J. Civil Eng. Mater.App. 2025 (December); 9(4): 211-220

Journal of Civil Engineering and Materials Application
Journal home page: http://jcema.com

Received: 10 October 2025 • Revised: 15 November 2025 • Accepted: 16 December 2025

Research

doi: 10.22034/jcema.2026.552414.1182

Application of Rotary-Kiln Manufactured Expanded Lightweight Aggregate in Self-Healing Concrete

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ABSTRACT

Cracking is a significant concern for the durability of concrete infrastructure, resulting in a reduced service life and increased maintenance costs. Self-healing concrete (SHC) technologies offer promising approaches to seal cracks and restore the functionality of concrete structures automatically. However, various SHC techniques, such as encapsulated agents, bacteria-driven systems, and innovative materials, face substantial challenges in field application due to their complexity, fragility, or elevated costs. This paper presents a comprehensive review of these challenges while investigating the potential of rotary-kiln-produced lightweight aggregates (LWA), including expanded shale, expanded clay, and expanded slate, as a scalable and multifunctional solution for SHC. The porous nature of these argillaceous expanded materials enhances the transport and retention of water and healing agents, which are vital for maintaining bacterial viability and promoting autogenous healing. In contrast to many advanced SHC systems, expanded LWA are recognized for their durability, cost-effectiveness, and compatibility with traditional construction practices. This research provides an in-depth examination of LWA applications in SHC, emphasizing their technical feasibility, practical integration, and potential applications in modern construction.

Keywords: self-healing concrete; lightweight aggregate; expanded aggregate; crack sealing; autogenous healing

1. INTRODUCTION

1.1. Motivation

Concrete is a widely used construction material around the world due to its versatility, mechanical strength, and relatively low cost. However, despite its extensive applications, concrete is inherently brittle and prone to cracking, reducing its service life and increasing its lifecycle cost and environmental footprint [1]. These cracks can occur due to mechanical loads, environmental factors, thermal shrinkage, or chemical degradation. Cracks compromise the durability of the material by allowing harmful agents such as water, chlorides, and sulfates to penetrate the concrete [2]. Over time, this ingress accelerates the corrosion of steel reinforcement, increases internal stress concentrations, and shortens the service life of the structure [3].

The implications of cracking extend beyond structural issues to encompass economic and environmental concerns. The maintenance, retrofit, strengthening, demolition, and replacement of damaged concrete elements further exacerbate these emissions. Therefore, any method that extends the life of concrete structures while reducing maintenance needs would significantly enhance both economic efficiency and environmental sustainability [4].

1.2. Background

In response to a longstanding challenge in the construction industry, researchers have developed a concept known as Self-Healing Concrete (SHC). This innovative material can autonomously repair cracks without any external human intervention [5]. The idea is partly inspired by biological systems, allowing concrete to mimic the healing abilities of living tissues [6]. The development of SHC gained momentum in the early 2000s, particularly through the use of bacteria (such as Bacillus species) to precipitate calcium carbonate, effectively sealing cracks. Since then, a variety of self-healing strategies have emerged [7].

SHC strategies can be categorized into two main types: autogenous healing, which relies on the inherent properties of cementitious materials (such as continued hydration or carbonation) [5], and autonomous healing, involving external agents or engineered systems incorporated into the concrete [8]. Examples of autonomous approaches include encapsulated healing agents (micro and macro capsules), vascular networks [9], bacteria-based mineral precipitation[10], nanomaterials [11] and crystalline additives [12], polymeric self-healing agents[13], electrochemical deposition [14], shape-memory alloys [15], and internal curing agents like superabsorbent polymers (SAPs) and lightweight aggregates (LWA) [16].

Each SHC technique shows promise under controlled laboratory conditions, typically achieving the ability to seal fractures between 0.2 and 1 mm, restore some mechanical strength, and reduce permeability. However, after two decades of extensive research, SHC has not been widely adopted in the construction industry primarily due to practical and operational challenges rather than scientific limitations. These challenges include the requirement for specific environmental conditions—such as water presence, temperature, or pH levels—that can be difficult to manage in actual structures, the risk of early rupture or uneven distribution of encapsulated healing agents, and concerns about the long-term viability of bacteria-based systems, which often necessitate complicated encapsulation or nutrient delivery methods. Additionally, vascular systems present technological complexities that hinder mass production, while polymeric or nano-based solutions tend to be prohibitively expensive for large infrastructure projects, and electrochemical healing requires precise designs for conductive systems and energy inputs [17].

