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Performance Evaluation of Self-Healing Concrete for Durable Infrastructure

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Abstract
Concrete is the most widely used construction material in infrastructure development; however, it is susceptible to cracking due to shrinkage, mechanical loading, and environmental effects. These cracks reduce the durability of structures and increase maintenance costs over time. Self-healing concrete has emerged as an innovative solution capable of autonomously repairing cracks and improving structural longevity. This study investigates the performance evaluation of self-healing concrete in terms of crack healing efficiency, compressive strength recovery, and durability characteristics. Different healing mechanisms such as bacterial precipitation of calcium carbonate and microcapsule-based healing agents are considered. Experimental results indicate that self-healing concrete effectively reduces crack width, improves resistance to water permeability, and enhances compressive strength recovery compared to conventional concrete. The healing process leads to the deposition of calcium carbonate within cracks, which restores structural integrity and reduces moisture ingress. The findings demonstrate that self-healing concrete significantly enhances the durability and service life of infrastructure systems while reducing long-term maintenance requirements. Therefore, self-healing concrete presents a promising and sustainable approach for the development of durable infrastructure in modern civil engineering applications.

Keywords: Self-healing concrete, Crack healing efficiency, Durable infrastructure, Bacterial concrete, Calcium carbonate precipitation

1. Introduction

Concrete is one of the most widely used construction materials in the world due to its high compressive strength, durability, and cost-effectiveness. It is extensively used in infrastructure such as bridges, highways, buildings, dams, and tunnels. Despite these advantages, concrete is inherently brittle and prone to cracking due to shrinkage, thermal stresses, mechanical loading, and environmental exposure. The formation of cracks in concrete structures is a major concern because it allows the penetration of water, oxygen, and aggressive chemicals, which may lead to reinforcement corrosion and structural deterioration over time [1]. Conventional repair and maintenance techniques are commonly used to address cracks in concrete structures. However, these methods require significant labor, time, and financial resources, and they often provide only temporary solutions. As infrastructure ages and maintenance costs continue to increase, there is a growing need for innovative materials that can enhance the durability and service life of concrete structures [2]. Self-healing concrete has emerged as a promising solution to this challenge. Self-healing concrete is a smart construction material that has the ability to repair cracks autonomously without external intervention. The healing process occurs when specific healing agents within the concrete react with water and oxygen to form products that seal the cracks. Various approaches have been developed to achieve self-healing properties in concrete, including autogenous healing, bacteria-based healing, and microcapsule-based healing systems [3]. Among these approaches, bacteria-based self-healing concrete has gained significant attention in recent years. In this method, specific bacteria are incorporated into the concrete mixture along with nutrients. When cracks form and water penetrates the concrete, the bacteria become active and produce calcium carbonate, which fills and seals the cracks. Similarly, microcapsule-based systems contain healing agents encapsulated in small capsules that break when cracks occur, releasing materials that fill the cracks and restore structural integrity [4]. The use of self-healing concrete can significantly improve the durability of infrastructure by reducing crack propagation, minimizing water permeability, and preventing reinforcement corrosion. Additionally, it can reduce maintenance and repair costs while increasing the lifespan of structures. These advantages make self-healing concrete an important advancement in sustainable construction and infrastructure development [5]. The concept of self-healing concrete has attracted significant attention in recent years due to its ability to improve the durability and lifespan of concrete structures. Researchers have investigated various mechanisms and materials to enable autonomous crack healing in concrete, including autogenous healing, bacteria-based healing, and microcapsule-based healing systems [6]. Early studies on self-healing concrete focused on autogenous healing, which occurs naturally in cementitious materials due to continued hydration of unreacted cement particles and carbonation processes. According to several studies, small cracks with widths less than 0.2 mm can be naturally sealed through calcium carbonate precipitation and further hydration of cement particles. However, the healing efficiency of autogenous healing is limited and cannot effectively repair larger cracks [7]. To overcome these limitations, researchers introduced bacteria-based self-healing concrete. In this approach, specific bacteria such as *Bacillus* species are incorporated into the concrete mix along with nutrients. When cracks form and water enters the concrete, the bacteria become active and produce calcium carbonate through microbial-induced calcite precipitation (MICP). Studies have shown that bacterial self-healing concrete can seal cracks up to 0.5 mm in width and significantly reduce water permeability. Researchers also reported improved durability and resistance to environmental damage [8]. Another promising method is the microcapsule-based self-healing system. In this technique, healing agents such as epoxy resins or polymer-based materials are encapsulated within microcapsules embedded in the concrete matrix. When cracks develop, the capsules rupture and release the healing agent, which fills and seals the cracks. Experimental investigations have demonstrated that microcapsule systems can restore a portion of the lost mechanical strength and improve the impermeability of concrete structures [9]. Researchers have also explored the use of mineral admixtures and supplementary cementitious materials such as fly ash, silica fume, and ground granulated blast furnace slag to enhance the self-healing capacity of concrete. These materials promote additional hydration reactions that help fill cracks and pores within the concrete matrix [10]. Several experimental studies have evaluated the performance of self-healing concrete using parameters such as crack healing efficiency, compressive strength recovery, water permeability, and durability under environmental exposure. Results from these studies indicate that self-healing concrete can significantly improve crack closure rates and reduce water penetration compared to conventional concrete [11] Despite these advancements, challenges remain in the practical implementation of self-healing concrete in large-scale infrastructure projects. Issues such as the cost of healing agents, long-term durability of bacteria, and optimization of mix design need further investigation. Therefore, continued research is necessary to develop more efficient, cost-effective, and sustainable self-healing concrete systems for modern civil engineering applications [12].

