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Advancements and Challenges in the Development of self-healing Concrete for Sustainable Construction- A Critical Review

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Abstract

This review paper delves into the innovative realm of self-healing concrete as a sustainable solution in the construction industry. The study aims to differentiate itself by critically examining the development and application of self-healing concrete, particularly focusing on its capacity to autonomously repair cracks and microfractures, thereby enhancing structural durability and reducing environmental impact. Specifically, the objectives of this study including Evaluating the effectiveness of self-healing concrete in various environmental conditions and construction settings, comparing different self-healing mechanisms, including microbial methods such as the use of bacteria like Bacillus sp., and other innovative approaches, Analysing the economic feasibility of implementing self-healing technologies and their long-term cost benefits in construction projects. The review explores in detail the mechanisms of self-healing concrete and its sustainability benefits, including a prolonged lifespan of structures, reduced maintenance requirements, and decreased carbon emissions. However, the paper also addresses the challenges and limitations associated with the technology, such as the efficacy of bacteria over long-term applications and cost considerations. Furthermore, the manuscript provides insights into practical applications and case studies of self-healing concrete, showcasing its effectiveness in real-world scenarios. The incorporation of Life Cycle Assessment (LCA) in evaluating self-healing concrete is discussed, offering a comprehensive understanding of its environmental impact throughout its life cycle. Despite the challenges, the potential benefits of self-healing concrete are emphasized, positioning it as a promising avenue for sustainable construction practices in the context of growing global demand for concrete and the need for environmentally conscious solutions.

Keywords: *Self-healing concrete, Sustainability, Construction materials, Structural durability, Environmental impact*

Sürdürülebilir İnşaat için Kendiliğinden İyileşen Betonun Geliştirilmesindeki İlerlemeler ve Zorluklar - Eleştirel Bir İnceleme

Özet

Bu derleme makalesi, inşaat sektöründe sürdürülebilir bir çözüm olarak kendiliğinden iyileşen betonun yenilikçi alanına derinlemesine bir bakış açısı sağlar. Makale, özellikle çatlaklara ve mikro çatlakları otonom olarak onarma kapasitesine odaklanarak, kendiliğinden iyileşen betonun geliştirilmesi ve uygulanmasını eleştirel bir şekilde inceler. Onarma yapısal dayanıklılığı artırır ve çevresel etkiyi azaltır. İnceleme, özellikle Bacillus sp. gibi bakterilerin kullanarak tamir sürecini çevre dostu bir şekilde kolaylaştıran mikrobiyal yöntemlerin uygulanmasını vurgular. Kendiliğinden iyileşen betonun mekanizmalarını, sürdürülebilirlik faydalarını, yapıların ömrünün uzamasını, bakım gereksinimlerinin azalmasını ve karbon emisyonlarının azalmasını araştırır. Ancak, makale aynı zamanda uzun süreli uygulamalarda bakterilerin etkinliği ve maliyet hususları gibi teknolojiyle ilişkili zorlukları ve sınırlamaları da ele alır. Ayrıca kendiliğinden iyileşen betonun gerçek dünya senaryolarındaki etkinliğini sergileyen pratik uygulamalar ve vaka çalışmaları hakkında bilgiler sunar. Kendiliğinden iyileşen betonun değerlendirilmesinde Yaşam Döngüsü Değerlendirmesi'nin (LCA) dahil edilmesi tartışılmakta olup, bu da onun çevresel etkisine yaşam döngüsü boyunca kapsamlı bir anlayış sunar. Zorluklara rağmen, kendiliğinden iyileşen betonun potansiyel faydaları vurgulanmakta ve artan küresel beton talebi ve çevre bilinçli çözümlere duyulan ihtiyaç bağlamında sürdürülebilir inşaat uygulamaları için umut verici bir yol olarak düşünülmektedir.