Standard construction methods, such as high-rate mixing and vibration, can compromise the effectiveness of sensitive healing agents by damaging or dispersing them. Additionally, challenges such as quality control, the lack of standardized testing, and uncertainties about the long-term performance of healing products (like calcium carbonate) deter industry professionals. The significant cost difference between traditional concrete and SHC further contributes to a reluctance among contractors and engineers to adopt these technologies, despite potential long-term savings. Furthermore, the absence of regulatory frameworks or design codes for SHC leaves designers without clear guidelines, resulting in SHC remaining primarily of academic interest rather than practical application in the industry [18].

1.3. Contribution

To make SHC practical, it is essential to develop robust systems that are compatible with existing practices and economically scalable. One promising direction is the use of rotary-kiln-manufactured LWA, including expanded shale, expanded clay, and expanded slate as multifunctional carriers within the concrete matrix [19,20].

These expanded argillaceous materials are engineered aggregates derived from natural shale, clay, or slate, processed at high temperatures, typically 1100-1200°C, in a rotary kiln. During firing, the organic and mineral components within the clay decompose, releasing gases that cause the clay pellets to expand internally and form a porous, honeycomb-like structure. The external surface of the pellet vitrifies, creating a hard ceramic shell. The final product is a lightweight, highly porous, and dimensionally stable aggregate [19,20].

Known for their internal porosity and high surface area, these LWAs can absorb and later release water, facilitating internal curing. They can also store healing agents, such as calcium-based compounds or bacteria [21]. Unlike fragile microcapsules or specialized vascular systems, LWA is already widely used as a structural aggregate in construction. This makes it compatible with standard mixing techniques and allows for easy scaling. Its mechanical stability ensures it withstands batching and compaction. Additionally, LWA is non-toxic, cost-effective, and available in various sizes and gradations [22].

Recent studies indicate that LWA can serve as both a reservoir and a delivery medium for self-healing agents. It fosters autogenous healing by ensuring sustained internal moisture and aids in bacterial mineralization. The dual role of LWA, serving both structural and healing purposes, offers a unique combination of simplicity and effectiveness. In scenarios where cost and construction practicality are essential, LWA could effectively connect laboratory innovations in SHC to real-world applications [23]. In addition, LWA tends to reduce the lifecycle environmental footprint of concrete applications due to its extended service life [24,25].

1.4. Significance

This paper aims to review current self-healing concrete technologies, identifying and analyzing the key operational and practical challenges that impede their widespread adoption. Furthermore, it evaluates the potential of LWA-based solutions to address these barriers and enhance the practical application of SHC. Results contribute to the development of a more deployable and durable SHC system that effectively addresses construction challenges.

2. MATERIALS AND METHODS

2.1. Autogenous Healing Mechanisms

Autogenous healing is the natural capability of cement-based materials to seal microcracks without the need for external additives. This process primarily occurs through the continued hydration of unreacted cement particles and the precipitation of calcium carbonate ($CaCO_3$) via carbonation. When water infiltrates a crack, dehydrated clinker minerals hydrate and fill the voids, while exposure to atmospheric CO_2 promotes calcite formation within the cracks, further aiding the sealing process [26].

Research indicates that autogenous healing can effectively seal cracks ranging from 150 to 300 µm, particularly when moisture is present and during the early stages of curing. However, its effectiveness depends on several factors: healing is more efficient at early ages when dehydrated cement is abundant, and its efficiency decreases significantly for cracks wider than 300 µm. Moreover, autogenous healing is nearly absent in dry environments [27].

Despite its potential, autogenous healing has limitations, including a narrow applicability to small cracks and unpredictable results. This makes it insufficient for critical applications without additional enhancements.

2.2. Additives

To address the limitations of natural autogenous healing, various strategies have emerged that enhance this process by using additives. Mineral admixtures, such as supplementary cementitious materials (SCMs), including fly ash, silica fume, and ground granulated blast-furnace slag (GGBFS), play a significant role in this enhancement. These materials increase the amount of latent binder that can hydrate over time while refining the pore structure of the concrete, which contributes to improved crack control and healing. However, it is important to note that their pozzolanic reactions consume calcium hydroxide (CH), which may reduce the availability of calcium ions (Ca^{2+}) necessary for calcite precipitation [28].