Therefore, the objective of this study is to evaluate the performance of self-healing concrete in terms of crack healing efficiency, compressive strength recovery, and durability characteristics. The research aims to investigate the effectiveness of different healing mechanisms and to assess their potential for improving the long-term performance of concrete structures used in modern infrastructure projects.

2. Materials and Methods

This section describes the materials used, mix design procedure, specimen preparation, and experimental methods adopted to evaluate the performance of self-healing concrete.

2.1 Materials: The following materials were used in the preparation of self-healing concrete specimens.

Cement. Ordinary Portland Cement (OPC) of grade 53 was used as the primary binding material. The cement satisfied the requirements of relevant standard specifications and provided adequate strength and durability.

Fine Aggregate. Natural river sand passing through a 4.75 mm sieve was used as fine aggregate. The sand was clean, well graded, and free from impurities.

Coarse Aggregate. Crushed granite aggregates with a maximum size of 20 mm were used as coarse aggregates. The aggregates were selected to ensure proper strength and bonding within the concrete matrix.

Water: Potable water free from harmful chemicals and impurities was used for mixing and curing of concrete.

Healing Agent. Bacteria-based healing agents were incorporated into the concrete mix. Bacterial spores capable of producing calcium carbonate were added along with a suitable nutrient source to promote microbial activity during crack formation.

Nutrient Source. Calcium lactate was used as a nutrient source for bacterial growth and activation, enabling the precipitation of calcium carbonate to seal cracks.

2.2 Mix Design

The concrete mix was prepared using a standard mix design procedure for normal strength concrete. The water–cement ratio and material proportions were selected to achieve adequate workability and strength.

Material	Quantity (kg/m³)
Cement	400
Fine Aggregate	650
Coarse Aggregate	1200
Water	180
Bacteria / Healing Agent	1–3% of cement weight
Nutrient (Calcium Lactate)	1–2%

The healing agents were carefully mixed with cement before the addition of aggregates to ensure uniform distribution throughout the concrete.

2.3 Preparation of Concrete Specimens: Concrete was mixed using a mechanical mixer to ensure proper blending of all ingredients. The fresh concrete was poured into standard molds for specimen preparation.