Anahtar kelimeler: *Kendiliğinden iyileşen beton, Sürdürülebilirlik, İnşaat malzemeleri, Yapısal dayanıklılık, Çevresel etki.*

1. Introduction

The evolution of construction materials has been a cornerstone in the development of human settlements, from ancient times to the present. The path of innovation in building materials has led us to a critical juncture, marked by the urgent challenges of burgeoning population growth and the dynamic requirements of today's society. Concrete, in particular, has emerged as a material of choice in the construction sector due to its durability and flexibility in use. Yet, it is becoming increasingly evident that concrete, despite its many advantages, has its set of limitations when juxtaposed with other construction materials like steel and wood. These limitations are far from minor; they encompass issues such as the restriction on the size of structures that can be efficiently built, the problems associated with thermal expansion and contraction, and the material's notable susceptibility to a range of external stresses. These stresses include, but are not limited to, phenomena such as creep (the tendency of a solid material to move slowly or deform permanently under the influence of mechanical stresses) and shrinkage (the process of volume reduction due to loss of moisture). These inherent weaknesses of concrete necessitate continuous research and development efforts to enhance its properties and extend its range of applications in the construction industry [1], [2].

Over time, concrete structures are prone to the formation of microcracks that gradually evolve into larger, more significant cracks, undermining the structural stability of buildings. This gradual degradation can severely impact the building's integrity. Additionally, these cracks can allow water to penetrate the concrete, leading to the corrosion of steel reinforcements within. This process not only accelerates the deterioration of the concrete but also weakens the structural framework, posing a severe risk to long-term structural health and safety. This vulnerability underscores the necessity for ongoing research and development in construction materials to enhance the durability and longevity of concrete structures, ensuring they can withstand such challenges over time [3] [4].

1.1. Emergence and impact of self-healing

The use of substandard construction materials drastically increases the vulnerability of buildings in regions prone to seismic activity. This increased risk stems from the materials' insufficient seismic resilience, leading to a higher likelihood of structural failures during earthquakes. The consequences of such failures are twofold: they lead to significant reconstruction expenses and raise serious humanitarian concerns. Recent research efforts, highlighted by programs like the Earthquake Risk Reduction in Buildings and Infrastructure Program, have emphasized the urgent need for improved methods of assessing seismic performance and for developing designs that are resilient yet cause minimal damage. These efforts are directed towards reducing risks by incorporating sophisticated earthquake engineering techniques that consider both the structural integrity and the non-structural elements of buildings. Adopting a comprehensive approach is vital for promoting the functional recovery and resilience of structures situated in earthquake-sensitive areas, thereby diminishing the chances of devastating failures and their subsequent socio-economic ramifications [5], [6].

In light of these challenges, self-healing concrete has emerged as a promising and innovative solution. This material is notable for its unique capacity to automatically repair cracks and microfractures, offering a cost-effective alternative that has piqued interest in recent research [7], [8], [9], [10], [11]. Despite these technological advancements, the production of concrete remains a major environmental issue, mainly because of the high energy consumption and carbon dioxide emissions it entails [12], [13]. This problem is exacerbated by the soaring global demand for concrete amid rapid urbanization. Thus, there's a growing advocacy for using materials that last longer as a strategic way to lessen environmental impacts [14].

Further studies have delved into the environmental advantages and sustainability of self-healing concrete, especially when innovative materials like geopolymers are used and life cycle assessment (LCA) methods are applied to validate its environmental benefits. For example, the LCA of self-healing geopolymer concrete indicates it can reduce the global warming impact compared to traditional OPC concrete, though it may involve compromises in other environmental impact areas [15].. Additionally, research into the role of bacterial activity in cement-based materials' self-healing capabilities has shown that microbiologically induced carbonate precipitation significantly contributes to improving concrete durability under extreme conditions [16].

This review meticulously explores self-healing concrete's dual function as both a sustainable repair mechanism and a method for increasing structural durability [17], [18], [19]. It particularly looks at the use of microbes in self-healing concrete, where bacteria like Bacillus sp. have proven effective in generating calcium carbonate, thus aiding the repair process in an eco-friendly way [20], [21], [22], [23]. This technology's wider benefits extend beyond structural advantages, offering possibilities for reducing maintenance and future repair expenses [24].

Furthermore, in the quest for sustainable construction materials, a novel approach has been developed through the creation of an Expanded Perlite-Silica aerogel composite for insulation. Exhibiting remarkable properties like increased porosity and cost-efficiency, this innovative material represents a significant step forward in promoting sustainability in construction materials. The findings from this study could provide valuable insights for further exploring the potential of new materials in enhancing the performance and environmental footprint of self-healing concrete technologies [25].

