Smart Concrete, a new Solution for Increasing the Stability and Lifespan of Concrete Structures

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Abstract

Concrete, the most widely used building material globally, has always required advancements to address challenges such as degradation, erosion, and the need for constant repairs. This article explores the concept of smart concrete (SM), a new generation of concrete materials that is fundamentally transforming the construction industry with advanced capabilities like self-sensing, self-healing, self-heating, and electrical conductivity. This research introduces the main types of SM and their operating mechanisms, while also discussing the diverse applications of this technology in various infrastructures and structures. Furthermore, the advantages and disadvantages of using SM are analyzed, and the challenges and future outlook for this innovative technology are outlined, with the aim of increasing durability, reducing maintenance costs, and improving structural safety. The results indicate that, despite some initial obstacles, smart concrete has high potential to change our approach to the design, construction, and management of structures, marking a significant step toward sustainable and intelligent construction.

Keywords: self-Healing, smart concrete, structural health monitoring, sustainable construction

1. Introduction

Concrete, the cornerstone of modern civilization, has been recognized as the most widely used building material for over a century due to its durability, strength, and easy accessibility [1]. From soaring skyscrapers to extensive networks of roads and bridges, concrete has played a pivotal role in the development of urban and industrial infrastructure. However, traditional concrete (TC), like any other material, has its limitations. These limitations include susceptibility to cracking caused by environmental factors, applied loads, or internal chemical reactions, which gradually leads to reduced strength, degradation, and ultimately the need for costly and continuous repairs [2]. Moreover, the production process of cement, the primary component of concrete, contributes significantly to greenhouse gas emissions, raising environmental concerns. For this reason, the construction industry is seeking environmentally friendly and sustainable solutions [3].

In response to these challenges and inspired by smart systems in nature, the concept of SM has been introduced as an innovative solution in the field of civil engineering and materials science. SM is not merely a building material with improved mechanical properties; rather, it is a dynamic and responsive system that possesses "smart" capabilities such as self-sensing, self-healing, and electrical conductivity [3-5]. These features allow the concrete to react to environmental changes and internal damage, monitor information, and even repair itself, which significantly contributes to increased structural service life, reduced maintenance costs, and enhanced safety [6-8].

The purpose of this article is to provide a comprehensive review of SM, introduce its various types based on their performance, and explain the key mechanisms that make these smart features possible. Relying on recent research, this study examines the practical and potential applications of SM, including Structural Health Monitoring (SHM) and autonomous crack repair [2, 3, 6]. Additionally, while exploring the ecological and economic benefits of this technology, the challenges ahead in its development and commercialization are discussed. Finally, by providing a future outlook for SM, the potential of this novel material to shape the next generation of resilient, sustainable, and safe structures will be emphasized. This approach represents a significant step toward sustainable and technologically advanced construction [3, 5].

2. What is SM?

SM, beyond being a simple building material, is defined as an advanced cementitious composite that exhibits novel functional properties by being able to respond to environmental stimuli and operational conditions [1, 5]. Unlike TC, which primarily focuses on static mechanical properties like compressive and tensile strength and requires external monitoring and repairs, SM can automatically sense its internal changes, react to them, and even repair itself [2, 4]. These "smart" features are achieved by adding special materials to the concrete mix or by embedding sensors and actuators within it.

The main distinction of SM lies in its "smart" capabilities, which include:

Self-Sensing: The ability to detect and measure changes such as strain, stress, temperature, humidity, and the presence of cracks without the need for external instruments [6, 7]. This feature is achieved by embedding conductive nanomaterials (such as carbon nanotubes (CNTs) or graphene) or optical fiber sensors, which report changes in the concrete's electrical or optical properties [2, 6, 7, 9]. Research shows that this capability enables real-time Structural Health Monitoring (SHM) [3, 6].

Self-Healing: The most important and impressive feature of SM is its ability to autonomously heal small cracks [3, 4]. This process can occur through a chemical reaction of added materials (e.g., capsules containing healing polymers) or microbial activity (using bacteria that produce calcium carbonate), which fills the cracks and restores the concrete's structural integrity [3, 8].

