



Experimental Study on Self-Healing Concrete Blended with Metakaolin & Glass Fibers

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ABSTRACT :

The self-healing process in concrete represents a progressive approach to enhancing structural durability and extending service life by enabling cracks to seal autonomously without external repair. This mechanism effectively restricts the ingress of water, chlorides and other deleterious agents responsible for corrosion and long-term degradation. By facilitating early crack closure the material's durability and sustainability are greatly improved while minimizing maintenance costs and resource consumption. The present experimental study investigates the self-healing potential of concrete incorporating *Bacillus subtilis* bacteria in combination with 20% metakaolin and 1.5% alkali-resistant glass fibers. The bacterial system with a concentration of 10^7 CFU/mL is activated through calcium lactate as a nutrient source promoting microbial-induced calcium carbonate precipitation (MICP). Metakaolin serves as a supplementary cementitious material to enhance pozzolanic reactivity and matrix densification whereas glass fibers limit microcrack propagation and improve tensile strength. Concrete specimens are cast, cured and subsequently induced with microcracks to evaluate autonomous healing under moist conditions. The efficiency of self-healing is assessed through crack closure observation, recovery of mechanical strength, permeability reduction and improvement in durability parameters after a 28-day healing period. The results demonstrate that the integration of bacterial agents with metakaolin and glass fibers produces a synergistic effect leading to notable improvements in mechanical performance and self-healing efficiency. This approach presents a sustainable and environmentally responsible solution for durable concrete structures with reduced maintenance requirements.

ARTICLE INFO: Bio-mineralization, Metakaolin, Glass fibers, *Bacillus subtilis*, Mechanical & Durability properties enhancement, Autonomic healing.

INTRODUCTION

Concrete as a fundamental material in modern construction is susceptible to cracking due to shrinkage, thermal variations, and applied mechanical stresses. Even minor cracks can compromise durability and structural integrity, increasing maintenance demands and reducing the service life of structures [1]. To address these challenges, self-healing concrete (SHC) has emerged as an innovative approach that enables autonomous crack repair, thereby improving structural longevity and sustainability. Among various SHC strategies, microbial-based healing has garnered significant attention. Certain bacteria, particularly *Bacillus* species, can precipitate calcium carbonate within cracks, effectively sealing them and restoring mechanical performance [3,6,7,9]. In addition, the use of supplementary cementitious materials such as metakaolin has been shown to enhance the matrix density, reduce porosity, and improve the efficacy of microbial bio-mineralization, leading to superior crack closure and mechanical performance [2,5]. Similarly, the inclusion of glass fibers has been found to restrict crack propagation, provide bridging across microcracks, and synergistically improve self-healing efficiency when combined with microbial or mineral admixtures [4,10].

Comprehensive reviews of SHC technologies have provided a classification framework, assessed their technology readiness levels, and highlighted suitable application scenarios [1]. Despite substantial progress, optimizing the combination of microbial activity, material additives such as metakaolin and fibers, and structural design remains critical for practical implementation. This study aims to investigate recent developments in microbial-based self-healing concrete and the influence of supplementary materials including metakaolin and glass fibers on its performance. By integrating experimental insights and literature findings, we provide a detailed perspective on SHC's potential to support sustainable and resilient infrastructure.

MATERIAL DATA

Cement: Ordinary Portland Cement (OPC 53 grade) was used as the primary binder for all concrete mixes. It provides the necessary hydraulic properties for hydration, setting and hardening, forming the structural backbone of the concrete matrix.

Metakaolin : Metakaolin, a high-reactivity pozzolanic material, was incorporated as a supplementary cementitious material replacing 20% of the cement by weight. Its addition enhances pozzolanic reactivity, reduces porosity and densifies the concrete matrix, thereby improving mechanical performance and promoting crack self-healing when combined with microbial agents.

Alkali-Resistant Glass Fibers: Glass fibers were added at 1.5% by volume to improve tensile strength and toughness. These fibers act as crack-bridging elements, restricting the propagation of microcracks and enhancing the overall durability and structural integrity of the concrete.

