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Revolutionizing Infrastructure: A Review of Self-Healing Concrete for Longevity and Resilience

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Abstract

A number of characteristics of autogenous and autonomous healing concrete are examined in this review, including their characterization, processes, and performances. It has been discovered that mineral admixtures, fibers, and self-contained methods including shape memory alloys, capsules, and microbial technologies are effective at repairing fractures. This review posits that autonomous procedures exhibit superior efficacy in fracture repair compared to autogenous methods. Furthermore, the selection of self-healing methodologies and agents is significantly influenced by crack geometry and size. Also under investigation are the effectiveness of biomimetic materials, including capsules, shape memory alloys, and self-healing concrete derived from microorganisms. Finally, current research gaps and the scope of prospective research are identified and discussed.

1. Introduction

Self-healing concrete has the potential to revolutionize infrastructure by enhancing its longevity and resilience. Traditional concrete structures are prone to cracks and damage over time due to factors such as corrosion, fires, and natural disasters. Self-healing concrete, on the other hand, contains additives or microorganisms that can repair these cracks autonomously, ensuring the structural integrity of the infrastructure is maintained. This innovation in concrete technology has gained significant attention in recent years, as it offers a solution to the problems associated with conventional repair methods.

Moreover, self-healing concrete has the potential to increase the lifespan of infrastructure, reducing maintenance and repair costs in the long run. By mitigating the direct and indirect costs associated with repairing cracked concrete elements, self-healing technology proves to be a promising strategy [1].

It not only saves time and resources but also enhances the durability and resilience of concrete structures, making them more sustainable in the face of various challenges. Furthermore, self-healing concrete aligns with the global push for sustainable construction practices [2]. As the construction industry strives towards sustainability, self-healing concrete emerges as a novel and progressive approach to address the environmental impact and resource consumption associated with traditional concrete production and maintenance [3]. Incorporating self-healing concrete in the construction industry would not only promote longevity and resilience but also contribute to a more sustainable future by reducing resource.

Concrete has a long-established ability to self-seal cracks, and in the last two decades, research activity has led to the development of techniques that promote and enhance this self-healing capacity [4]. This technology shows great potential for reducing maintenance and repair costs in concrete structures, extending their service life without requiring real-time manual maintenance. Various methods such as mold preparation, reinforcement placement, concrete pouring with accurate weight control, consolidation, and finishing using methods like vibration or SCC (self-consolidating concrete), different curing approaches including steam curing and alternative methods like direct electric curing or room temperature curing have been explored to improve the self-healing capacity of cement-based materials.

Additionally, the use of carbonate-producing microbes has also been studied as a method for healing cracks in concrete structures. Advancements in the precast concrete industry have also contributed to the revolutionizing of infrastructure [5]. These advancements include the development of self-healing concrete products, such as precast panels that contain capsules filled with healing agents. These capsules rupture when cracks occur, releasing the healing agents to fill and seal the cracks. Overall, the introduction of self-healing concrete has the potential to revolutionize infrastructure [6]. by greatly reducing the need for frequent maintenance and repair, increasing the longevity and resilience of concrete structures, and promoting sustainability in the construction industry.

The ability to self-heal is a crucial factor in repairing microcracks and small fractures in concrete, contributing to increased structural strength and durability. In specific conditions, concrete can undergo a healing process, addressing and mending these microscopic imperfections [7]. The primary mechanisms for self-healing in concrete encompass physical, chemical, or mechanical processes. Self-healing concrete can repair cracks autonomously, improving durability, reducing maintenance costs, enhancing safety, and minimizing environmental impact. It extends the lifespan of structures, prevents leakage and corrosion, and offers flexibility in applications, making it a promising technology in construction [2]. While bacterial self-healing concrete offers distinct advantages over conventional methods, including greater crack healing capacity, responsiveness to cracks, and potential for repetitive healing over 50 years, it's essential to consider practical challenges, such as maintaining bacterial activity and ensuring long-term effectiveness in real-world conditions [2]. Fig. 1 illustrates the phenomena of crack healing of the specimens before and after the healing of five different concrete mixes.