Adaptive/Responsive: SM can respond to environmental stimuli such as temperature or humidity. For example, some types are capable of self-heating at low temperatures to prevent freezing [4].

Multi-functional Performance: In addition to mechanical properties, SM can exhibit other features such as the ability to absorb electromagnetic waves, reduce noise, or even act as an anode in cathodic protection [4].

The development of SM is a major step toward creating more resilient, durable, and longer-lasting structures that minimize the need for human intervention for monitoring and repairs [6, 7]. This technology not only helps improve structural safety but also leads to a significant reduction in project lifecycle costs and environmental impacts [3].

3. Types and Properties of SM

SM is a general term that encompasses a wide range of advanced concretes with diverse capabilities. This variety stems from different application goals and the unique operational mechanisms each type of SM employs to achieve its specific "smartness." The following sections introduce the most important types of SM and examine their features and operational mechanisms.

3.1. Self-Healing Concrete

This type of concrete has the ability to automatically repair fine and medium cracks that naturally occur due to various factors like shrinkage, loading, or thermal changes [3]. The primary goal of this technology is to increase the durability and service life of the structure by preventing the penetration of destructive agents such as water and chloride ions into the concrete through cracks. The main mechanisms for self-healing are:

Bacteria-Based Healing: This innovative approach involves adding spores of specific bacteria (typically calcium carbonate-producing bacteria) to the concrete mix [8]. When cracks form and water penetrates the concrete, the bacteria become active and produce calcium carbonate, which gradually fills the cracks and restores the concrete's structure. This method is considered an environmentally friendly solution for crack repair [3, 8].

Encapsulated Agents: In this method, microcapsules containing healing agents are dispersed in the concrete mix. When a crack forms, the capsules break, releasing the healing agents to fill the crack [4].

3.2. Self-Sensing Concrete

Self-sensing concrete has the ability to monitor and detect changes in its own condition without the need for external sensors [6, 7, 9]. This feature is achieved through changes in the concrete's electrical or magnetic properties in response to strain, stress, temperature, or humidity [2, 6].

Conductive Nanomaterials: The addition of conductive nanomaterials such as carbon nanotubes (CNTs) or graphene nanoparticles to the concrete mix increases the concrete's electrical conductivity [2, 6, 9]. When a crack forms or strain changes, the conductive network is disrupted, and the concrete's electrical resistance changes. By measuring these changes, the presence and size of cracks or the amount of strain can be detected [6]. Research indicates that this method is a promising tool for real-time Structural Health Monitoring [2, 6, 7].

Optical Fibers: Optical fibers are embedded within the concrete. Any change in strain or temperature in the concrete causes a change in the optical properties of the fiber, which can be measured to monitor the concrete's condition.

3.3. Self-Heating Concrete

This concrete is capable of increasing its own temperature using internal mechanisms. Its main application is to prevent the freezing of concrete surfaces in cold climates, especially on roads, bridges, and airport runways.

Carbon Fibers or Conductive Particles: The addition of carbon fibers, steel fibers, or other conductive particles to the concrete mix turns the concrete into a semiconductor material. By applying an electrical current to this concrete, its electrical resistance generates heat (Joule effect), thereby warming the concrete surface [4].

3.4. Electrically Conductive Concrete (ECC)

This type of concrete is specifically designed to achieve high electrical conductivity [4]. This feature allows it to have applications beyond mechanical load-bearing [4, 9].

Conductive Admixtures: By adding conductive materials like carbon fibers, graphite powder, or metallic particles, the concrete becomes capable of conducting an electrical current.

Applications: In addition to preventing freezing, ECC can be used for electromagnetic shielding, as a sensor (by monitoring changes in electrical resistance), and as an anode in cathodic protection [4].