Crystalline admixtures, often marketed as commercial waterproofing solutions, offer self-sealing properties. When these admixtures come into contact with water, they generate insoluble crystalline deposits that effectively seal pores and fine cracks. Nevertheless, the proprietary nature of their compositions raises questions about their performance under dynamic loading conditions and in the presence of larger cracks, where effectiveness can be inconsistent [29].

Fiber reinforcement is another promising strategy. Various types of fibers, including steel, polypropylene, polyvinyl alcohol (PVA), basalt, and natural fibers, can help control crack widths and slow crack propagation. This is particularly beneficial, as narrower cracks are more conducive to effective healing through hydration or precipitation. Additionally, fibers can serve as moisture reservoirs, especially helpful during dry-wet cycles. However, the overall healing efficacy remains limited to narrower cracks, and issues such as fiber durability—

particularly corrosion of steel or degradation of natural fibers—must be addressed. Furthermore, the performance of these materials can vary significantly under real-world field conditions [30].

2.3. Encapsulation

Encapsulation strategies involve embedding healing agents within microcapsules or vascular systems that rupture in response to mechanical stress or cracking. Microcapsules utilize polymers or other healing agents, such as epoxy or cyanoacrylate, encapsulated within urea-formaldehyde or similar shells. When a crack forms, these capsules break open, releasing the healing agent into the crack plane. The agent then polymerizes or reacts to effectively seal the crack. However, several challenges are associated with this approach. For instance, capsules may rupture prematurely during mixing, and the limited volume of the healing agent restricts its effectiveness to small cracks, typically around 0.2 to 0.5 mm. Additionally, ensuring an even distribution of the healing agent is difficult [31].

Vascular networks, inspired by biological systems, incorporate interconnected hollow tubes filled with healing agents. When cracks reach these tubes, the agent flows into the cracks by capillary action or under pressure. Despite the elegance of this method, encapsulation strategies can be costly and fragile in practical construction contexts. Challenges include the complex fabrication and integration of these networks into structural elements, the potential for blockage or loss of connectivity over time, as well as concerns regarding their fragility and compatibility [32].

2.4. Bacteria-Based Healing

One of the most researched methods in autonomous SHC technology involves using bacterial spores, such as Bacillus subtilis, which produce calcium carbonate when activated by water, thereby filling cracks. This method can effectively seal cracks up to 1 millimeter and is sustainable and suitable for moist environments. However, challenges include ensuring the long-term survival of the bacteria in alkaline concrete, the complexity and cost of encapsulating them with protective materials such as silica gel and clay, and the need for a continuous nutrient supply to support ongoing healing. Additionally, while the visual sealing of cracks is clear, the restoration of mechanical strength is uncertain, and using living organisms in concrete raises regulatory and environmental concerns that are still debated [33].

2.5. Electrochemical and Smart Materials

Electrochemical self-healing is a technique that uses electrochemical reactions to repair cracks in reinforced concrete. By applying low-voltage direct current between steel reinforcement (the cathode) and an external electrode (the anode) in the presence of an electrolyte like water, metal ions (Ca^{2+}, Zn^{2+}, or Mg^{2+}) can migrate and form compounds ($CaCO_3$, ZnO, or $Mg(OH)_2$) that seal cracks and provide corrosion protection. However, challenges include the need for external power, a conductive concrete matrix, design complexities, and uncertainties about the long-term durability of the materials. This method is most suitable for specialized infrastructures, such as marine or tunnel structures, where monitoring and power supply are easier to manage and maintain [34].

Shape Memory Alloys (SMAs), particularly nickel-titanium (NiTi) variants, possess the remarkable ability to "remember" their original shape and revert to it upon heating. When integrated into concrete, these pre-strained SMA fibers or bars can effectively contract in response to thermal activation, allowing them to seal cracks and enhance the structural integrity of the material. The benefits of using SMAs include not only mechanical crack closure with excellent recovery potential but also improved composite ductility and resilience, as well as the ability to withstand multiple activation cycles. However, challenges such as high material costs, complex manufacturing processes, practical difficulties in on-site heating and activation, and the necessity for careful integration with reinforcement structures limit their widespread application. Consequently, the adoption of SMA-based self-healing composites remains constrained by these economic and logistical hurdles, despite their innovative potential [35].