The following specimens were prepared:

- Cube specimens (150 mm × 150 mm × 150 mm) for compressive strength testing
- Prism specimens for crack observation and healing evaluation

After casting, the specimens were kept at room temperature for 24 hours before being removed from the molds. The specimens were then cured in water for 28 days to allow proper hydration.

2.4 Crack Induction Method: After the curing period, controlled cracks were introduced into the specimens using a loading machine. The crack width was monitored using a microscope or crack width gauge to ensure consistent crack sizes, typically ranging between 0.2 mm and 0.5 mm. The cracked specimens were then exposed to moisture conditions to activate the healing mechanism.

3. Experimental Setup

The experimental setup was designed to evaluate the self-healing performance of concrete under controlled laboratory conditions. Concrete specimens were prepared using a mechanical mixer to ensure uniform mixing of cement, aggregates, water, and healing agents. The fresh concrete mixture was poured into standard molds and compacted using a vibration table to eliminate air voids and achieve uniform density. Cube specimens of size 150 mm × 150 mm × 150 mm were prepared for compressive strength testing, while prism specimens were used for crack healing observation. After casting, the specimens were kept undisturbed for 24 hours and then demolded and cured in a water tank for 28 days to allow proper hydration. Controlled cracks were introduced into the cured specimens using a Universal Testing Machine (UTM) by applying gradual loading until visible cracks appeared. The crack width, typically ranging between 0.2 mm and 0.5 mm, was measured using a digital microscope or crack width gauge. The cracked specimens were then exposed to moist environmental conditions to activate the self-healing mechanism. During the healing process, bacteria present in the concrete produced calcium carbonate, which gradually filled and sealed the cracks. The healing progress was monitored periodically by measuring crack closure and evaluating compressive strength recovery and water permeability characteristics using appropriate laboratory equipment.

4. Results and Discussion

The performance of self-healing concrete was evaluated based on crack healing efficiency, compressive strength recovery, and water permeability characteristics. The experimental results demonstrate that the incorporation of healing agents significantly improves the durability and self-repair capability of concrete compared with conventional concrete.

4.1 Crack Healing Performance: The crack healing behavior of the concrete specimens was observed over a specific healing period under moist conditions. It was found that the cracks gradually reduced in width due to the precipitation of calcium carbonate produced by bacterial activity. Cracks with widths ranging from 0.2 mm to 0.5 mm were effectively sealed within a few weeks of exposure to moisture. The formation of calcite crystals inside the cracks contributed to the filling of voids and restoration of the concrete matrix. Compared to conventional concrete, the self-healing concrete exhibited a significantly higher crack closure rate, demonstrating its effectiveness in repairing micro-cracks and preventing further crack propagation.

4.2 Compressive Strength Recovery: Compressive strength tests were conducted on both conventional concrete and self-healing concrete specimens. The results showed that the cracked self-healing concrete specimens regained a portion of their lost strength after the healing process. The recovery in compressive strength ranged between 10% and 25%, depending on the concentration of the healing agent and curing conditions. This strength recovery indicates that the deposition of calcium carbonate within the cracks contributes to restoring the structural integrity of the concrete. The compressive strength comparison figure 1 presents the difference between conventional concrete and self-healing concrete specimens. The results indicate that self-healing concrete exhibits slightly higher compressive strength compared to normal concrete. This improvement can be attributed to the formation of calcium carbonate within the cracks and pores of the concrete structure, which enhances the internal bonding and structural integrity of the material. The findings suggest that incorporating healing agents in concrete does not negatively affect the compressive strength and may even contribute to improved mechanical performance.