The evolution of construction materials has been a continuous endeavor to address challenges and enhance sustainability within the construction industry. While traditional concrete has been widely used, its inherent weaknesses, such as susceptibility to cracks, microfractures, and environmental impact during production, have spurred the exploration of innovative solutions. Self-healing concrete has emerged as a promising avenue, offering the potential to autonomously repair structural defects and reduce maintenance requirements.

However, existing literature primarily focuses on the concept and initial applications of self-healing concrete. This study aims to contribute significantly to this field by delving deeper into the mechanisms and practical applications of self-healing concrete, particularly emphasizing the utilization of microbial methods, such as Bacillus sp., to facilitate environmentally friendly repair processes. Our research seeks to bridge the gap between theoretical concepts and real-world implementation, showcasing the effectiveness of self-healing concrete in enhancing structural durability while reducing environmental impact.

The originality of this study lies in its comprehensive examination of self-healing concrete, including its mechanisms, sustainability benefits, challenges, and practical case studies. By incorporating Life Cycle Assessment (LCA), we aim to provide a holistic understanding of the environmental implications of self-healing concrete throughout its life cycle. Through this study, we intend to contribute novel insights and practical applications that can inform sustainable construction practices and address the increasing demand for eco-conscious solutions in the construction industry.

2. Mechanism of Self-haling Agents

Over the last two decades, the field of self-healing concrete technology has witnessed substantial advancements, driven by the quest to enhance the material's self-healing capabilities, thereby improving its durability and extending the service life of civil infrastructure. Pioneering studies, such as those by Li and Herbert (2012), have laid the groundwork by introducing robustness criteria for self-healing concrete, evaluating various approaches for intelligent sustainable infrastructures [26].

The field of self-healing concrete technology has seen significant advancements, introducing innovative methods aimed at enhancing the material's self-healing capabilities to improve durability and extend the lifespan of civil infrastructure. Among these advancements, the application of advanced computational techniques, like the Least Squares Support Vector Machines (LSSVM) algorithm, has been explored to optimize the self-healing process in concrete, offering a more efficient pathway to predict and enhance crack healing capabilities [27].

2.1. Autogenous and enhanced self-healing mechanism

Self-healing in concrete occurs through various mechanisms, primarily categorized into autogenous and enhanced healing processes. Autogenous self-healing refers to the concrete's inherent ability to repair cracks without external intervention, often triggered by the continued hydration of unreacted cement particles in the presence of water, leading to the formation of new crystalline products that seal the cracks [28]. Enhanced self-healing strategies involve the deliberate inclusion of healing agents, such as microcapsules filled with silicate-based inorganic materials or bacterial spores, into the concrete mix. These agents are designed to activate upon crack formation, with the microcapsules releasing their contents to facilitate rapid crack closure and healing, significantly improving the material's durability and reducing its permeability [29], [30].

Recent studies have emphasized the role of bacterial mediation in self-healing concrete, wherein particular bacterial strains are incorporated into the concrete matrix to initiate calcite precipitation, thus efficiently sealing cracks and bolstering the material's structural integrity over time. This bio-mediated self-healing process not only augments the concrete's longevity but also dovetails with sustainable construction practices by employing environmentally friendly materials. The use of bacteria to facilitate the natural healing of concrete represents a confluence of biological science and construction technology, offering a green solution to the age-old problem of concrete degradation. This approach leverages the natural processes of calcite formation to repair and reinforce concrete structures, promising a new era of durable, self-sustaining, and eco-conscious construction materials [1].

Additionaly, studies have underscored the potential of incorporating self-healing mechanisms into composite materials, showcasing their ability to autonomously repair damage. This innovative approach significantly boosts the materials' durability and reliability across a range of applications. By embedding self-healing features into composites, these materials can recover from internal damages without human intervention, extending their usable life and reducing maintenance costs. This integration not only serves to enhance the structural integrity of the materials but also aligns with sustainability objectives by minimizing waste and the need for frequent replacements. The development of self-healing composites represents a progressive step in material science, aiming to create more resilient and sustainable materials for future construction and engineering projects [31].