Bacillus subtilis Bacteria: The microbial agent used for self-healing consisted of *Bacillus subtilis* at a concentration of 10^7 CFU/mL. These bacteria facilitate microbial-induced calcium carbonate precipitation (MICP) within cracks, sealing them autonomously and restoring mechanical strength.

Calcium Lactate: Calcium lactate served as the nutrient source for the bacteria, activating their metabolic activity to promote the precipitation of calcium carbonate inside microcracks.

Aggregates: Standard fine and coarse aggregates were used as per (IS383-2016) to provide structural bulk and maintain dimensional stability of the concrete. Proper grading ensured uniform distribution and workability of the mix. Aggregate properties are determined as per IS 2386-1963. Both the fine and coarse aggregates are collected from the locally available crushers.

Water: Potable water was used both for concrete mixing and curing. It is essential for cement hydration and activation of the microbial self-healing system based on (IS 456: 2000)

Admixtures: sulfonated melamine formaldehyde (SMF) Superplasticizer was added to maintain workability and ensure proper dispersion of fibers and bacteria throughout the mix.

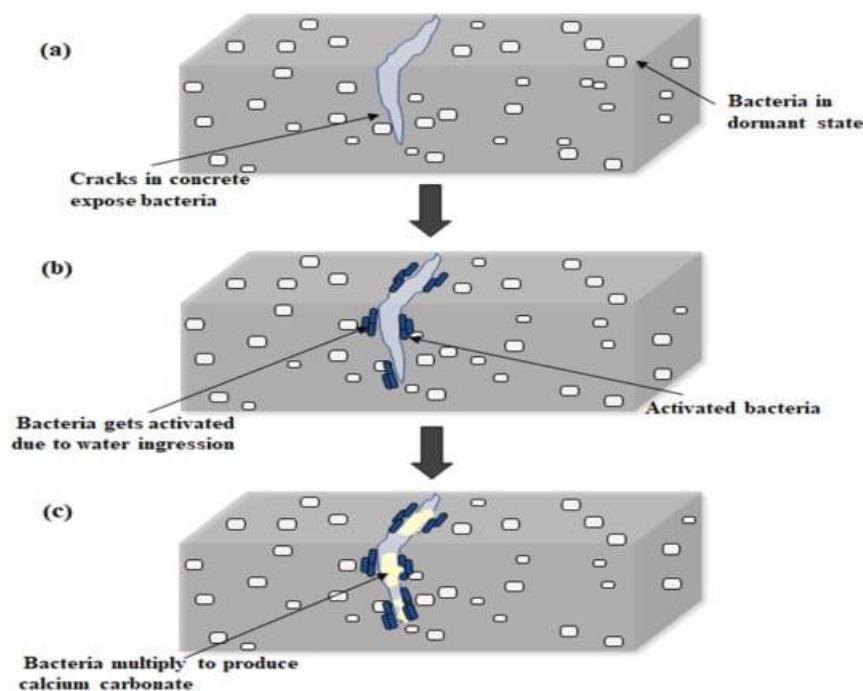
METHODOLOGY

Mix proportions

The mix was designed concrete by following IS 10262-2019 guidelines for GFRC, with trial mixes conducted to achieve the required strength and workability as per EFNARC standards. The final mix included 80% Ordinary Portland Cement (OPC-53 Grade) and 20% metakaolin (MK) as a partial replacement by weight of cement. Metakaolin, a highly reactive pozzolanic material obtained by calcination of kaolinite clay at 650–800°C, reacts with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H) gel, thereby enhancing compressive, flexural, and split tensile strength. Its chemical composition consists primarily of silica (SiO_2 : ~50–55%) and alumina (Al_2O_3 : ~35–40%), with minor oxides of Fe_2O_3 , TiO_2 , and alkali metals, providing higher reactivity compared to conventional supplementary cementitious material