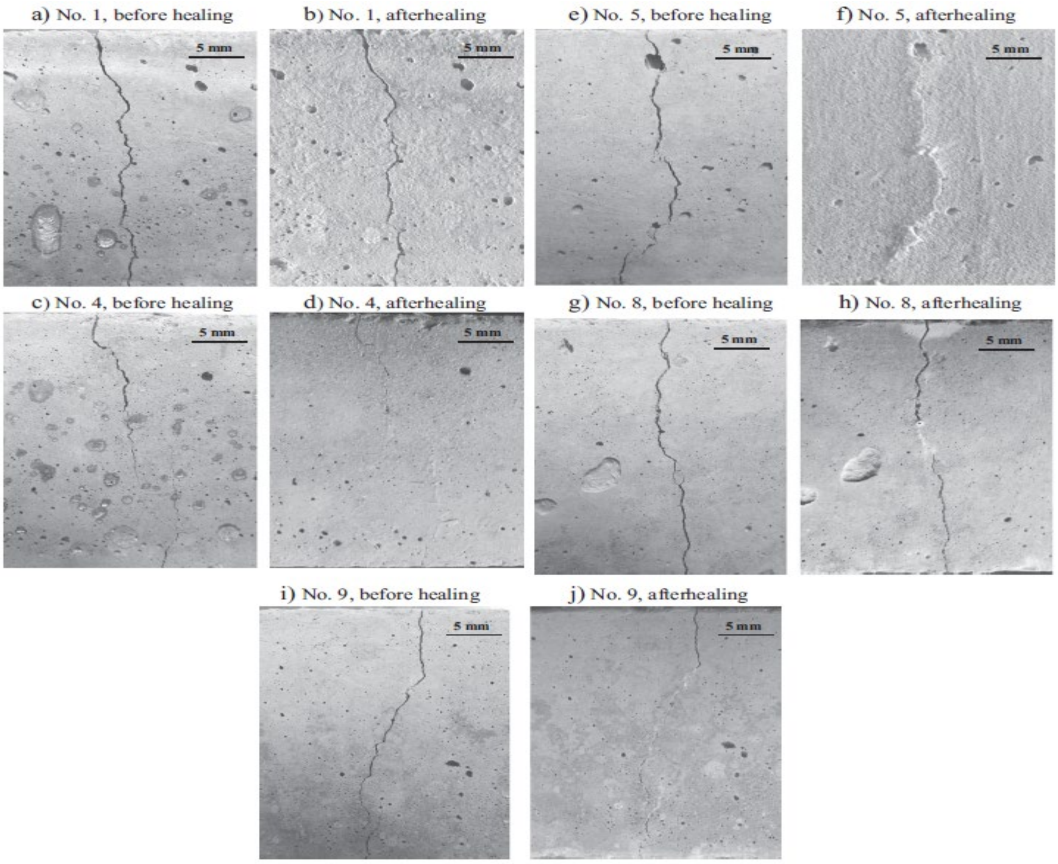

Fig. 1 *Photographical images of crack healing process (2)*

2. Materials and Fabrication Technique

The pursuit of sustainable and resilient infrastructure has led to significant developments in the realm of self-healing concrete [8]. This essay explores the materials and fabrication techniques integral to the evolution of this innovative technology, shedding light on the potential it holds for revolutionizing the construction industry. One

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pivotal aspect of self-healing concrete involves the strategic use of mineral admixtures, which act as partial substitutes for traditional cement. This not only reduces cement consumption but also influences the mechanical qualities of the material. Materials like fly ash, silica fume, and slag have emerged as potential candidates, each offering distinct advantages in enhancing the healing properties of concrete.

To optimize the healing capacity of self-healing concrete, a judicious mixture percentage for each healing substance must be determined [9]. Scientific experimental design methods, such as the uniform design, provide a systematic approach to studying the impact of various proportions of mineral admixtures, fibers, and autonomous healing agents. This scientific approach aids in identifying the most effective combination of healing substances for maximizing the concrete's self-healing potential. The characteristics of freshly formed and cured cementitious composites are significantly influenced by mixing methods, speed, and duration. The control and understanding of these parameters are crucial for the successful fabrication of self-healing concrete. Employing advanced mixing techniques, including high-speed mixing and specialized equipment, can enhance the distribution and activation of healing agents within the concrete matrix.

The fabrication of self-healing concrete encompasses various methods, each presenting unique advantages and challenges [6]. Techniques such as incorporating shape memory alloys, capsules, and microbial technologies contribute to the autonomous healing of concrete. Precise control of the fabrication process is essential to ensure the uniform distribution of healing agents, fostering the creation of a robust, self-healing infrastructure. Self-healing concrete (SHC) possesses a unique system, as illustrated in Fig. 2, and is frequently characterized by its capacity to autonomously repair cracks either through autogenous or autonomous mechanisms [10].

