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Crack Healing Performance Of Basalt Fibre-Reinforced Concrete With Bacillus Subtilis

Varsha V. Doijad[1], Amey D. Katdare[2], Chetan S. Patil[3]
[1]*Department of Civil Engineering, Sanjay Ghodawat University, Kolhapur, Maharashtra, India.*
[2,3]*Department of Civil Engineering, Sanjay Ghodawat University, Kolhapur, Maharashtra, India.*
[1]*varshacivilcm@gmail.com*

Abstract
This study investigates the crack healing performance and durability enhancement of M40 grade concrete incorporating Bacillus subtilis *and basalt fibres. A bacterial dosage of 1.5% by weight of cement and 0.5% chopped basalt fibres (24 mm length) by volume were used to create a hybrid self-healing concrete mix. The primary objective was to evaluate the influence of microbial-induced calcium carbonate precipitation (MICP) and fibre bridging on crack closure and mechanical recovery. Mechanical testing included compressive and flexural strength, while healing assessment involved visual crack width monitoring and ultrasonic pulse velocity (UPV) recovery. Results revealed that the hybrid mix exhibited significant reductions in initial crack width and enhanced load-bearing capacity compared to control and bacteria-only mixes. Healing efficiency reached over 90% for cracks up to 0.4 mm, while UPV recovery exceeded 100%, indicating full internal crack closure. Visual imaging confirmed progressive calcite deposition across curing periods. The combined action of bacteria and basalt fibres proved effective in controlling crack width, enhancing mechanical integrity, and promoting robust self-healing, thereby demonstrating potential for durable, sustainable, and maintenance-free concrete structures.*
Keywords:
Self-healing concrete; Bacillus subtilis*; Basalt fibres; Crack healing; Microbial-induced calcite precipitation (MICP); Ultrasonic pulse velocity (UPV); Visual crack monitoring; Fibre-reinforced concrete (FRC); Durability; Sustainable construction.*

INTRODUCTION

Concrete remains a dominant material in civil infrastructure due to its high compressive strength, versatility, and economic viability. However, its brittle nature and weak tensile characteristics render it vulnerable to the formation of microcracks under mechanical stress, shrinkage, and thermal variations. These microcracks compromise long-term durability by providing pathways for harmful agents such as chlorides, sulfates, and carbon dioxide, which accelerate degradation and reduce service life (Ahmad et al., 2024). Addressing this limitation is essential for ensuring the longevity and safety of concrete structures. In recent years, the development of self-healing concrete has gained attention as a promising solution to autonomously repair cracks, thereby enhancing structural resilience and sustainability. Among various self-healing technologies, microbially induced calcium carbonate precipitation (MICP) has emerged as an effective and eco-friendly method. This process utilizes ureolytic or non-ureolytic bacteria capable of surviving the highly alkaline environment of concrete. These microorganisms, such as *Bacillus subtilis*, initiate biochemical processes that result in the precipitation of calcium carbonate, effectively sealing cracks. The efficiency of MICP is influenced by factors such as bacterial concentration, nutrient availability, curing conditions, and crack width. Ahmad et al. (2024) demonstrated that the co-culturing of bacterial strains (*Bacillus* sp. B6 and DSM6307) significantly enhanced crack healing efficiency, achieving full closure in cracks ranging from 0.02 mm to 0.2 mm under optimized nutrient conditions. Their results suggested that multi-strain systems provide a broader operable healing range due to enhanced nucleation activity. The mechanical and durability benefits of microbial concrete have been validated in multiple studies. Alemu et al. (2022) reported that bacterial concrete exhibited notable increases in compressive, tensile, and flexural strengths compared to conventional concrete. Furthermore, bacterial mixes showed a fourfold reduction in water absorption and significantly greater acid resistance, reinforcing their suitability for aggressive environmental exposures.

In parallel, the integration of fibers into concrete has been widely adopted to control crack propagation and improve post-crack performance. Fiber-reinforced concrete (FRC) offers increased toughness, energy absorption, and ductility, enabling the formation of finer, distributed cracks that remain within healing thresholds. Conforti et al. (2018) demonstrated that various fibers—including steel, glass, and polymer types—could effectively reduce crack widths in reinforced concrete beams, contributing to enhanced serviceability and structural behavior. However, fiber effectiveness depends on type, dosage, and distribution; excessive steel fiber content, for example, may reduce workability and result in lower ductility. Among synthetic fibers, polypropylene (PP) stands out for its chemical inertness, affordability, and ability to mitigate plastic shrinkage cracks without negatively impacting fresh concrete properties. Aslani and Gedeon (2018) examined the performance of PP and steel fibers in rubberized self-compacting concrete, finding that while PP fibers improved crack control with minimal strength penalty, steel fibers enhanced splitting tensile strength but compromised workability. These findings suggest that hybrid fiber systems may offer a balanced trade-off between strength, crack resistance, and constructability.