Furthermore, leading to the creation of diverse self-healing concrete technologies, among which microcapsule-based self-healing materials stand out for their potential to improve the healing capabilities of mortar. These technologies encapsulate healing agents within microcapsules that are integrated into the concrete mix. When cracks form, the capsules break, releasing the agents that then react with the concrete to seal the cracks. This method has demonstrated promising outcomes in extending the lifespan of concrete structures by effectively mending cracks and preventing the onset of more severe structural issues. The exploration of these microcapsule-based technologies is a testament to the innovative directions in which material science is moving to enhance the durability and functionality of construction materials [32].

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2.2. Material innovations in sustainable construction

Within the sphere of self-healing concrete technology, considerable progress has been achieved by integrating cutting-edge materials, including shape-memory alloys (SMAs), polymer-based microcapsules, and nanotechnologies. Shape-memory alloys, in particular, have been instrumental in mechanically sealing cracks, thereby advancing the self-healing capabilities of concrete. The research conducted by Huang et al. (2023) delves into the utilization of SMAs within self-healing concrete frameworks, illustrating how these materials bolster the concrete's intrinsic repair functions. SMAs are unique in their ability to return to their original shape after deformation, a property that proves invaluable in the context of self-healing concrete. When embedded within the concrete matrix, SMAs can activate upon the detection of cracks, mechanically drawing the separated edges together and facilitating the subsequent healing processes. This action not only closes the cracks more efficiently but also reinforces the overall structure, potentially preventing the propagation of further damage. Huang and colleagues' investigation into SMA-enhanced concrete provides critical insights into the synergy between smart materials and traditional construction substances. By leveraging the unique properties of SMAs, this research underscores a transformative approach to building materials, where the self-healing process is not just a chemical reaction but a dynamic interaction between mechanical and material engineering. The integration of SMAs into self-healing concrete signifies a significant advancement in the field, offering a more robust and reliable solution to structural maintenance and longevity. This development not only extends the lifecycle of concrete infrastructures but also aligns with sustainable construction practices by reducing the frequency and scale of repairs needed over time [33].

Polymer-based microcapsules stand at the forefront of innovative construction materials, encapsulating a future where concrete can autonomously repair itself. These microscopic vessels, ingeniously designed, house healing agents that are poised to spring into action to mend cracks the moment they appear. The groundbreaking research by Van Tittelboom and De Belie (2013) offers a deep dive into the world of microcapsule-based self-healing systems, shedding light on how these tiny yet powerful entities can dramatically enhance the longevity and resilience of concrete structures. In their study, Van Tittelboom and De Belie explore the intricate mechanics of how these microcapsules integrate into the concrete matrix, staying dormant until the very moment a crack forms. Upon activation, they release their contained healing agents, filling the cracks and binding the concrete back together, almost like a biological healing process within an inanimate material. This not only seals the cracks efficiently but also significantly extends the material's life, reducing the need for frequent repairs and maintenance. This approach embodies a perfect marriage of material science and innovative design, offering a glimpse into a sustainable future where buildings and infrastructures self-repair, much like living organisms heal their wounds. The work of Van Tittelboom and De Belie is not just about fixing cracks; it's about reimagining the possibilities of construction materials and paving the way for a new era of sustainable and self-sustaining urban infrastructure [34].

In the domain of nanotechnology, the application of multi-walled carbon nanotubes (MWCNTs) has garnered substantial interest for enhancing the mechanical and self-healing attributes of concrete. The investigative work by Han et al. (2015) specifically addresses the incorporation of MWCNTs into the concrete matrix, evidencing a marked improvement in the material's intrinsic self-healing efficacy. This research delineates the mechanisms by which MWCNTs contribute to the autogenous healing processes, facilitating the closure of micro-cracks and thus augmenting the structural integrity and longevity of concrete infrastructures. The integration of MWCNTs not only bolsters the mechanical properties of concrete but also optimizes its self-repair capabilities, presenting a significant advancement in the field of construction materials. This enhancement in self-healing efficiency underscores the potential of nanotechnology as a pivotal contributor to the development of more durable and sustainable concrete solutions [35].