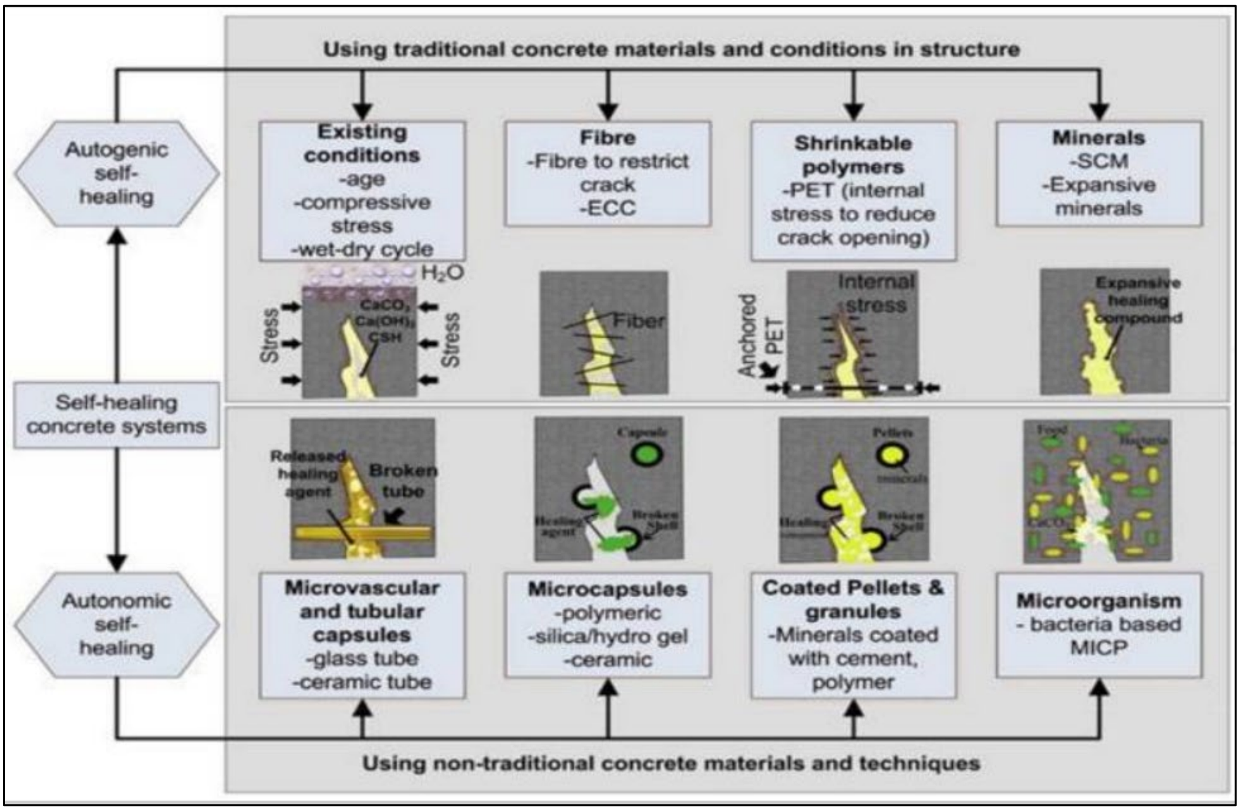

Fig. 2 *SHC systems (10)*

3. Advancements in Self-Healing Concrete

This approach has garnered significant attention for its cost-effectiveness and environmental sustainability. Research has demonstrated that self-healing concrete presents a viable remedy for addressing the prevalent problem of steel reinforcement corrosion in the construction sector [11]. The addition of self-healing agents, such as bacteria and organic compounds, to the concrete mixture improves the material's ability to heal cracks. In addition, sealing cracks enhances both the structural integrity and compressive strength of concrete. The advancement of self-healing technology in concrete has led to increased durability of infrastructure and the potential to reduce economic losses resulting from concrete damage caused by corrosion, fires, and natural disasters [12]. Moreover, this technological progress presents novel opportunities for enhancing the durability and robustness of concrete constructions in the presence of diverse obstacles. The utilization of self-healing concrete can substantially decrease the frequency of repairs and replacements, resulting in notable cost savings and promoting a more sustainable construction sector. Self-healing concrete is achieved by integrating healing agents, such as bacteria or encapsulated chemicals, into the concrete mixture. These agents remain inactive until cracks or damages arise, at which point they become activated and initiate the healing process [13]. The process involves the reaction of healing agents with water or other compounds in the concrete, resulting in the formation of new materials that fill and seal the cracks. The self-healing process not only restores the structural integrity of the concrete but also mitigates the risk of additional damage or deterioration. Self-healing concrete has the potential to significantly transform the infrastructure industry by enhancing the durability and resilience of structures. Self-healing concrete is an innovative technology with the capacity to significantly impact the construction sector through the provision of infrastructure that is more durable and resilient [6] The production of self-healing concrete involves a series of complex procedures that enhance its strength and longevity. Mold preparation, previously reliant on labor-intensive techniques, has now transitioned to more cost-effective methods like additive manufacturing.

