the cement over time (Tian et al., 2024). Some of the most commonly used SCMs include fly ash, ground granulated blast furnace slag, silica fume, and metakaolin. These materials will react with calcium hydroxide produced during cement hydration and help to generate additional calcium silicate hydrate (C-S-H), the primary binding phase that improves concrete strength. As these reactions continue, cracks and pores slowly become filled with the newly formed cementitious products, improving both the durability and healing performance of the cement matrix.

SCMs are especially promising for their ability to combine self-healing functionality with sustainability benefits. Many SCMs are created from industrial by-products that would be discarded. This allows the SCMs to partially replace Portland cement while reducing the amount of embodied carbon (Coffetti et al., 2022; Dunant et al., 2024). This matters because Portland cement's clinker production is responsible for most of concrete's carbon footprint, so replacing part of it with an industrial by-product directly cuts emissions rather than simply offsetting them elsewhere (Andrew, 2018). At the same time, the additional hydration products generated through pozzolanic reactions help to refine pore structure, decrease permeability, and greatly improve resistance to various types of chemical attacks. SCMs are viewed by many as one of the most practical approaches for improving both the environmental and long-term performance of concrete infrastructure.

However, the effectiveness of the SCM-assisted healing process depends heavily on the specific type of SCM used, curing conditions, moisture availability, and reaction kinetics. Most SCMs react significantly more slowly than ordinary Portland cement, which contributes to delays in healing and strength development during the early stages of a structure's life (Ebead et al., 2022; Tian et al., 2024). While long-term performance improvements are frequently significant, these slower reaction rates may limit effectiveness when rapid crack repair is required.

It may be possible to maximize healing efficiency while maintaining structural performance by optimizing the selection of SCMs, particle characteristics, and replacement percentages. Researchers are investigating combinations of multiple different SCMs to take advantage of complementary reaction pathways and improve long-term durability (Coffetti et al., 2022; Tian et al., 2024). Because SCMs support self-healing, sustainability, and mechanical performance all at the same time, they have become a foundational component of many modern concrete design strategies. Rather than being simply a standalone healing technology, SCMs are increasingly used alongside other self-healing approaches to create stronger and more environmentally sustainable infrastructure systems.

4.2.5 Superabsorbent Polymers

Superabsorbent polymers (SAPs) contribute to self-healing through moisture management rather than directly helping with crack repair. These materials are made up of various cross-linked polymer particles capable of absorbing and storing large quantities of water compared to their own mass (Snoeck et al., 2014; Tian et al., 2024). When incorporated into concrete, SAPs act as an internal water reservoir that slowly releases moisture as the surrounding cement matrix dries up (Snoeck et al., 2014). The stored water from the SAPs helps to support continued hydration of cement particles and other healing reactions long after the conventional curing has ended. In addition, SAPs become larger when exposed to water, allowing them to block cracks within the concrete and reduce the transportation of fluids through damaged regions. Because water availability is a key limiting factor for self-healing, SAPs provide a unique method of supporting healing processes within the concrete matrix.

By maintaining moisture within the concrete, SAPs help to reduce autogenous shrinkage, which significantly limits early-age cracking and promotes continued hydration that contributes to not only strength development but also crack repair (Coffetti et al., 2022; Tian et al., 2024). In short, SAPs can improve internal curing conditions throughout the lifespan of a structure. This is particularly valuable in environments that have difficult or inconsistent external curing. Improved durability and reduced cracking extend service life, lower maintenance requirements, and decrease the environmental impacts associated with repair and replacement activities. SAPs support mechanisms that already occur naturally within concrete, making them quite straightforward to incorporate into existing construction production methods.

When it comes to concrete production, though, SAPs present several challenges. Their performance depends on particle size, absorption capacity, dosage, and distribution throughout the concrete. Too much SAP content creates additional voids once absorbed water is released, which increases porosity and reduces compressive strength (Tian et al., 2024). Snoeck et al. (2014) found that a dosage of around 1% by mass of cement gave the best crack-sealing results in their mortar mixtures, illustrating how narrow the useful range can be before the added voids start to outweigh the healing benefit. Mixtures that are improperly designed may therefore experience tradeoffs between healing performance and mechanical properties. In addition, SAPs do not directly generate healing products, meaning their effectiveness ultimately depends on the presence of hydration reactions or other healing mechanisms that can take advantage of the stored moisture that the SAPs provide.