Alkali-resistant glass fibers were incorporated at 1.5% by weight of cementitious materials in the form of short chopped strands (~12 mm length). These fibers restrict microcrack propagation, control plastic shrinkage cracks, and improve tensile, flexural, and impact resistance. for biological self-healing, *Bacillus subtilis* spores were added to the mixing water at a concentration of 10^7 CFU/mL. Calcium lactate was added as a nutrient source to facilitate microbial-induced calcium carbonate precipitation (MICP), sealing microcracks autonomous

Mechanism of Autonomous healing.(Extrinsic Healing)



The self-healing mechanism in concrete using bacteria and calcium lactate works through microbial-induced calcium carbonate precipitation (MICCP). Bacterial spores, typically from *Bacillus subtilis*, are added to the concrete mix along with calcium lactate, which serves as a nutrient. The spores remain dormant inside the concrete until cracks appear and moisture enters. When exposed to water, the spores activate and consume calcium lactate and oxygen.

This process leads to the formation of calcium carbonate crystals that fill the cracks. These crystals act like a natural adhesive, sealing the cracks, restoring the concrete's structure, and reducing its permeability. This microbial process is sustainable and helps extend the concrete's lifespan. However, it is important to maintain the right balance of bacteria and calcium lactate, as too much of either can reduce bacterial activity and healing efficiency. Overall, this method provides an effective, eco-friendly way to repair cracks within concrete autonomously and improve durability.

Tests conducted

Concrete specimens were cast in different standard sizes to evaluate mechanical and self-healing properties. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were used for split tensile tests, while cubes measuring 150 mm × 150 mm × 150 mm and beams measuring 100 mm × 100 mm × 500 mm were prepared for compressive and flexural strength assessments respectively, following Indian standards. For the split tensile, compression, flexural tests 28-day cured cylindrical specimens were subjected to load until the first crack appeared. The width of the initial crack was measured for cube tested under compression testing machine and beams tested under flexural testing machine and the specimens were returned to curing for an additional 28 days to evaluate autonomous healing. This procedure allowed the assessment of self-healing efficiency along with the recovery of mechanical properties.



Compressive Strength



Split Tensile Strength



Flexural Strength

Ultrasonic Pulse Velocity(UPV) Test:

The UPV test was conducted to evaluate the quality, uniformity, and integrity of the concrete matrix. Cylindrical specimens (150 mm diameter × 300 mm height) and cube specimens (150 mm × 150 mm × 150 mm) were used following IS 516:1959 – “Methods of Tests for Strength of Concrete” and IS 13311 (Part 1):1992 – “Non-destructive testing of concrete – Ultrasonic pulse velocity”. A portable UPV instrument with paired transducers was employed, with the transducers placed on opposite faces of the specimen. The pulse was propagated through the concrete, and the transit time was recorded. Higher UPV values indicate a denser, more homogeneous concrete matrix and reflect improved microstructural integrity, which can be correlated with crack closure and self-healing efficiency. Measurements were taken at 28 days and after a 28-day healing period to assess improvements in concrete quality due to microbial healing, metakaolin incorporation, and glass fibers.

Sorptivity Test:

Sorptivity tests were performed to evaluate the permeability and durability characteristics of the concrete. Cube specimens (150 mm × 150 mm × 150 mm) were dried to a constant weight and then partially immersed in water, following IS 3085:1965 – “Specification for test for water absorption of concrete”. The increase in mass due to water absorption was recorded at regular intervals, and sorptivity was calculated as the slope of cumulative water uptake versus the square root of time curve. Lower sorptivity values indicate reduced water ingress, enhanced microstructure and effective crack sealing, reflecting the contribution of bacterial activity, metakaolin, and glass fibers in improving durability.

Results and discussions

Compressive Strength

Compressive strength is a fundamental property indicating concrete's ability to withstand axial loads without failure. In the developed Glass Fiber Reinforced Concrete (GFRC) mix, compressive strength is primarily enhanced by replacing 20% of Ordinary Portland Cement (OPC-53 Grade) with metakaolin (MK). Metakaolin is a highly reactive pozzolanic material produced by calcining kaolinite clay at temperatures between 650–800°C. It reacts with calcium hydroxide—produced during cement hydration—to form additional calcium silicate hydrate (C-S-H) gel, which densifies the concrete

matrix and improves its mechanical properties. The chemical composition of metakaolin, mainly silica (~50–55%) and alumina (~35–40%), provides higher reactivity than ordinary supplementary cementitious materials, contributing to significant strength gains in the concrete.

