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Advancing Sustainable Construction: A Critical Analysis of Microbial Concrete and its Self-Healing Mechanisms

Sandeep Singh[1], Sougata Chattopadhyay[2]

[1]Research Scholar, Department of Civil Engineering, Faculty of Engineering Technology and Computing, Desh Bhagat University, Mandi Gobindgarh, Punjab-147301, India
[2]Assistant Professor, Department of Civil Engineering, Faculty of Engineering Technology and Computing, Desh Bhagat University, Mandi Gobindgarh, Punjab-147301, India

ABSTRACT

This paper reviews critically and analyses the advancements in microbial concrete as a sustainable construction material. It explores the integration of microbial processes into concrete technology. The study highlights the theoretical foundations and implications of these processes for material science. Advanced techniques such as Scanning Electron Microscopy, X-ray Diffraction, and Thermogravimetric Analysis are used to characterize microbial concrete. These techniques provide significant insights into its microstructural behaviour and chemical composition. The findings demonstrate its potential to redefine material performance standards. A key innovation of microbial concrete is its self-healing mechanism. This mechanism relies on bacterial activity, where ureolysis facilitates calcium carbonate precipitation. This process effectively seals microcracks in the concrete. It represents a theoretical leap in addressing material degradation. As a result, it extends the lifespan of concrete structures. The economic analysis reveals a tension between initial costs and long-term benefits, raising questions about its feasibility for large-scale applications. Additionally, gaps exist in understanding how microbial agents interact with concrete matrices under varying environmental conditions, highlighting the need for a refined analytical framework. The study contributes to the narrative of resilient construction materials by situating microbial concrete within broader sustainability discussions. It argues for a rigorous interdisciplinary approach in future research. This includes optimizing healing mechanisms and assessing durability in diverse climatic scenarios. The study positions microbial concrete as an innovative material with significant theoretical and practical implications for sustainable construction technology.

Keywords: Microbial Concrete, Self-Healing Mechanisms, Mechanical Properties, Material Characterization, Sustainable Construction.

INTRODUCTION

The demand for infrastructure services and amenities tends to increase as the population grows. Additionally, the general public expects infrastructure services to be permanent. However, there was significant deterioration in the structures constructed in the latter half of the previous century. Buildings that are deteriorating require maintenance at an early stage, which accounts for about half of the capital investment.

Numerous academics are figuring out the best way to build structures with very little or no upkeep costs. Extending the lifespan of infrastructure facilities will undoubtedly minimize the demand for new construction, which will lower the consumption of raw materials and, ultimately, the amount of carbon dioxide released into the atmosphere.

Concrete is second only to water in terms of global use, making it the most used artificial construction material on the globe. Significant infrastructure development has taken place both domestically and internationally, and producing concrete with higher strengths to meet demand has been essential. This composite material, which is widely utilized in the construction industry, has exceptional mechanical and physical qualities. The most widely used building material worldwide is concrete, which is a fundamental substance [1].

It comes with a range of characteristics and attributes. It is an affordable product made of recyclable and long-lasting materials. It is the most widely utilized composite material in building worldwide due to its economy, sustainability, and versatility. For the intended compressive strength and outstanding durability over the structures' service life, it is typically chosen. The characteristics of the two constituent phases and the presence of their interfaces affect the properties of concrete. Additionally, it is a composite material composed of coarse aggregates joined by fluid mortar that solidifies with time.

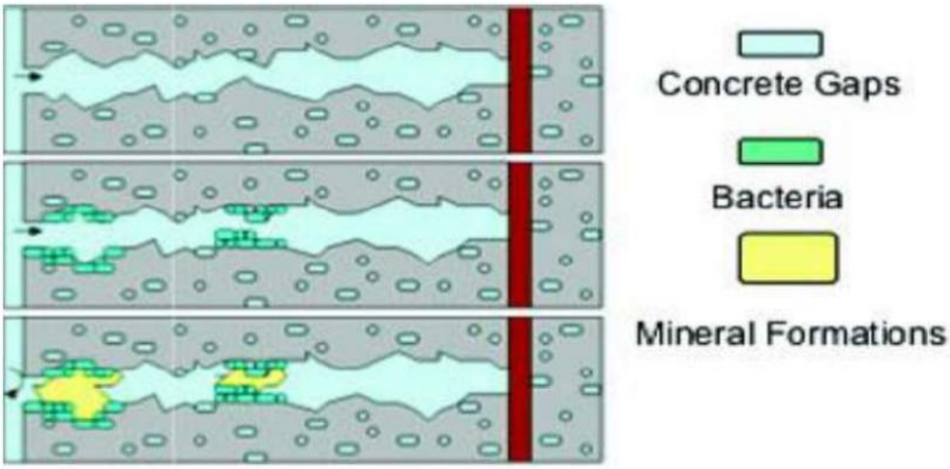

Figure 1: Self-Healing Process [2]