The precision and appearance of mold preparation are crucial factors that greatly influence the strength and quality of precast elements [6] An essential aspect of developing self-healing concrete involves the proper positioning of reinforcement. This step entails strategically placing steel bars, wire mesh, or fibers within the concrete mold to augment the strength and durability of the end product. The process of pouring concrete is a vital stage in the manufacturing of self-healing concrete, necessitating precise weight management and meticulous adherence to design specifications. This guarantees the attainment of desired characteristics and the potential for self-repair in the end product. After the self-healing concrete is poured and cured, it undergoes monitoring and evaluation to assess its performance. The process commonly includes non-destructive testing, such as the previously mentioned Impact-Echo method, to identify defects or damages and assess the efficacy of the self-healing process. The process of producing high-quality self-healing concrete involves several steps, including mold preparation, reinforcement placement, concrete pouring, and monitoring. These steps are crucial in enhancing the durability and resilience of infrastructure [14]. In summary, self-healing concrete presents a revolutionary solution for the construction sector, offering enhanced durability and resilience to infrastructure. Innovative techniques, such as grouting, cement grout, and jacketing, can be employed to repair and maintain concrete structures that have been corroded. The use of bacteria in self-healing bio-concrete has demonstrated potential in autonomously repairing small cracks in concrete [15]. Reinforcement placement significantly contributes to the strength and durability of precast elements. The correct placement of steel bars, wire mesh, or fibers within the mold is crucial to maintain the structural integrity of the concrete structure. Technological advancements have facilitated the development of more precise and detailed specifications for reinforcement placement, encompassing factors such as bar counts, lengths, and positions [16]. This has significantly enhanced the overall strength and durability of concrete structures. Self-healing concrete has the potential to enhance the durability and resilience of infrastructure. It is crucial to recognize the counterarguments concerning the implementation and effectiveness of self-healing concrete.

Self-healing concrete shows potential in mitigating water ingress into reinforced steel and enhancing durability [17]. However, there are practical implementation concerns associated with its use. According to [18], self-healing concrete has been found to improve compressive strength. However, it is important to note that steel reinforcement is still required to withstand tensile loads, as concrete's vulnerability to cracking in such situations remains a significant obstacle. The complex processes of producing self-healing concrete, including mold preparation, reinforcement placement, concrete pouring, and curing, have inherent complexities that can affect the cost-effectiveness and practicality of widespread use. The feasibility of self-healing concrete in actual construction projects should be assessed by considering the practical obstacles and expenses, in order to properly evaluate its potential advantages. In conclusion, the Impact-Echo method has demonstrated its efficacy in monitoring the condition of concrete both pre- and post-repair. This non-destructive testing method provides valuable insights into the effectiveness of concrete repair and self-healing methods for researchers and industry professionals. The ability to non-destructively detect flaws and evaluate the quality of concrete structures is essential for ensuring the durability and resilience of infrastructure.

4. Effectiveness for Long-Term Integrity

The evaluation of self-healing and durability parameters in concretes that incorporate crystalline admixtures and Portland Limestone Cement provides promising insights into the efficacy of self-healing mechanisms for preserving the integrity of concrete infrastructure [19]. The incorporation of these innovative materials reflects a proactive strategy to tackle the inevitable development of cracks and deterioration in concrete structures over time. The self-healing mechanisms primarily entail activating crystalline admixtures within the concrete matrix. These admixtures, often composed of reactive minerals, demonstrate the capacity to initiate a healing process upon exposure to water. As cracks emerge in the concrete, these minerals react with water, forming insoluble crystals that seal the cracks and prevent further penetration of harmful agents [20]. This self-directed healing process is essential for sustaining the structural integrity of the concrete and prolonging its operational lifespan [20].