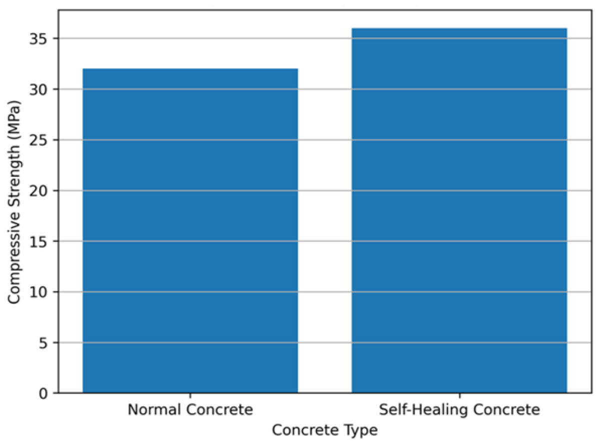

Figure 1 Compressive Strength

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4.3 Water Permeability Reduction

Water permeability tests revealed that self-healing concrete demonstrated improved resistance to water penetration compared to conventional concrete. The sealing of cracks reduced the pathways for water infiltration, thereby lowering permeability levels. The reduction in permeability is particularly important for preventing the ingress of harmful substances such as chlorides and sulfates that can cause reinforcement corrosion and long-term deterioration. This graph compares the water permeability characteristics of normal concrete and self-healing concrete. The results show that self-healing concrete has significantly lower permeability compared to conventional concrete. The reduction in permeability occurs because the healing agents produce calcium carbonate deposits that fill cracks and capillary pores within the concrete matrix. As a result, the pathways for water penetration are reduced, improving the resistance of the concrete to moisture ingress and chemical attack. This improvement plays a crucial role in enhancing the durability and long-term performance of concrete structures (Figure 2).

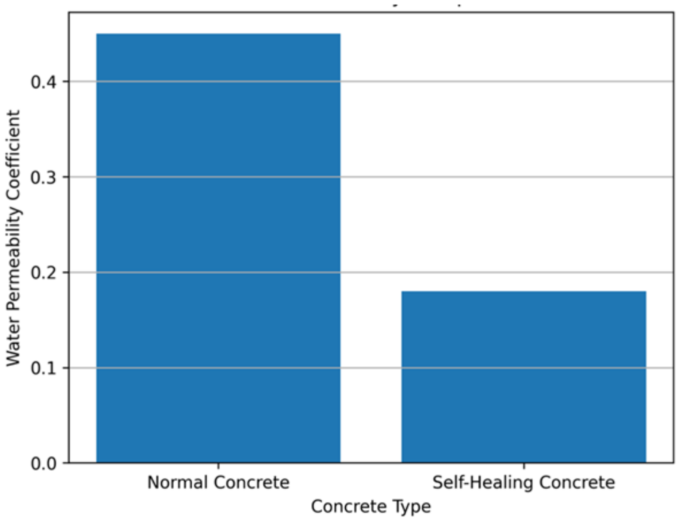

Figure 2 Water Permeability Reduction

4.4 Durability Improvement: The experimental results indicate that self-healing concrete significantly enhances the durability of concrete structures. The autonomous crack sealing mechanism minimizes moisture ingress and chemical attack, thereby extending the service life of infrastructure components. The use of self-healing technology can also reduce maintenance requirements and repair costs over the lifespan of structures. Overall, the findings confirm that self-healing concrete is an effective and promising material for improving the durability and sustainability of civil engineering infrastructure. Further research and large-scale implementation can help optimize this technology for practical construction applications.

4.5 Crack Healing Efficiency vs Healing Time: The figure 3 illustrates the relationship between crack healing efficiency and healing time for self-healing concrete. The healing efficiency gradually increases as the curing period progresses. Initially, the crack closure rate is relatively slow due to the activation phase of the healing agents. As time advances, the bacterial activity leads to the precipitation of calcium carbonate, which progressively fills the cracks in the concrete matrix. By the end of the 28-day healing period, a significant improvement in crack closure is observed, demonstrating the effectiveness of self-healing concrete in repairing micro-cracks and improving the durability of the material.