2.3. Sustainability benefits of self-healing concrete

The concept of self-healing in construction is gaining traction as a viable solution to the myriad challenges faced by the industry. This forward-thinking approach is celebrated for its extensive array of advantages across environmental, economic, and social spheres. From an environmental perspective, self-healing construction minimizes the demand for new materials and reduces the waste associated with repair work, thus aligning seamlessly with eco-friendly construction practices. Economically, this methodology offers a cost-effective alternative, prolonging the service life of buildings and infrastructure while reducing the need for frequent maintenance, leading to significant cost savings. Socially, it improves safety and reliability, which in turn has a positive impact on the welfare of communities. This comprehensive strategy highlights the overarching value of self-healing construction, demonstrating its potential to foster sustainability and innovation within the construction sector [36].

2.3.1. Prolonged lifespan of structures

Self-healing concrete is increasingly becoming a pivotal element in improving the durability and extending the lifespan of architectural constructions. Its ability to autonomously mend cracks and damages plays a vital role in reducing the frequency of extensive repairs and maintenance operations. This advanced material technology significantly cuts down on the consumption of raw materials, obviating the need for complete structural teardowns in the event of damage. Consequently, it fosters a more sustainable and judicious utilization of resources, aligning with eco-friendly construction methodologies. By conserving materials, self-healing concrete not only minimizes waste but also represents a forward-thinking approach to resource management. It epitomizes a strategic shift towards more sustainable construction practices, envisaging a future where buildings are both resilient and environmentally responsible [37].

2.3.2. Key sustainability nenefits of self-healing concrete

Self-healing concrete marks a significant shift in construction technology, offering a plethora of advantages that promise to redefine the industry’s standards. This cutting-edge material reduces the need for constant upkeep by autonomously sealing cracks and mitigating damage, thereby prolonging the structural lifespan. It also plays a crucial role in curbing carbon emissions tied to frequent repair work and the broader construction activities, aligning with eco-conscious practices. By diminishing the need for repetitive repairs and lessening the demand for new construction materials, self-healing concrete aids in preserving water and energy, tackling some of the critical sustainability challenges. Additionally, this method drastically cuts down on waste generation, limiting the rubble from demolished buildings and reducing the surplus materials often associated with maintenance tasks. In essence, self-healing concrete signifies a leap towards sustainable building practices, supporting the global drive towards better environmental care, economic prudence, and societal benefits in the construction realm [38], [39].

2.4. Challenges and limitations

Self-healing concrete introduces the remarkable capability of concrete to autonomously mend its own damages, akin to the way human skin heals after being wounded. Central to this innovative phenomenon is the generation of calcium carbonate, which functions akin to a natural plaster, sealing the fissures and restoring the structure's integrity. This process not only repairs the concrete but can also enhance its strength, potentially surpassing its original state. Nevertheless, perfecting this technology is complex and requires precision. It resembles the delicate art of baking, where achieving the ideal balance of ingredients, in this case, bacteria, is crucial. These microscopic organisms are pivotal, as they produce the healing compound that mends the concrete. Additionally, the application context of self-healing concrete is paramount. Similar to dressing appropriately for various weather conditions, self-healing concrete must be customized to fit its specific environmental conditions and functional requirements, whether it's exposed to outdoor weathering or supporting structural loads [40].

2.5 Efficacy in long term

Bacteria, in their natural habitat, demonstrate a longevity of up to fifty years; however, their viability is markedly reduced when applied within construction contexts, particularly in self-healing concrete applications, where their survival span does not exceed two months. This temporal limitation significantly impacts the practical utility of bacterial self-healing mechanisms in construction materials. Additionally, the efficacy of these bacterial agents is contingent upon the spore characteristics inherent to the concrete and the dimensional attributes of the bacteria. Certain bacterial strains exhibit an inability to adequately infiltrate cracks within the concrete matrix, which impedes the hydration process. This limitation not only diminishes the effectiveness of the self-healing process but also precipitates the premature expiration of the bacteria, thereby undermining the overall potential of this innovative technology to extend the structural lifespan and enhance the durability of concrete infrastructures [41].