Effect Of Bacterialconcrete

The development of self-healing concrete based on microorganisms was extensively studied, as reported by Jonkers and Schlangen (2008) [3]. They created a novel kind of self-healing concrete that improved the corrosion resistance of the steel reinforcement that was implanted and reduced the permeability of the concrete by using bacteria to aid in the formation of minerals. As self-healing agents, spore-forming alkaliphilic bacteria and organic mineral precursor chemicals can combine to generate calcite particles as small as 100 microns, which can be utilized to fix both big and small fractures.

Bacillus sphaericus, which converted urea into ammonium and carbonate in its surroundings, showed $CaCO_3$ precipitation in the microenvironment Van Tittelboom (2010) [4] studied the application of a technology for healing injured biological tissue. When urea is broken down by bacteria in an area with a higher pH than the surrounding environment, carbonate deposition—a calcium salt—occurs. It may be possible to use $CaCO_3$-precipitating microbes to repair cracks.

Jonkers et al. (2010) [5] looked into the potential of bacteria to act as a self-healing agent in concrete, meaning that they can repair cracks that have already formed. Bacterial spores remained viable for up to four months after being directly introduced into the cement paste mixture. Since pore widths decreased below 1mm, the typical size of Bacillus spores, during cement stone setting, Bacillus spores are known to have a short lifespan because of a continuous decrease in pore size diameter. Bacterial spores in a cement stone were demonstrated to be able to change concurrently absorbed calcium lactate-based minerals into calcium carbonate-based minerals when activated by crack ingress water.

Feng et al. (2023) [6] proposed an environmentally acceptable way to functionalize carbon nanofibers so they may be readily incorporated into cementitious materials by employing tannic acid (TA), a plant-based biomolecule. In contrast to the current chemicals used to functionalize carbon nanofibers, tannic acid is non-toxic and renewable. Tannic acid can be effectively applied to the surfaces of carbon nanofibers, stabilizing them in the water-based solution, according to experimental research.

Cavalieri et al. (2023) [7] examined a few noteworthy case studies and examples, beginning with contemporary self-healing systems. One of the less harmful techniques for repairing cracks is microbially induced calcium carbonate precipitation (MICP). Innovative methods that not only increase concrete's durability but also seek to lower carbon emissions have been made possible by the building industry's push towards sustainability. Both these elements of self-repair and carbon reduction are especially targeted by a number of self-healing concrete systems.

Kaushal and Saeed thoroughly (2024) [8] examine the literature and available case studies in order to investigate these technologies and their uses in the construction sector. According to the study's findings, concrete has seen some encouraging developments, especially when it comes to enhancing its autogenous healing capabilities. Future study is advised to look into additional strategies for achieving net-zero carbon emissions in the cement manufacturing and concrete industries.

Panza et al. (2023) [9] proposed an approach that can help the building industry choose its product and material selections from the very beginning of design. Given its impact on the necessary maintenance activities (and associated investments) and the achievable residual value, the material service life is emphasized as a critical consideration in guiding investment decisions. The results provide comprehensive proof of the potential advantages of using self-healing materials in construction, including lower maintenance costs, longer building and structure lifespans and associated residual values, and subsequently less environmental impact.

Self-Healing Of Cracks Using Bacteria

The self-healing impact of fly ash as a mineral ingredient in self-consolidating concrete was studied by Sahmaran et al. (2008) [10]. With a constant water binder ratio of 0.35, the fly ash replacement ratios used in this study were 35% and 55%. Preloading the specimens by 70% and 90% of their ultimate compressive strength caused microcracks. The compressive strength, UPVT, fast chloride permeability, and sorptivity tests were used to assess the degree of damage and the effectiveness of self-healing.

According to Blaiszik et al. (2010) [11] there are three distinct systems—the capsule-based healing system, the vascular healing system, and the intrinsic healing system—can accomplish the self-healing mechanism. After cracks have healed in a single damage event, the capsule-based healing system seizes. Although vascular healing may repair fissures caused by numerous damage events, it can be challenging to integrate with the current material system. Simple intrinsic healing systems repair the fissures created by minor harm incidents.