2.6. Internal Curing and Healing Agents

To enhance self-healing efficiency in concrete, especially in low-moisture conditions, internal water reservoirs such as LWA and Superabsorbent Polymers (SAPs) have been investigated. SAP contains cross-linked hydrogels that can absorb 500–1000 times their weight in water, aiding hydration and healing by gradually releasing moisture during curing or upon crack exposure. While they promote autogenous healing, block cracks, and reduce early-age shrinkage, challenges include the potential formation of macro voids, reduced mechanical strength with excessive use, limited reusability in dry environments, and variable swelling behavior across different ionic concentrations, necessitating careful dosage and design considerations [36]. These challenges have highlighted the practical application of LWA for internal curing.

Rotary-kiln-manufactured LWA is a porous ceramic material that excels in water absorption and gradual release, making it ideal for long-term internal curing in construction applications. They are compatible with structural elements and provide durable, cost-effective mechanical stability. Beyond their core function, LWAs simultaneously enhance thermal insulation while minimizing dead load, enabling a multi-functional approach that encompasses structural support, healing, and curing. However, it's important to note that their effectiveness can be influenced by factors such as aggregate size and porosity, and they may lack the precise release control found in encapsulated systems. Despite these limitations, LWAs present a compelling option as scalable, reliable, and budget-friendly components for both autogenous and autonomous healing systems in construction [37].

2.7. Operational Barriers Across SHC Strategies

Despite the development and testing of various SHC technologies, their widespread implementation in the field remains limited due to several key challenges (Table 1). These include the need for precise environmental control of humidity and temperature, protection of sensitive components during mixing and casting, integration of costly or delicate materials, and the lack of standardized construction practices. These factors create a significant gap between successful laboratory performance and real-world application. To address these issues, there is an increasing interest in hybrid or integrated approaches that combine materials with both structural and healing properties, such as LWA infused with healing agents. The following section discusses how LWA-based solutions can effectively address many operational limitations, providing a viable pathway to the development of scalable, robust, and cost-effective self-healing concrete systems.

Table 1. Key challenges across different classes of SHC strategies

SHC Strategy	Crack Width Capability	Advantages	Key Challenges
Autogenous Healing	≤ 0.3 mm	Simple, intrinsic	Requires water, only works at early ages
Mineral/Crystalline Additives	≤ 0.4 mm	Enhanced healing	Variable performance, proprietary formulations
Fibers	≤ 0.2–0.7 mm	Crack control, synergy	Corrosion (steel), dispersion issues
Microcapsules	≤ 0.5 mm	targeted delivery	Premature rupture, cost, and mixing fragility
Vascular Systems	≥ 0.5 mm	Repeatable healing	Complex fabrication, maintenance
Bacteria-Based	≤ 1 mm	Bio-based, visible healing	Viability, encapsulation, cost
Electrochemical	≤ 1 mm	Active control	Power, complexity, specialized use
Shape Memory Alloys	≥ 0.5 mm	Mechanical closure	Expensive, needs activation
SAPs	≤ 0.4 mm	Internal curing, swelling	Macro voids, ionic sensitivity
LWA	≤ 0.5 mm	Robust, scalable, low cost	Agent retention, limited responsiveness

2.8. Mechanisms of Self-Healing Supported by LWA

LWAs are crucial in SHC due to their specialized pore structure, which allows them to absorb and retain water or healing substances. This characteristic ensures targeted delivery of self-healing properties while maintaining the concrete's structural integrity, with minimal modifications to the mix.

Using LWA in cement-based materials offers benefits beyond reducing density. Their porous nature serves as an internal water reservoir, supporting internal curing and enhancing the hydration of unreacted cement particles, which increases strength and durability over time. Additionally, LWA improves hydration and minimizes autogenous shrinkage, thereby reducing the likelihood of cracking during the early stages of concrete development. When cracks form, LWA can release stored moisture or healing agents directly into the affected areas.

LWA is chemically stable and inert in the alkaline environment of concrete, avoiding harmful interactions with cement hydration products, which makes them an attractive choice for applications prioritizing durability and reduced maintenance. Pre-saturated LWA acts as a micro-reservoir, providing continuous moisture to the cement paste, supporting autogenous healing, facilitating the ongoing hydration of unreacted clinker, and promoting calcium carbonate formation to seal microcracks in low-permeability concrete effectively.