Similar to other additives, optimizing SAP formulations is a work in progress. As optimization is achieved, healing effectiveness will increase while adverse effects on structural performance will decrease. Researchers are investigating improved polymer chemistries, particle geometries, and absorption characteristics. This would help to provide more controlled water release and would improve compatibility with cementitious materials (Snoeck et al., 2014; Tian et al., 2024). As understanding of internal curing mechanisms continues to improve, SAPs remain among the most promising approaches for improving self-healing through moisture management and long-term durability improvement.

4.2.6 Encapsulated Healing Agents

Encapsulation is one of the most engineered approaches to self-healing concrete. Rather than just relying on naturally occurring hydration, mineral precipitation, or moisture retention processes, encapsulated systems seek to store healing agents inside microcapsules, nanocapsules, hollow fibers, and vascular networks embedded within the concrete matrix (Tian et al., 2024; Zhang et al., 2024). When a crack spreads through the material, it affects the capsule that activates the delivery system, releasing the healing agent specifically into the damaged region. The released material then undergoes various chemical, mineral, or biological reactions that seal the crack, restoring the concrete's original functionality. Because the healing occurs only when damage is present, encapsulation provides an efficient, targeted, autonomous method for the repair of cracks (Zhang et al., 2024).

Encapsulated healing systems have a unique ability to actively repair damage without requiring any type of external intervention. Unlike the traditional passive self-healing mechanisms that depend on favorable environmental conditions, encapsulated agents can be delivered exactly where and when they are needed. This more targeted repair can significantly reduce crack growth, limit the ingress of water and aggressive chemicals, thereby extending the service life of infrastructure (Coffetti et al., 2022; Tian et al., 2024). From the perspective of sustainability, autonomous crack repair helps to reduce maintenance demands, lower material consumption associated with repair activities, and decrease the environmental burden of reconstruction and replacement.

Encapsulated healing systems are sensitive, though: capsules must be very carefully designed in order to survive the mixing and placement processes while also remaining fragile enough to rupture when the necessary cracking occurs (Tian et al., 2024). If capsules break prematurely, healing agents will be lost before damage develops. On the other hand, capsules that are too strong often fail to release their contents when needed. Cost and manufacturing complexity are two separate but related concerns here. Producing the capsules and distributing them evenly through the mix adds processing steps that make the concrete more complex to manufacture than a conventional mixture, and that added complexity, together with the price of the healing agents themselves, is what ultimately drives the cost up (Zhang et al., 2024). In addition, most encapsulated systems possess a finite healing capacity, meaning that once a capsule has ruptured and released its contents, that location typically cannot heal again unless additional healing reservoirs are present.

As the design of encapsulated healing systems continues to be refined, the focus is on improving capsule durability, healing efficiency, and scalability for real-world applications. Researchers are actively investigating the polymeric, ceramic, glass, and hybrid capsule systems designed to improve release behavior and compatibility with the surrounding cement matrix (Tian et al., 2024; Zhang et al., 2024). Other efforts include the development of methods to create vascular networks capable of delivering healing agents multiple times, potentially overcoming the single-use limitation associated with one-time-use capsules. As manufacturing techniques continue to improve and costs decrease, encapsulation remains one of the most promising engineered self-healing technologies because of its ability to provide autonomous and targeted crack repair while maintaining compatibility with a wide variety of healing agents and concrete systems (Coffetti et al., 2022; Tian et al., 2024).