The self-healing process of smart concrete is illustrated in the flowchart presented in Fig.1. This comprehensive diagram visualizes the vital cycle of a self-healing event, from the initial moment of crack formation to the restoration of structural integrity

The flowchart begins with the first step (Crack formation in concrete). This point is the moment of structural damage, which can be caused by various factors such as excessive loading, stresses from temperature changes, shrinkage from drying, or internal chemical reactions.

In the second step (Water penetration into the crack), as a vital factor for activating the self-healing mechanisms, water from the surrounding environment penetrates into the created cracks. This water penetration is especially important for self-healing methods based on bacterial activity, as moisture provides the necessary conditions for their life and activity.

The third step (Have the bacteria or capsules been activated?) is a key decision point. At this stage, depending on the type of self-healing agent embedded in the concrete (dormant bacteria or capsules containing healing agents), a different reaction occurs. If the conditions for bacterial activation (presence of water and nutrient) are met or if the capsules have broken due to crack expansion (the "Yes" answer to the question), the process is directed to the fourth step. Otherwise (the "No" answer), the process returns to the second step, which indicates waiting for the activation conditions to be met.

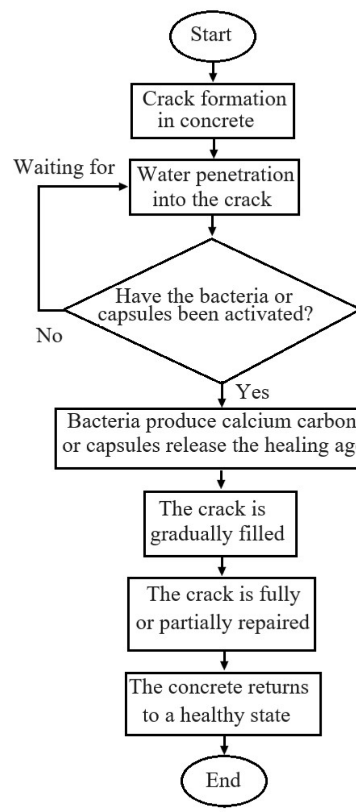

Fig.1. Flowchart of the Self-Healing Process in SM

The fourth step (Bacteria produce calcium carbonate or capsules release the healing agent) is the stage where the self-healing agent becomes active. In biological methods, activated bacteria consume their nutrients and begin to produce calcium carbonate deposits. In capsule-based methods, the healing agent (which can include polymers, resins, or special cement materials) is released from the broken capsules into the crack.

In the fifth step (The crack is gradually filled), the produced or released healing agents begin to fill the empty space inside the crack. This process may take a different amount of time depending on the type of healing agent and the size of the crack. The goal of this step is to reduce the crack width and restore structural integrity in the damaged area.

The sixth step (The crack is fully or partially repaired) indicates the successfulness of the self-healing process. At this stage, the crack space is filled with healing agents to an acceptable extent, and a connection is established in the damaged area. The amount of repair may differ depending on the type and size of the crack, but the main goal is to improve the mechanical properties and reduce the permeability of the concrete in the damaged area.

Finally, the seventh step (The concrete returns to a healthy state) represents the return of the concrete structure to a stable and safe condition. After the completion of the repair process, SM still maintains its ability to monitor its condition, and in case of any future potential damage, the self-healing cycle can begin again.

Fig.2 is a detailed technical illustration of a cross-section of SM [11]. The textured concrete matrix is shown in light gray. Embedded within the concrete are several small, metallic or dark-colored sensors with thin wires. Cracks of varying widths are prominently visible in the figure. Inside these cracks, a lighter-colored polymer gel (a crystalline substance) is shown, partially filling the gaps and demonstrating the self-healing process. A fine, dark, and fuzzy network of conductive nanomaterials and thin, transparent optical fibers is woven throughout the concrete matrix and connected to the embedded sensors.