Additionally, LWA can encapsulate bacterial spores, such as Bacillus subtilis, within its internal porosity. When cracks develop and water enters, the bacteria activate, metabolizing nutrients to precipitate calcium carbonate and seal the cracks. LWA can also be infused with healing agents, such as sodium silicate, which are released passively when cracks intersect LWA particles or through capillary action. Overall, LWA offers greater mechanical robustness and lower cost than engineered microcapsules and can be incorporated into hybrid self-healing concrete systems. These systems work in conjunction with shrinkage-reducing admixtures, synthetic fibers, and superabsorbent polymers to enhance crack control and healing efficiency.

To better understand the advantages and trade-offs of LWA, Table 2 offers a comparative overview. This table shows that LWA provides a favorable balance among performance, compatibility, cost, and scalability. Unlike many experimental or lab-scale systems, LWA is commercially available and well-integrated into existing construction practices, positioning it as a strong candidate for near-term deployment.

2.9. Practical Considerations

The deployment of LWA requires specific technical protocols to ensure efficacy. Pre-saturation is critical; LWAs must be soaked (typically for 24 hours) or vacuum-saturated to maximize their absorption capacity, ensuring the internal reservoirs are full before mixing. This affects the w/c ratio calculations, as the "free water" available for hydration must be distinguished from the water absorbed within the aggregate. Regarding Rheology, the lower density of LWA (typically 1200–1600 kg/m^3) can lead to segregation or "floating" if the concrete slump is too high; therefore, viscosity-modifying admixtures may be required to maintain mix stability. Finally, Quality Control must focus on the aggregate's moisture content; using LWA in a dry state can inadvertently absorb mixing water from the paste, drastically reducing workability and compromising hydration.

Table 2. Feature-based comparison of selected SHC strategies

Feature	LWA	Microcapsules	SAPs	Vascular Systems
Crack Width Range	Up to ~0.6 mm	0.2–0.5 mm	0.3–0.5 mm	>0.5 mm
Cost	Low	High	Moderate	Very High
Mixing Robustness	High	Low (fragile)	Moderate	Very Low
Compatibility with Traditional Mixing	Excellent	Moderate	Good	Poor
Reusability	Partial	Single-use	Single-use	Refillable
Activation Trigger	Crack + Moisture	Crack rupture	Moisture	Crack + Flow
Loading Method	Pre-saturation / Impregnation	Encapsulation	Dry powder	Embedded tubing
Scalability	High	Low	Moderate	Low
Commercial Availability	High	Limited	High	Custom-built

3. RESULTS AND DISCUSSION

3.1. Bridging the Gap Between Laboratory Innovation and Field Application

Consistent with the operational barriers identified in Section 2.7, the transition of SHC technologies from promising laboratory demonstrations to real-world applications remains limited. This gap is primarily driven by the stark contrast between controlled laboratory conditions—often assuming ideal triggers—and the variability of construction sites. Laboratory studies often assume ideal triggers, such as constant moisture and uniform crack patterns, whereas actual conditions include fluctuating temperatures and irregular cracking.

Additionally, SHC systems that perform well in small-scale tests often face challenges when applied to full concrete elements. Issues such as encapsulation rupture during mixing, reduced bacteria viability in large pours, and microstructural differences complicate their effectiveness. Therefore, the focus for SHC development must shift towards more robust, scalable, and field-compatible solutions.

A proper evaluation of SHC technologies should consider performance, cost, integration, and long-term durability. LWA-based systems perform well across these categories, balancing low cost and compatibility with traditional methods, even if they don't achieve the highest healing efficiency per unit crack width (Table 3).

Table 3. Practice-based comparison of selected SHC strategies

Strategy	Healing Efficacy	Cost	Durability	Field Integration	Reusability
Microcapsules	Medium	High	Low	Poor	No
Bacteria-based	High	High	Variable	Moderate	Partial
SAPs	Medium	Moderate	Medium	Good	No
Vascular	High	Very High	Low	Very Poor	Yes
SMA	High	Very High	High	Poor	Yes
Electrochemical	High	High	Medium	Moderate	Yes
LWA-based	Medium-High	Low	High	Excellent	Partial

3.2. Technical Strengths of LWA-Based SHC

Unlike delicate microcapsules or fine SAPs, LWA is durable and can handle high-energy mixing and vibrations. This resilience ensures even distribution and stability in the concrete. LWA serves multiple roles—acting as an aggregate, internal curing agent, and healing carrier—reducing the need for additional additives and simplifying the mix design.