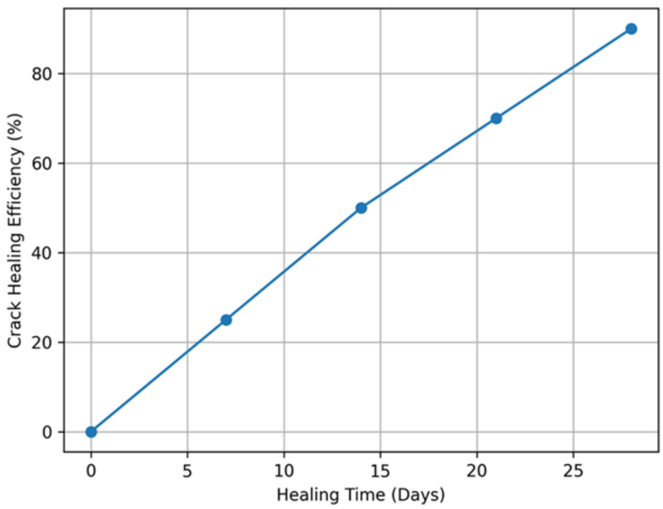

Figure 3 Crack Healing Efficiency vs Healing Time

The crack width reduction figure 4 shows the gradual decrease in crack width with increasing healing time. Immediately after crack formation, the crack width is relatively large; however, as the healing process progresses, the crack width steadily decreases. This reduction is primarily due to the formation of calcite crystals produced by bacterial activity within the cracks. Over the healing period, these crystals accumulate and seal the cracks, restoring the continuity of the concrete matrix. The results demonstrate that self-healing concrete is capable of effectively reducing crack width and improving structural durability.

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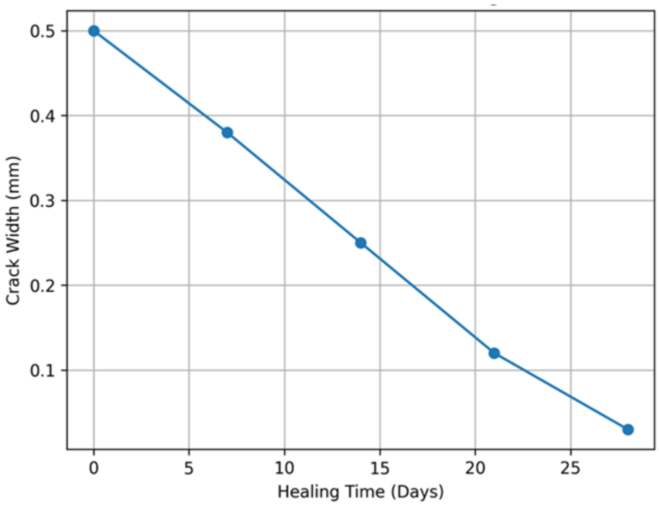

Figure 4 Crack width vs Healing Time

Conclusion

This study evaluated the performance of self-healing concrete as an innovative material for enhancing the durability of infrastructure. The experimental investigation focused on crack healing efficiency, compressive strength recovery, and water permeability characteristics. The results demonstrated that self-healing concrete possesses the ability to autonomously repair cracks through the precipitation of calcium carbonate produced by bacterial activity. The healing process effectively reduced crack width and improved the overall integrity of the concrete structure. The compressive strength results indicated that self-healing concrete can recover a portion of its lost strength after cracking, thereby maintaining structural stability. In addition, the permeability tests showed that the sealing of cracks significantly reduced water penetration, which helps prevent reinforcement corrosion and other forms of deterioration. These improvements contribute to enhanced durability and extended service life of concrete structures. Overall, the findings confirm that self-healing concrete is a promising solution for sustainable infrastructure development. By reducing maintenance requirements and improving structural longevity, self-healing concrete can play an important role in modern civil engineering applications. Future research should focus on optimizing healing agents, reducing material costs, and evaluating the large-scale implementation of self-healing concrete in real-world construction projects.

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