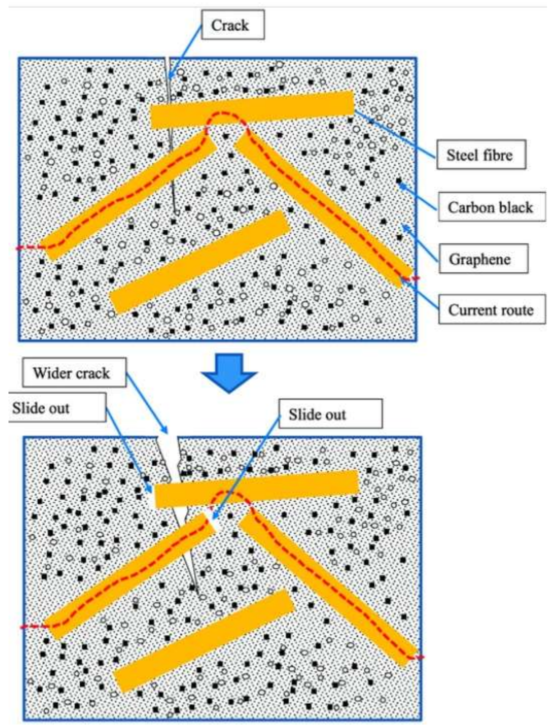

Fig.2. Schematic representation of a SM cross-section.

Fig.3 presents a real microscopic image of the self-healing process in SM [12]. This image, obtained from a SM sample containing conductive nanomaterials, not only confirms the presence of a crack but also clearly demonstrates the healing activity. In this view, one can observe how the conductive nanomaterials, embedded within the concrete matrix, are strategically positioned around and inside the cracks. This intelligent network not only provides the concrete with its self-sensing capability (by changing its electrical resistance) but also acts as a physical substrate for initiating, guiding, and completing the healing process.

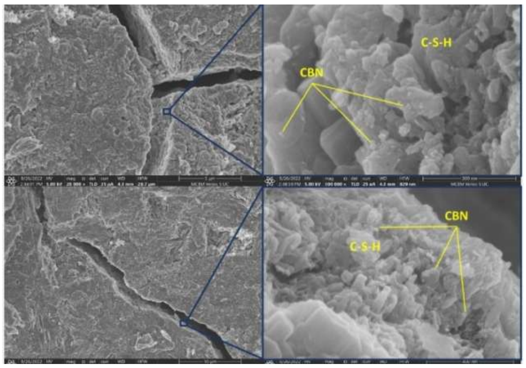

Fig.3. Microscopic Evidence of the Self-Healing Process

4. Advantages and Disadvantages/Challenges of SM

4.1. Advantages of SM

By introducing new capabilities, SM offers significant advantages over TC that can have a profound impact on the construction and infrastructure management industry:

Increased Durability and Service Life: Self-healing and self-sensing capabilities allow the concrete to actively combat minor degradation and prevent the spread of damage [2, 3, 8].

Reduced Maintenance and Repair Costs: By self-healing cracks and continuously monitoring structural health, the need for periodic inspections and costly repairs is minimized [7].

Enhanced Structural Safety: Self-sensing systems can detect structural anomalies and problems in their early stages, before they reach a critical state [3, 6].

Continuous Structural Health Monitoring (SHM): Self-sensing concrete enables real-time and continuous monitoring of critical structural parameters such as strain, temperature, and cracking [2, 6, 7].

Reduced Environmental Impact: Increasing the service life of structures and using materials like bacteria and cement substitutes means a reduction in natural resource consumption and greenhouse gas emissions from cement production [1, 3, 5, 8].

Improved Energy Efficiency: Self-heating concrete can reduce the need for separate heating systems and optimize energy consumption for melting snow and ice [4].

4.2. Disadvantages and Challenges of SM

Despite its many advantages, SM still faces significant challenges that affect its widespread development and adoption:

High Initial Cost: The production of SM typically requires the use of special additives (such as nanoparticles or healing capsules), which significantly increases its initial cost compared to TC [3, 4].

Complexity in Design and Construction: Designing and producing SM requires a high level of specialized knowledge in materials science and nanotechnology [3, 9].

Lack of Industry Awareness and Acceptance: Many professionals and stakeholders in the construction industry are not yet fully familiar with the benefits and potential of SM [3].