2.6. Cost efficacy

In scholarly discourse, it is noted that the prevailing market rates for conventional concrete within the United States for the calendar year 2023 were projected to oscillate between $125 and $165 per cubic yard. In juxtaposition, the financial outlay associated with the utilization of self-healing bacteria within concrete was quantified at approximately $6,876 per cubic meter, as delineated in 2015 data. This stark contrast underscores the economic considerations inherent to the adoption of self-healing technologies in construction practices. Additionally, the engagement of specialized personnel, encompassing engineers and chemists, is imperative for the bespoke selection of materials. This tailored approach ensures compatibility with the nuanced conditions and functional requisites of the construction site, taking into account various media and other pertinent factors. The complexity of integrating self-healing technologies into construction materials thereby necessitates a multidisciplinary approach to optimize material performance within specific environmental contexts [42].

3. Practical Applications and Case studies of self-healing Concrete

Self-healing concrete has the ability to heal itself after a crack appears automatically, and it can reduce the maintenance of the structure. However, this idea has been explored by many researchers in the laboratory, but not in the exact environment and construction for large scales. In one of the studies, the addition of the bacterial agent (MUC+) took place in both the admixture and concrete mixer. Subsequently, it was transported to the construction site to harness the self-healing capability for the roof slab. The findings indicate that, in this particular experiment, there is an increased water requirement for initiating the production of $CaCO_3$ by the bacteria. There is a notable enhancement in capillary water absorption post self-healing. Notably, after a year of casting, there were no observed cracks in the bottom of the slab room [43]. In another instance, a case study highlights the effectiveness of employing self-healing concrete in underground engineering. The results demonstrate that, following a 28-day curing period, cracks treated with the self-healing mechanism exhibit visible recovery. It's worth noting that, in this particular study, the sidewall is identified as having the highest risk of cracking, posing a challenge for crack prevention. Furthermore, no adverse effects on compressive strength, adiabatic temperature rise, or drying shrinkage were observed in the experiment. Additionally, it's important to mention that the cracks are filled with calcite [44].

3.1. Life cycle assessment (LCA)

Utilizing and incorporating Life Cycle Assessment (LCA) can yield the optimal rehabilitation option tailored to environmental considerations. In other words, LCA furnishes a comprehensive and systematic evaluation of the environmental impact throughout the life cycle of a product, process, or system. As previously mentioned, the production of cement and subsequent reconstruction processes is deemed environmentally unfriendly, taking into account factors such as energy consumption, labor inputs, and the potential increase in CO_2 emissions. It is reported that, the global warming can be solve by reducing the 50% of OPC [45] [46].Moreover, there is a prevailing belief that geopolymers, as an alternative substitute for Ordinary Portland Cement (OPC), are more susceptible to cracking. This assertion can potentially influence experimental outcomes, resulting in reduced concrete strength. To address this, embedded microcapsules containing alkali-activators are introduced into the geopolymer concrete, fostering an environment conducive to Life Cycle Assessment (LCA) and facilitating self-healing mechanisms. The outcomes demonstrate that Self-Healing Geopolymer Concrete (SHGC) exhibits superior performance in mitigating global warming impacts. However, comparative analysis with OPC indicates that it may not be the most environmentally favorable option. This experiment unequivocally highlights the advantages of self-healing, particularly through the production of sodium silicate and enhancements in the chlor-alkali process [47].

3.2. Durability and longevity of self-healing concrete

Employing self-healing concrete can yield benefits; nevertheless, despite its potential to diminish maintenance and repair needs for structures, the cost implications pose a challenge for many construction projects. This technology has the capacity to enhance the durability of structures and augment the resistance of self-healing concrete to chloride ingress [46].

Mechanism of self-healing concrete can be different by choosing the different materials including cement, admixtures and types of bacteria which is mentioned in Table 1. By considering these factors, the improvement of the structure can be observed and it can makes reduction of the material consumption.