4.2.7 Bacterial Spores and Nutrients

Bacteria-based self-healing systems are especially unique because they utilize microscopic organisms to repair damage within the concrete matrix. Unlike the previously discussed healing approaches, bacteria-based systems rely on dormant bacterial spores in the concrete matrix until cracking allows water to enter (Tian et al., 2024). Once activated by the water, the bacteria metabolize supplied nutrients and initiate different biochemical reactions that produce calcium carbonate ($CaCO_3$) (Amran et al., 2022). Jonkers et al. (2010) were among the first to embed bacterial spores together with a nutrient source directly in the mix and demonstrate that, once cracking let water in, the bacteria precipitated calcium carbonate and stayed viable for months. These mineral deposits slowly accumulate within the cracks, helping fill voids and reduce permeability. Bacterial precipitation has since been shown to seal cracks slightly wider than autogenous healing can close on its own, on the order of a few tenths of a millimeter (Amran et al., 2022; Jonkers et al., 2010). Although the resulting healing product is the same calcium carbonate discussed in the previously mentioned mineralization-based systems, bacterial healing differs because the mineral formation is actively controlled by biological processes rather than occurring only through environmental carbonation reactions.

Because of this property, bacterial self-healing can generate healing products autonomously over extended periods of time. As long as the viable spores and nutrients remain available, bacterial systems are able to respond to the newly formed cracks without requiring any type of external repair interventions. The resulting calcium carbonate deposits help to significantly reduce water infiltration, chloride penetration, and other forms of environmental degradation that contribute to concrete deterioration (Coffetti et al., 2022; Tian et al., 2024).

Despite bacterial healing's strong promise, maintaining long-term bacterial viability within concrete is exceedingly difficult, as the material presents an extremely alkaline and mechanically demanding environment (Jonkers et al., 2010; Tian et al., 2024). Nutrient availability also naturally declines over time, limiting the ability of bacteria to remain active throughout the lifespan of the structure. Healing rates are often slower than those achieved by some engineered repair systems, and effectiveness generally decreases as crack widths increase.

Current research focuses on improved survival of bacteria, improved nutrient delivery, and improved healing efficiency. Researchers have developed promising encapsulation techniques that protect bacterial spores during mixing and shield them until activation is required (Amran et al., 2022; Tian et al., 2024). Advances in bacterial strain selection, carrier materials, and nutrient formulations continue to improve performance and reliability. Some researchers are also exploring the possibility of combining bacterial healing with fibers, supplementary cementitious materials, and encapsulated delivery systems to create a more robust self-healing concrete technology.

Table 3. Comparison of self-healing mechanisms across key dimensions

Mechanism	Healing action	Crack width / capacity	Relative cost	Readiness
Unhydrated cement (autogenous)	Continued hydration fills cracks with C-S-H	Small cracks, ≤100 µm (Van Tittelboom & De Belie, 2013)	Negligible	Inherent in all concrete
Calcium carbonate / mineral	Mineral precipitation seals voids	Small to moderate cracks	Low to moderate	Emerging
Fibers (enabling)	Keep cracks narrow enough for other mechanisms to heal	Controls width; no healing on its own	Low to moderate	Established as reinforcement
Supplementary cementitious materials	Ongoing pozzolanic reactions; lower clinker content	Fills cracks; cuts embodied carbon	Low (by-products)	Widely used
Superabsorbent polymers	Store and release water; swell to block cracks	Internal curing; ~1 wt% optimal (Snoeck et al., 2014)	Moderate	Emerging
Encapsulated agents	Capsules release healing agent into the crack	Targeted, usually single use	High	Research / pilot
Bacterial	Bacteria precipitate $CaCO_3$ when water enters	A few tenths of a mm (Jonkers et al., 2010)	High	Research / demonstration

5. CHALLENGES TO WIDESPREAD ADOPTION OF SMART, SUSTAINABLE CONCRETE

Although there is ample evidence to suggest that smart concrete offers significant benefits in durability, structural monitoring, and reduced maintenance requirements, it has yet to experience widespread adoption in the industry. Barriers to adoption arise from several related challenges, including cost, manufacturability, technological maturity, regulatory uncertainty, and system integration requirements. Each barrier varies in terms of significance depending on the sensing or self-healing technology used for production, meaning each barrier must be evaluated in a comparative context.