The impact of alkali-resistant glass fibers, incorporated at 1.5% by weight of cementitious material in short chopped strands (~12 mm), on compressive strength is limited but beneficial. These fibers help control plastic shrinkage cracks and microcrack propagation, indirectly supporting the concrete's load-bearing capacity after cracking for testing 150 mm cube specimens were cast according to IS 10262–2019 mix design guidelines and cured in water for 28 days following IS 516 standards. The specimens were subjected to compressive loading until initial cracks occurred. Crack widths were measured, and then the cubes were re-cured for an additional 28 days to evaluate self-healing effects induced by *Bacillus subtilis* spores (10^7 CFU/mL) and calcium lactate as a nutrient source. This process allowed assessment not only of strength development but also of the autonomous healing potential of the blended GFRC at 0.2% bacterial growth, the compressive strength showed a consistent increase compared to the control mix without bacteria and nutrients. The microbial activity facilitated crack sealing and matrix refinement, resulting in enhanced load-bearing capacity. However, beyond this dosage strength declined slightly. Excessive calcium lactate may interfere with cement hydration or create an imbalance for microbial activity there by reducing the formation of beneficial calcium carbonate deposits. Similarly, overdosing *Bacillus subtilis* spores could adversely affect the microbial viability due to overcrowding and nutrient depletion, lowering overall effectiveness and strength.

Flexural Strength:

Flexural strength represents the concrete's resistance to bending forces and the ability to withstand tensile stresses that cause cracking. Glass fibers play a major role in enhancing flexural performance by bridging cracks once they form, enabling the concrete to carry load even after cracking. This crack-bridging effect improves post-cracking ductility, toughness, and energy absorption. Metakaolin contributes indirectly by improving the bond between the fibers and the cement matrix, enhancing stiffness and load transfer efficiency.

in this research flexural strength followed a similar trend with improvements noted at bacterial levels up to 0.2%. The combination of glass fibers and optimal microbial healing produced better crack bridging and post-cracking load capacity. The biological self-healing led to enhanced ductility and toughness. However increasing calcium lactate or bacterial concentration beyond the optimum reduced flexural strength likely because overnutrition or microbial cell death disrupts the delicate bio-chemical balance necessary for effective crack sealing, weakening the fiber-matrix interface.

Split Tensile Strength

Split tensile strength measures concrete's resistance to tensile stresses that cause cracking perpendicular to the applied load. It is a critical property for structural elements subjected to tension. The presence of glass fibers significantly improves tensile strength by arresting microcrack propagation and controlling crack growth. Metakaolin enhances the bond between the fibers and the cement matrix, leading to better load transfer and increased resistance to crack initiation and growth along with this strength increased at controlled dosages of calcium lactate and *Bacillus subtilis* spores showing improved resistance to tension-induced cracks due to effective microcrack sealing. Yet exceeding the 0.2% calcium lactate threshold or bacterial overdosing led to diminished strength. Excess calcium lactate may form excessive precipitates that block pores reducing matrix permeability and weakening fibers bonding effectiveness. Overuse of bacteria can cause cell death or metabolic exhaustion, limiting their self-healing capability and thus reducing tensile performance.

Overall, the results confirm that both calcium lactate and *Bacillus subtilis* spores require careful proportioning. Moderate dosages (up to 0.2%) enhance the mechanical properties of blended GFRC due to synergistic effects of microbial healing and pozzolanic action of metakaolin. Overdosing either component can have detrimental effects, reducing strengths due to biological inhibition or unfavorable chemical conditions. Therefore, maintaining bacterial viability and nutrient balance is critical for optimizing self-healing efficiency and the mechanical performance of bio-enhanced GFRC.