Long-Term Durability and Performance: While the goal of SM is to increase durability, the long-term stability and performance of the smart mechanisms themselves (such as bacteria or sensors) in the harsh concrete environment require further research [8].

Table 1 comprehensively summarizes the results of various academic studies and practical work in the field of both traditional and SM. By comparing key features, this table clearly illustrates the advantages and disadvantages of SM in relation to its traditional counterpart.

Table 1. Comparison of TC and SM

Feature	TC	SM
Maintenance	Requires continuous inspection & manual repair	Self-monitoring, reduces need for external intervention
Durability	Vulnerable to cracking, leading to degradation	Enhanced durability with self-healing capabilities
Service Life	Limited; depends on maintenance and environmental factors	Significantly extended due to proactive repair and monitoring
Cost	Lower initial cost	Higher initial cost due to special additives & technologies
Environmental Impact	High carbon footprint from cement production; frequent repairs increase waste	Lower long-term environmental impact from reduced material consumption
Functionality	Primarily mechanical properties (compressive strength)	Multi-functional; includes sensing, healing, and thermal properties

5. The Future of SM

The future of SM is not only exciting but also rapidly evolving, promising fundamental changes in the construction industry. With continuous advancements in materials science, nanotechnology, Artificial Intelligence (AI), and the Internet of Things (IoT), SM is on the verge of entering a new phase of applications and capabilities. In the future, structures will no longer be static masses of material but active, dynamic entities capable of interacting with their environment, monitoring and maintaining their own health, and responding to the changing needs of humanity.

5.1. Technological Trends and Innovations:

Deeper Integration with AI and Machine Learning: Advanced AI algorithms can be used to analyze data collected from SM sensors. These analyses can identify complex patterns, predict minor changes in structural behavior, and even determine the optimal time for repair or preventive maintenance [10].

Internet of Things (IoT) and Connectivity: The future of SM is deeply intertwined with the concept of IoT. Sensors embedded in concrete can connect to extensive networks of connected devices, transmit data wirelessly, and enable real-time, remote monitoring of structures. This will enable smart city management and connected infrastructure.

Advancements in Nanomaterials and Metamaterials: The use of nanoparticles and metamaterials can dramatically change the physical and chemical properties of concrete. These materials can add new capabilities to concrete, such as faster and more efficient self-healing, increased sensor sensitivity, and even electromagnetic stealth or energy absorption capabilities [1, 3].

Energy Harvesting: Research is underway to develop concretes with the ability to harvest energy from the environment (e.g., mechanical vibrations or temperature changes). This capability could reduce the need for external power sources for sensors and smart systems, allowing them to be independently and sustainably powered.

6.2. Future Applications and Outlook:

Self-Managing Infrastructure: Roads, bridges, and tunnels could continuously monitor their own health, repair cracks, and transmit real-time information about traffic and environmental conditions to autonomous vehicles and control centers. This would significantly improve the safety and efficiency of transportation networks.

Fully Smart and Responsive Buildings: Buildings could adjust their temperature, optimize energy consumption, detect the presence of people, and even automatically react to damage [5]. SM in walls, floors, and ceilings would act as the central sensor and actuator network for these buildings.

Construction in Extreme and Space Environments: The self-healing and monitoring capabilities of SM could make it suitable for construction in challenging environments such as polar regions, underwater, and even in space, where human repairs are difficult or impossible.

This transformation will not only increase sustainability and safety but also lead to unprecedented efficiency and flexibility in the built environment.

6. CONCLUSION

In summary, SM represents a technological revolution in civil engineering, evolving from a pioneering research concept into a developing practical solution. This innovative material, by integrating advanced knowledge of materials science, nanotechnology, and computer science, has challenged the limitations of TC in terms of monitoring, repair, and responsiveness, opening up new horizons in the design, construction, and maintenance of infrastructure.