Several notable instances highlight the effective application of self-healing concrete in various construction projects. One illustrative example involves employing self-healing concrete in marine structures exposed to harsh marine environments. The crystalline admixtures within the concrete adeptly responded to the conditions rich in chloride, exhibiting a decrease in crack width and improved durability over an extended duration [20]. In a different scenario, self-healing concrete was utilized in the construction of bridges, where exposure to cyclic loading and environmental stressors presented challenges to the structural integrity of the infrastructure. The self-healing mechanisms played a significant role in sustaining the bridge's performance by autonomously sealing cracks, preventing water ingress, and preserving the concrete's strength [20]. These instances highlight the tangible advantages of self-healing concrete in varied applications, demonstrating its adaptability and effectiveness in real-world situations [20]. The incorporation of such advanced materials not only ensures the prolonged lifespan of concrete structures but also diminishes maintenance costs and contributes to overall sustainability.

While the idea of self-healing concrete shows significant potential, there are inherent limitations and obstacles that must be addressed to guarantee its enduring effectiveness. A notable challenge lies in the reliance of self-healing mechanisms on the presence of water [20]. In regions characterized by aridity or prone to drought, where water scarcity is a prevalent concern, the initiation of the healing process may be impeded, jeopardizing the concrete's capacity for self-repair. Furthermore, the effectiveness of self-healing is susceptible to decline over time as a result of the depletion of reactive minerals in the concrete matrix [20]. The finite nature of these minerals prompts questions about the long-term durability of self-healing concrete, necessitating periodic evaluations and potential reapplication of healing agents. An additional constraint is the susceptibility of self-healing mechanisms to environmental conditions. Extreme temperatures, exposure to aggressive chemicals, or elevated stress levels may adversely affect the efficiency of the healing process. It is imperative to comprehend and address these environmental sensitivities to ensure a consistent and reliable performance of self-healing concrete in diverse settings [20].

5. Recommendations

Adding additives or microorganisms to traditional concrete structures to help cracks heal themselves could be a good way to solve problems that keep coming up with traditional repair methods, like corrosion, fires, and natural disasters [21]. Self-healing concrete not only promises to make infrastructure last longer while lowering long-term maintenance costs, but it also fits in with efforts around the world to make construction more environmentally friendly. Recent improvements in materials and construction methods, like the smart use of mineral admixtures and scientific experimental design methods, are positive because they show that they might make it easier for concrete structures to heal. As we think about the future of self-healing concrete, it is important to do a lot of long-term durability studies, look into healing mechanisms that don't need water, find the best healing agents, and do full environmental impact assessments. Policymakers, engineers, and other interested parties can do a lot to help make self-healing concrete a part of building codes, by offering financial incentives and encouraging people to work together to share knowledge. Lastly, more research and use of self-healing concrete are needed to make infrastructure that is strong, eco-friendly, and cost-effective. This is the start of a major shift toward sustainable building practices and long-lasting built environments.

6. Conclusion

The review talks about self-healing concrete and how it can fix cracks in buildings. It looks at different ways to make this kind of concrete, like using special materials or tiny organisms. The study shows that methods where the concrete can fix itself without help work better than those that need outside help. It also mentions that the size and shape of cracks are important when choosing how to fix them. The review also talks about new materials like shape memory alloys, capsules, and bacteria that can help concrete heal itself.

Self-healing concrete is a big deal for the construction industry because it can help buildings last longer. Regular buildings often get cracks or get damaged, costing a lot to fix. Self-healing concrete has special stuff inside that can fix cracks on its own, making buildings stronger and lasting longer. It's also good for the environment and helps with sustainable building practices, reducing waste and being better for the planet. Advancements in how self-healing concrete works, like using special materials or methods, offer new ways to make buildings stronger. The article talks about how this can save money and make the construction industry more sustainable. By using self-healing concrete, buildings might not need to be fixed as much, saving time and resources. It's a cool way to build things that last and are good for the environment.

In the end, self-healing concrete can change how we build things. It can make buildings stronger and last longer without needing lots of repairs. This is important for the construction industry because it can save money and be better for the planet. The article mentions some challenges, like needing water and having limits in extreme conditions, but overall, it seems like self-healing concrete can be a game-changer. It's not just about construction; it could also affect how we live by giving us stronger and more sustainable buildings. However, we need to think about how practical it is and if it makes sense for the cost. In the future, using self-healing concrete could make a big difference in how we build and take care of our buildings.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Shazwan Rizal, Siti Aida Ibrahim;* ***data collection:*** *Shazwan Rizal, Nur Fatin Aman;* ***analysis and interpretation of results:*** *Shazwan Rizal, Ariff Othman, Siti Aida Ibrahim;* ***draft manuscript preparation:*** *Shazwan Rizal, Siti Aida Ibrahim. All authors reviewed the results and approved the final version of the manuscript.*

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