Ultrasonic Pulse Velocity (UPV):

UPV measures the velocity of ultrasonic waves traveling through concrete and reflects its internal quality and integrity. Higher UPV values indicate denser, less cracked, and more homogeneous material. In this study, GFRC specimens with *Bacillus subtilis* demonstrated significantly higher UPV after crack induction and healing periods compared to control specimens without bacteria. This improvement confirms effective microbial-induced calcium carbonate precipitation (MICP) that filled and sealed microcracks, thereby restoring concrete continuity and stiffness. different bacterial dosages influenced UPV results distinctly. Optimal bacterial concentrations enabled active self-healing and significant UPV recovery. However, excessive bacterial content occasionally led to reduced UPV gains due to possible microbial die-off or nutrient limitations, hampering effective crack sealing and resulting in persistent micro voids. This aligns with literature findings where the ultrasonic self-sealing ratio can quantify crack filling extent and material densification, with bacterial action critical in this process.

Sorptivity Test:

Sorptivity measures the rate of capillary water absorption then indicating the concrete's permeability and durability. Lower sorptivity after healing periods suggests that microbial precipitation effectively blocked pore pathways and microcracks and reducing water ingress. In GFRC samples with *Bacillus subtilis*, sorptivity decreased compared to non-bio specimens, reinforcing that the biological self-healing mechanism improved concrete's resistance to moisture penetration. Similar to UPV variations in bacterial and calcium lactate dosages affected sorptivity results. Moderate dosages resulted in notable reductions in sorptivity while overdosing caused inconsistent results, likely due to over-saturation of nutrients or bacterial inactivity which compromised crack filling and left capillary pathways partially open.

Discussion on Bacterial Influence:

Across both UPV and sorptivity tests the presence of *Bacillus subtilis* spores markedly enhanced mechanical and durability-related properties by autonomously repairing microcracks. Optimal bacterial dosages ensured active metabolism and sustained calcium carbonate deposition improving internal microstructure and water tightness. In contrast, overdosing bacteria or calcium lactate hindered microbial viability and nutrient balance adversely affecting self-healing efficiency as reflected by lower UPV recovery and higher sorptivity.

This dual-test approach convincingly demonstrates that bacterial self-healing in GFRC is quantifiable through improvements in wave velocity and decreased permeability. These non-destructive techniques offer valuable tools for monitoring self-healing progress and optimizing microbial dosages to maximize durability and mechanical performance from this study we conclude that UPV and sorptivity data confirm that bacterial bioactivity significantly promotes crack healing in GFRC up to an optimal threshold beyond which excess bacterial spores or calcium lactate can reduce self-healing effectiveness due to biological and chemical limitations. This finding is crucial for tailoring bio-enhanced concrete mixes for practical structural applications.

Conclusions

In this experimental work the mechanical properties of GFRC were tested alongside the examination of self-healing capacity and strength recovery rate for various mixes. The study employed mechanical tests including compressive, flexural and split tensile strength evaluations supplemented by non-destructive testing methods such as Ultrasonic Pulse Velocity (UPV) and sorptivity measurements to assess internal integrity and durability. UPV results demonstrated improved internal quality and microcrack healing due to microbial calcium carbonate precipitation facilitated by *Bacillus subtilis* spores which enhanced crack sealing and matrix densification. Sorptivity tests further confirmed a reduction in water absorption rates indicating effective pore blockage and enhanced resistance to moisture ingress. However both UPV and sorptivity results revealed that the self-healing efficiency depended on the dosage of bacterial spores and calcium lactate. Optimal dosages yielded maximum healing and strength recovery while overdosing caused microbial viability issues and diminished healing effectiveness resulting in decreased mechanical properties and increased permeability. Overall the combined mechanical and durability assessments confirm the substantial benefits of bacterial self-healing in GFRC when proper bio-nutrient balance is maintained. This research highlights the potential of integrating microbial agents in concrete to achieve enhanced crack repair durability and sustainability for structural applications.

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