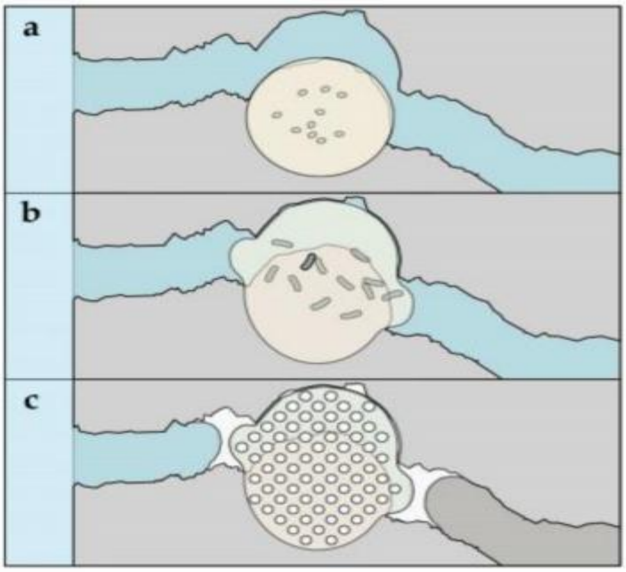

Figure 2: Schematic diagram illustrating the healing mechanism: (a) in the event of cracking and water ingress; (b) the bacteria-based beads incorporated in the composite will swell (c) the magnesium will precipitate as magnesium-based minerals [12].

The impact of fly ash and blast furnace slag on the capacity of concrete structures to cure cracks has been investigated by Tittelboom et al. (2011) [13]. Because blast furnace slag and fly ash reacted slowly to form hydration products and because the hydration reaction took too long, the majority of the slag and fly ash particles contributed to hydration by forming a dense matrix, this caused them to be considered good self-healing agents. Isothermal calorimetry was used to measure the heat produced by the hydration reaction. The response of unhydrated particles exposed to moisture would result in a greater amount of heat being produced.

Huang and Guang (2013) [14] looked into how calcium hydroxide solution worked as an activator to help silica mend cracks on its own. Thermogravimetric analysis, environmental energy dispersive spectroscopy, and Fourier transform infrared spectroscopy were used to characterize the medicinal compounds. Air permeability and ultrasonic pulse velocity measurements were used to evaluate the self-healing efficiency as a function of time. The existence of gel-like healing materials was revealed by the sliced samples' morphology and Energy Dispersive X-ray Spectroscopy examination.

Self-repairable concrete of M30 grade (IS 10262: (2019) was used to create the specimens by Prabahar et al. (2017) [15]. They used 0-6% sodium silicate capsules by weight of cement. After 28 days of recuring, the cube specimens' cracks are repaired. The compressive strength remained unchanged as a result of the capsules. Because the cracks are filled, the reinforcement bars are shielded from corrosion, allowing the concrete to last a very long time. According to Praveen kumar and Vijayalakshmi (2019) [16], rice husk ash and nanosilica were the most effective nanoparticles due to their pozzolanic nature and increased strength over time. It functions as a superior binding agent because of its nanostructure and increased surface area to volume ratio. The interfacial transition zone is strengthened as a result of silica's nanosize filling the cement matrix's pore system.

An equation based on the mechanical strengths of virgin concrete and self-healed concrete following pre-cracking was used by Chindasiriphan et al. (2020) [17] to calculate the self-healing efficiency. Calcium silicate hydrate production is responsible for the crisp products that appear in scanning electron microscopy images.

CONCLUSION

In the concrete commercial, cracking is a frequent source of complaints. At any point in a structure's life, cracks may appear. Concrete constructions may become less durable and less aesthetically pleasing if they have cracks. In addition to cracks, concrete's porous matrix may also be problematic. In the event that the pores form a network, harmful materials may seep into the concrete and cause both the reinforced steel and the concrete to physically or chemically deteriorate. One of the main causes of both material and structural failures in plain and reinforced concrete constructions is fatigue.It has been discovered that adding trash and wastewater to concrete causes pores and cracks, which reduces the material's qualities. One of the worst factors affecting the longevity of concrete is cracking. Because they offer a preferred route for the entrance of hostile substances, cracks encourage a number of harmful mechanisms that compromise the strength and longevity of concrete buildings. Concrete cracks may hasten the rate of reinforcing corrosion and chemical deterioration, which compromises the longevity of infrastructures. Concrete, regrettably, may sustain damage from a variety of sources. A frequent occurrence in concrete structures is the production of fractures, which let water and other chemicals seep into the material and reduce its strength and longevity. When exposed to water, CO_2, and other harmful substances, its reinforcements are also impacted. Concrete requires frequent maintenance and repair methods, which are highly costly, to fix the cracks that have formed in it. This problem might be lessened if concrete were to acquire the capacity for self-healing.

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