5.1 Cost Barriers and Economic Uncertainty

A primary obstacle to widespread adoption of smart concrete is economic cost. Carbon-based nanomaterials such as carbon nanotubes (CNTs), graphene oxide (GO), and carbon fibers provide excellent sensing and mechanical performance, but because their production requires energy-intensive methods, they are not widely used across various applications. As a result, their use is currently concentrated in specific high-performance applications, including strategic infrastructure projects and research demonstrations, rather than more general and routine construction. Steel fibers provide a much more economically efficient alternative and can often be sourced from recycled materials, reducing not only material cost but also embodied carbon. Nevertheless, steel fiber-reinforced smart concrete still increases the amount of upfront economic capital needed relative to conventional concrete due to requirements of additional processing and quality control.

The economic feasibility of the various self-healing technologies covered above also varies considerably. Intrinsic healing mechanisms, like continued hydration of unreacted cement particles or secondary reactions that use supplementary cementitious materials (SCMs), often are achieved with little or no increase in economic material cost. In contrast, the bacteria-based systems and encapsulated healing agents, while being highly effective, require significant upfront capital investment, including specialized production methods, protective carriers, and additional quality assurance. One way to lower cost without giving up performance is to combine fillers rather than rely on a single expensive one. Lee et al. (2017), for instance, showed that a hybrid of 0.1% carbon fibers and 0.5% carbon nanotubes matched the sensing performance of a 1.0% nanotube mix at roughly half the conductive-filler content. Although many smart concrete technologies have been proven in laboratory settings to reduce lifecycle costs through lower maintenance demands and longer service life, there is limited evidence proving that these technologies would save money at a larger commercial scale. The economic uncertainty surrounding these self-healing technologies limits industry confidence and therefore industry adoption.

5.2 Manufacturing and Dispersion Challenges

Challenges with manufacturing represent another crucial barrier to widespread commercial implementation. Sensing additives like CNTs, graphene derivatives, and carbon fibers naturally tend to agglomerate within cement matrices. This poor dispersion negatively affects the conductive networks, thereby reducing both sensing reliability and mechanical performance. Achieving uniform distribution can require expensive specialized techniques such as ultrasonication, chemical functionalization, or polymer-based dispersants. While the incorporation of steel fibers is generally easier than the incorporation of nanoscale materials, they too can still cluster during mixing, creating both local weaknesses and reducing sensing consistency.

On the other hand, autogenous healing mechanisms and SCM-based healing strategies can often be implemented using the same conventional concrete production methods, limiting implementation costs. Such advanced healing technologies present their own challenges, though. Bacteria-based systems require encapsulation or protective carrier materials to maintain sufficient microbial viability during mixing, while encapsulated healing agents must be designed so as to prevent premature rupture and ensure proper release when cracking does occur.

These challenges are indicative of an important trend within the development of smart concrete: increased sensing or healing functionality often results in much greater manufacturing complexity. This means that some of the most advanced smart concrete systems are the most difficult to produce consistently at a larger industrial scale.

5.3 Lack of Standardization and Testing Frameworks

Existing concrete methodological standards mainly evaluate properties like compressive strength, durability, and permeability. However, these metrics fail to fully capture performance characteristics unique to smart concrete, like piezoresistive behavior, sensing accuracy, crack-healing efficiency, and long-term monitoring reliability. This lack of standardized testing methods is yet another reason smart concrete has yet to be widely adopted.

Engineers currently do not possess thoroughly reviewed and widely accepted design methodologies, while regulatory agencies have difficulty transitioning to smart concrete within the existing approval and building-code frameworks. Without standardized procedures for evaluating performance and durability, obtaining the necessary certification for safety-critical infrastructure applications will be very difficult.

This challenge affects each technology to varying levels. Steel fiber-reinforced systems leverage parts of existing fiber-reinforced concrete standards, which allows for a more straightforward regulatory pathway. By contrast, CNT- and graphene-based concretes do not currently have internationally recognized guidelines that help govern material quality, dispersion requirements, dosage limits, and worker safety during handling. In the same way, bacterial self-healing systems introduce new regulatory concerns related specifically to microbial viability, biosafety, and environmental exposure. Until certification frameworks are established for these technologies, regulatory uncertainty is likely to remain a significant barrier to widespread implementation.