The unique capabilities of SM, including self-healing [8], self-sensing, and its electrical-magnetic properties, not only contribute to an unprecedented increase in the durability and service life of structures but also lead to a reduction in risky human interventions and costly repairs, optimized resource use, and a significant decrease in environmental impacts. The extensive applications of this technology in transportation infrastructure, high-rise buildings, and specialized structures serve as a testament to its immense potential to enhance the safety, efficiency, and resilience of civil engineering systems.

Despite its many advantages, challenges such as high initial cost and the complexity of large-scale production still stand in the way of its widespread adoption. However, given the rapid advancements in the fields of materials science and nanotechnology, it is expected that these challenges will be gradually overcome through continuous research. The use of AI methods, such as Artificial Neural Networks (ANN), to optimize concrete mixes and predict strength also points to innovative pathways for overcoming these obstacles.

SM will not only revolutionize the efficiency and safety of structures but also empower engineers and architects to design and build active, intelligent structures. These structures can then actively adapt to meet the future needs of humanity on a changing planet. This transformation paves the way for more sustainable, safer, and more efficient construction, which in turn will improve the quality of life and the resilience of communities.

REFERENCES

[1] B. Abro et al., "Smart Concrete Strength Measurement Device," in 2022 International Conference on Emerging Technologies in Electronics, Computing and Communication (ICETECC), 2022, doi: 10.1109/ICETECC56662.2022.10069766.

[2] H. Allam, F. Duplan, S. Amziane, and Y. Burtschell, "About the self-sensing behavior of smart concrete and its interaction with the carbon fiber percolation status, sand connectivity status and grain size distribution," Construction and Building Materials, vol. 324, p. 126609, 2022, doi: 10.1016/j.conbuildmat.2022.126609.

[3] A. D'Alessandro, "Smart sustainable concrete materials and structures," in Sustainable Concrete Materials and Structures, Woodhead Publishing, 2024, pp. 601–624.

[4] I. Kamal, "Smart Concrete: The deep revolution to the field of conventional concrete materials," Webinar, May 2021, doi: 10.13140/RG.2.2.24957.49123.

[5] J. Li et al., "Research on performance of smart concrete materials and self-monitoring of cracks in beam members," Materials Today Communications, vol. 35, p. 105775, 2023, doi: 10.1016/j.mtcomm.2023.105775.

[6] N. Makul, "Advanced smart concrete - A review of current progress, benefits and challenges," Journal of Cleaner Production, vol. 274, p. 122899, 2020, doi: 10.1016/j.jclepro.2020.122899.

[7] M. Rama, J. S. Sudarsan, N. Sunmathi, and S. Nithiyanantham, "Behavioral assessment of intrinsically formed smart concrete using steel fibre and carbon black composite," Heliyon, vol. 10, no. 5, p. e26948, 2024, doi: 10.1016/j.heliyon.2024.e26948.

[8] S. Shahzad, A. Toumi, J.-P. Balayssac, and A. Turatsinze, "An Experimental Approach to Assess the Sensitivity of a Smart Concrete," Buildings, vol. 13, no. 8, p. 2034, 2023, doi: 10.3390/buildings13082034.

[9] Q. Tian et al., "Building the future: Smart concrete as a key element in next-generation construction," Construction and Building Materials, vol. 429, p. 136364, 2024, doi: 10.1016/j.conbuildmat.2024.136364.

[10] Y. Yan et al., "“Smart” concrete based on microbially induced carbonate precipitation - A review," Construction and Building Materials, vol. 451, p. 138904, 2024, doi: 10.1016/j.conbuildmat.2024.138904.

[11] S. Wang, A. Singh, and Q. Liu, "Experimental Study on the Piezoresistivity of Concrete Containing Steel Fibers, Carbon Black, and Graphene," Frontiers in Materials, vol. 8, 2021, doi: 10.3389/fmats.2021.652614.

[12] Z. Shi, Y. Lu, H. H. Bui, L. Hua, and D. Shen, "A combined experimental–numerical modelling approach for self-crack monitoring in conductive cementitious materials," Construction and Building Materials, vol. 390, p. 131812, 2023, doi: 10.1016/j.conbuildmat.2023.131812.