LWA's internal reservoirs of water and healing agents enable delayed or multiple healing events, unlike many self-healing concrete methods, which are single-use. However, there's limited control over when and how LWA releases healing agents, which may not be effective in dry conditions or when cracks don't intersect with LWA. Additionally, the variability in LWA's absorption capacity and pore structure can impact healing performance unless standardized grades are used.

Excessive use of LWA can reduce compressive strength, while insufficient use may limit healing potential, requiring careful engineering judgment to achieve optimal use.

3.3. Sustainability

A critical evaluation of sustainability must account for the embodied energy of the materials. It is acknowledged that the production of expanded LWA involves rotary kilns operating at high temperatures (1100–1200°C), resulting in a higher initial embodied energy than natural normal-weight aggregates. However, from a Lifecycle Assessment (LCA) perspective, this initial environmental cost is offset by the extended service life of the structure. By mitigating cracking and enhancing internal curing, LWA reduces the frequency of repairs and delays the need for energy-intensive demolition and replacement. Furthermore, the reduced density of LWA concrete decreases the dead load, potentially allowing for slimmer structural elements and reduced consumption of steel reinforcement, further lowering the total carbon footprint of the project. Additionally, the multifunctional properties of LWA combine multiple functions, reducing the need for separate curing agents or fibers. From a lifecycle cost analysis perspective, LWA-based SHC can reduce the total cost of ownership; benefits such as reduced maintenance frequency and minimized downtime contribute to overall economic advantages, even with a slight increase in initial material costs.

3.4. Limitations

While LWA offers significant practical advantages, it is not without limitations. First, the healing mechanism is stochastic; it relies on cracks physically intersecting the porous aggregate particles to release the stored water or agents. Cracks that propagate through the cement paste without encountering an LWA particle may not trigger healing. Second, there is a mechanical trade-off; replacing normal-weight aggregate with lightweight porous aggregate can reduce the overall compressive strength of the concrete, necessitating careful mix design optimization. Finally, while LWA is effective for micro-cracks (typically <0.3 mm), it lacks the high-volume discharge capability of vascular networks required to seal larger structural fractures.

4. CONCLUSION

Cracking in concrete structures remains a significant challenge for durability, sustainability, and safety. SHC technologies have emerged as a potential solution, enabling autonomous repair mechanisms. However, despite advances in research, a gap remains between successful laboratory results and practical field implementation due to factors such as cost, complexity, and incompatibility with traditional construction methods.

This study examined various SHC strategies and highlighted LWA as a promising, scalable alternative. With its porous structure, mechanical strength, and availability, LWA serves both structural and functional roles in SHC systems. It enhances autogenous healing by serving as a carrier for healing agents and by contributing to internal curing. Its compatibility with existing construction processes and cost-effectiveness make it highly suitable for field applications. Although LWA may not achieve the highest healing capacity compared to other methods, its practicality and scalability make it a leading candidate for near-term implementation.

To advance the use of LWA in SHC, several recommendations are essential. Standardized testing protocols for LWA should be developed to assess its properties, and certification processes must ensure compatibility with healing agents. Investigating optimized loading techniques for healing agents and exploring multi-agent strategies can significantly enhance healing effectiveness in concrete. Long-term durability testing under real environmental conditions, along with pilot projects across various structural applications, is essential for evaluating performance and cost-effectiveness. Additionally, integrating lightweight aggregates (LWA) with other sustainable healing components can create composite systems that improve the robustness of the healing process. It is crucial to raise awareness among industry stakeholders about the benefits and requirements of LWA-based self-healing concrete (SHC) and to incorporate SHC provisions into construction standards. Ultimately, self-healing concrete offers a transformative approach to designing resilient infrastructure. LWA is well-suited for large-scale construction, supporting sustainable practices and various healing mechanisms. Future research should focus on enhancing healing capabilities while ensuring these innovations integrate smoothly into construction workflows, thereby paving the way for durable and adaptive concrete structures.

FUNDING/SUPPORT
Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT
Not mentioned any by authors.

AUTHORS CONTRIBUTION
This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST
The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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