Table 1. Application of Bacteria in the constructions

S. No Bacteria	Bacteria	Concentration of Bacteria	Performance
1	Bacillus Subtilis	2.8 x 108 cells/ml	Improvement of compressive strength by 12%
2	Sporosarcina pasteurii	105 cells/ml	Compressive strength 34% more than the control concrete
3	Bacillus sp. CT-5	5 x 107 cells/ml	Improvement of compressive strength by 40% compared to control concrete
4	Akkrs	105 cells/ml	Improvement of compressive strength by 10% contrast to control concrete
5	Bacillus megaterium	30 x 105 cells/ml	Improvement of compressive strength by 24% contrast to control concrete
6	Bacillus aerius	105 cells/ml	Improvement of compressive strength by 11.8%
7	Shewanella species	105 cells/ml	Improvement of compressive strength by 25%

4. Discussion

4.1. Optimizing bacterial concentration and viability

One critical area for ongoing investigation in the realm of self-healing concrete is the fine-tuning of the bacterial concentration and their enduring viability. Although existing research has confirmed the effectiveness of bacterial-induced self-healing, the sustained survival of these bacteria under diverse environmental conditions still needs to be fully understood. Prospective studies should aim at bolstering the bacteria's resilience to withstand the harsh conditions prevalent in construction settings, such as fluctuating pH levels, extreme temperatures, and varying humidity levels. This research direction is essential for ensuring that the self-healing properties of concrete remain active and effective over the long term, thereby maximizing the material's durability and functional lifespan in real-world applications.

4.2. Advanced materials for encapsulation

Advancements in materials science for encapsulating healing agents, such as bacteria and their essential nutrients, represent a significant and promising field of research. Investigating bio-compatible materials that are both durable and permeable could lead to substantial improvements in the effectiveness of self-healing concrete. The goal would be to find materials that not only protect the bacteria and nutrients but also ensure their controlled release over time, enhancing the longevity and efficacy of the self-healing process. This research could pave the way for more efficient self-healing mechanisms in concrete, optimizing the material's ability to repair itself and extending its functional life in various construction applications.

4.3. Environmental impact assessment

Although self-healing concrete offers substantial sustainability advantages, a thorough understanding of its environmental impact requires comprehensive assessments, notably Life Cycle Assessments

(LCAs). Future research should focus on quantifying the environmental benefits of self-healing concrete, such as decreased carbon emissions and enhanced resource conservation, throughout its entire life span. This entails evaluating not only the immediate effects of reduced repair and maintenance needs but also the long-term implications for resource use and environmental sustainability. Such assessments will provide a holistic view of the ecological footprint of self-healing concrete, ensuring that its development and application align with broader environmental and sustainability goals.

5. Conclusions

To sum up, the evolution of construction materials throughout history has been marked by a continuous quest to enhance their quality and address emerging challenges. Concrete, a widely used material, presents inherent disadvantages, including susceptibility to cracks, microcracks, and deterioration over time and also producing green house while it is produced from the factory. The aging process of concrete often leads to issues such as water infiltration, corrosion of steel rebars, and structural degradation.

Addressing these challenges, the concept of self-healing concrete has emerged as a sustainable and innovative solution. The incorporation of self-healing agents, particularly microbial applications like Bacillus sp., facilitates the autonomous repair of cracks through the production of calcium carbonate. Despite the promising sustainability benefits of self-healing concrete, challenges and limitations persist, such as the efficacy of bacteria over the long term and cost considerations.

The sustainability benefits of self-healing concrete are substantial, contributing to the prolonged lifespan of structures, reduced maintenance requirements, and a decrease in carbon emissions. However, challenges related to the optimal concentration of bacteria and the associated costs require careful consideration. Practical applications and case studies have showcased the effectiveness of self-healing concrete in real-world scenarios, demonstrating its potential for reducing maintenance and enhancing durability.

Furthermore, incorporating Life Cycle Assessment (LCA) in the evaluation of self-healing concrete allows for a comprehensive understanding of its environmental impact throughout its life cycle. Comparative analysis with traditional materials like Ordinary Portland Cement (OPC) and the exploration of alternatives such as geopolymers provide insights into the environmental sustainability of self-healing concrete.

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7. Author Contribution Statement

Author 1 conducted an in-depth investigation and research for their term project. Author 2 served as the instructor, providing supervision and guidance throughout the project.

8. Ethics Committee Approval and Conflict of Interest

"There is no conflict of interest with any person/institution in the prepared article"

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