5.4 Limitations Surrounding Data Management and Integration

Unlike traditional concrete, self-sensing concrete functions as part of a larger monitoring ecosystem that includes the acquisition of data, as well as signal processing, interpretation, storage, and maintenance infrastructure. While many studies demonstrate impressive sensing capabilities under laboratory-controlled environments, widespread deployment would require robust systems capable of operating reliably in complex and widely different field environments.

Interpreting sensing data can be quite challenging for nanomaterial-based systems. CNT- and graphene-reinforced concretes often generate very sensitive electrical responses that require highly specialized electronics, calibration procedures, and analytical techniques to distinguish meaningful signal from environmental noise. Steel fiber-based systems generally provide a much simpler sensing pathway, meaning they may be easier to implement in practical applications.

The supporting infrastructure required for long-term monitoring remains cost-ineffective and lacks the necessary standardization, making these monitoring systems difficult to adopt throughout the construction industry. Consequently, the availability of reliable and affordable data management systems is just as important as the smart concrete materials themselves. Addressing these integration challenges will be essential for translating these promising laboratory technologies into practical solutions that can be used for large-scale industrial purposes.

5.5 Summary of Adoption Barriers

Although smart concrete technologies have demonstrated substantial potential for improving structural durability, monitoring capability, and sustainability in laboratory settings, several barriers remain that will limit their adoption. These limits include high material costs, manufacturing challenges, regulatory uncertainty, and integration requirements. Furthermore, these barriers tend to scale with sophistication: the same nanoscale fillers and engineered healing systems that deliver the strongest sensing and repair performance are also the most expensive, the hardest to disperse and manufacture consistently, the least covered by existing standards, and the most demanding to monitor in the field. Simpler options, such as steel fibers, supplementary cementitious materials, and autogenous healing, clear these hurdles far more easily but offer more modest performance. This trade-off between capability and readiness, more than any single barrier on its own, is what currently keeps the most advanced forms of smart concrete confined to research and high-value projects rather than routine construction.

6. SUSTAINABILITY CHALLENGES IN SMART, SUSTAINABLE CONCRETE

While smart concrete technologies have the potential to improve sustainability through their demonstrated ability to improve durability, reduce maintenance requirements, and provide a longer service life, the materials and systems that actually enable these capabilities introduce new environmental challenges. There are concerns related to material sourcing, manufacturing emissions, ecological safety, and end-of-life management that must be considered when evaluating the overall impact that smart concrete will have on sustainability efforts. In many cases, the environmental costs that result from the advanced sensing or self-healing technologies end up partially offsetting the sustainability benefits they intend to provide.

6.1 Environmental Cost of Advanced Additives

Many advanced additives used in smart concrete, like carbon nanotubes (CNTs), graphene-based materials (GBMs), and carbon fibers, require significant energy-intensive manufacturing processes in their creation. Although these materials are proven to significantly improve sensing performance, durability, and mechanical properties by adding relatively small amounts to the mix, their production often involves both high-temperature chemical and physical treatments that are associated with substantial energy consumption and carbon emissions. This means that CNT- and graphene-enhanced concretes end up having higher embodied carbon than the traditional concrete alternative. There is a need for comprehensive lifecycle assessments in order to determine whether the durability benefits outweigh the initial environmental costs of production (Coffetti et al., 2022).

In contrast, steel fibers, which can be produced from recycled materials, tend to have a lower environmental impact while still contributing to improved durability and resource efficiency. Supplementary cementitious materials (SCMs) provide even more of a sustainability advantage by helping to replace Portland cement, thereby limiting the carbon emissions of concrete production (Coffetti et al., 2022; Dunant et al., 2024). Industrial by-products like fly ash and blast furnace slag help to reduce embodied carbon while still supporting self-healing mechanisms and improving durability. Because of this, the sustainability of smart concrete must not only be evaluated on the performance gains themselves, but also on the environmental impact of creating the materials used in the smart concrete.

6.2 Safety and Ecological Risks of Nanomaterials and Biological Systems

The use of nanomaterials introduces many environmental and occupational safety hazards that must be considered. CNTs and graphene-based particles pose potential risks during manufacturing, handling, and disposal because of their small size and potential respiratory hazards. Additionally, the long-term ecological impacts of nanoparticle release through weathering, demolition, or recycling processes are not sufficiently understood.

Biological self-healing systems present a separate and unique set of challenges. Although the bacteria-based healing mechanisms rely only on natural organisms, uncertainties about long-term microbial viability, nutrient sourcing, and environmental containment persist (Jonkers et al., 2010). Lastly, potential consequences of unintended microbial release into surrounding ecosystems have not been fully evaluated, creating additional uncertainty regarding large-scale deployment. By comparison, intrinsic healing mechanisms (unhydrated cement particles or SCM-driven reactions) do not introduce any new synthetic nanomaterials or living organisms into the production system. This means that these approaches present fewer ecological and safety concerns than CNTs, graphene-based particles, and bacteria-based healing mechanisms.

6.3 End-of-Life Barriers and Circularity Limitations

End-of-life management of smart concrete is another important sustainability challenge for these new technologies. Conventional concrete recycling involves crushing of demolished structures and recovering the aggregates for reuse. If additives are incorporated, however, there can be complications in these recycling pathways.

Encapsulated healing agents, synthetic polymers, and nanomaterials are permanently embedded within the hardened concrete, meaning that removing these materials from the mix will be very difficult. As a result, many advanced smart concrete systems are not built with material recovery strategies in mind. Carbon nanotubes and graphene particles, for example, cannot be extracted and reused once placed into concrete. On the other hand, steel fibers, self-healing systems based on SCMs, and intrinsic hydration mechanisms do not significantly alter existing recycling practices. Emerging processes that recover and reactivate cement paste from demolished concrete may further improve the circularity of these simpler systems

(Dunant et al., 2024). Because of this, the simpler smart concrete technologies are more in line with recycling pathways than highly engineered alternatives.

6.4 Sustainability Trade-Offs and Lifecycle Uncertainty

The sustainability of smart concrete is largely based on whether improvements to durability and service life of the concrete outweigh the various environmental costs that result from material production and implementation. There is a lack of real-world evidence exploring these tradeoffs, creating uncertainty when evaluating claims about lifecycle sustainability. Many projected benefits are largely theoretical instead of based on decades of operational performance. As a result, it is possible that sustainability assessments overestimate benefits because the long-term behavior could substantially deviate from laboratory expectations.

7. CONCLUSION

Concrete is the most widely used construction material in the world and is responsible for a large amount of worldwide carbon emissions. Consequently, improving the sustainability, durability, and efficiency of concrete infrastructure is an urgent research priority. Smart concrete technologies aim to address these challenges by incorporating materials that help with sensing capabilities, self-healing mechanisms, and advanced materials. The overall effectiveness of smart concrete is heavily dependent on the materials and systems employed. Carbon-based nanomaterials offer exceptional sensing performance but have many obstacles with regard to manufacturing complexity and sustainability. Steel fibers provide a practical and scalable sensing solution. Self-healing approaches range from naturally occurring autogenous mechanisms to more sophisticated bacterial and encapsulated systems. Each technology presents its own set of unique advantages and disadvantages in terms of performance, economic feasibility, manufacturability, and environmental impact.

Despite substantial progress in recent years, several barriers remain that limit widespread adoption: high costs, manufacturing challenges, regulatory uncertainty, monitoring infrastructure requirements, and sustainability. In order to overcome these limitations, future research should focus not just on improving sensing and healing performance but also on reducing their associated environmental impacts. Additionally, there is a strong need for standardized testing frameworks and validated long-term field performance. Addressing these challenges will be essential for translating promising laboratory advances into practical, sustainable infrastructure solutions capable of meeting the ever-growing demand for environmentally friendly construction.

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