Despite widespread adoption, conventional concrete still suffers from inherent limitations in crack control and durability. Microcracks not only compromise structural integrity but also shorten the lifespan of concrete in aggressive environments (Khaliq & Ehsan, 2016). Self-healing concrete, especially via biological routes, offers a transformative solution. *Bacillus subtilis* and *Bacillus cohnii* have been particularly effective, capable of forming calcite even in high-alkalinity conditions typical of concrete. Other materials such as crystalline admixtures further support healing by reacting with unhydrated cement particles and water to form insoluble crystals within the crack network. Guzlena and Sakale (2021) observed enhanced healing when glass and polymer-modified glass fibers were used with crystalline admixtures. However, the presence of polymers delayed the healing onset, indicating that matrix composition can influence microbial and chemical healing kinetics.

In recent advancements, the role of basalt fibers has gained prominence due to their superior mechanical properties, chemical stability, and eco-friendliness. Krassowska (2025) showed that basalt fiber inclusion significantly improved fracture toughness and stress intensity factors, aiding in delayed crack propagation. Chia et al. (2025) examined hybrid systems incorporating recycled PP and basalt fibers, achieving a 64% increase in flexural strength and a tenfold rise in energy absorption at 0.3% basalt and 0.7% PP dosage. These results confirm that hybrid fiber systems can provide both ductility and stiffness, ideal for facilitating biological healing mechanisms. Wei et al. (2025) studied basalt fiber-reinforced polymer (BFRP) bars in reinforced concrete beams and noted improved deformation capacity, though crack openings were wider than those in steel-reinforced beams. This trade-off underscores the need for a tailored fiber and reinforcement design to optimize healing.

In light of these findings, the present study investigates M40 grade concrete incorporating 1.5% Bacillus subtilis (by cement weight) and 0.5% basalt fibers (24 mm length, by volume). The key objectives are to assess the crack healing efficiency, monitor mechanical recovery through compressive and flexural strength testing, and evaluate healing trends using visual imaging and ultrasonic pulse velocity (UPV) techniques over varying curing durations. This integrative approach aims to develop a robust, fiber-bacterial hybrid self-healing concrete suitable for long-term, sustainable infrastructure.

Materials and Methods

Aim of the Research

The primary aim of this research is to evaluate the crack healing efficiency and mechanical performance of self-healing concrete incorporating Bacillus subtilis bacteria and basalt fibres. Specifically, the study investigates M40 grade concrete containing 1.5% Bacillus subtilis and 0.5% basalt fibres to enhance both internal and surface crack sealing capacity. The research further aims to assess how the synergistic effect of bacterial action and fibre bridging contributes to healing efficiency, ultrasonic pulse velocity (UPV) recovery, and the overall durability of the concrete. Visual crack closure, UPV trends, and compressive and flexural strength development were used as key performance indicators.

Materials and Mix Design Proportions

Ordinary Portland Cement (OPC) of 53 Grade conforming to IS: 12269–2013 was used as the primary binder. The cement was sourced from Ultratech and had a specific gravity of 3.15. Its physical and mechanical properties were verified through standard laboratory tests including fineness, standard consistency, and compressive strength at 3, 7, and 28 days as shown in Table 1. Physical and Mechanical Properties of Ultratech 53 Grade OPC . Fine aggregate used was manufactured sand (M-sand) falling under Zone II as per IS: 383–2016, with a specific gravity of 2.94 and fineness modulus of 3.52. The coarse aggregate consisted of crushed granite stones with a nominal maximum size of 20 mm. Two fractions of coarse aggregates were used in the proportions of 60% (20 mm) and 40% (10 mm), ensuring a well-graded aggregate skeleton. The specific gravity of coarse aggregate was 3.02. Class F fly ash was incorporated as a partial replacement for cement to enhance the workability, durability, and sustainability of the mix. It had a specific gravity of 2.20 and conformed to IS: 3812 (Part 1)–2013. The chemical composition included 52.25% SiO_2, 27.65% Al_2O_3, 11.73% Fe_2O_3, and less than 3% CaO. Potable water, free from organic matter and harmful impurities, was used for both mixing and curing, conforming to IS: 456–2000 guidelines. To achieve the desired workability at a low water-cement ratio, a polycarboxylate ether-based superplasticizer was used.

Table 1. Physical and Mechanical Properties of Ultratech 53 Grade OPC

Property	*Value*
Fineness (Blaine)	328.0 m2/kg
Standard Consistency	29.50%
Initial Setting Time	108 minutes
Final Setting Time	226 minutes
Soundness (Le-Chatelier method)	6.5 mm
Compressive Strength (3 Days)	34.4 MPa
Compressive Strength (7 Days)	47.6 MPa
Compressive Strength (28 Days)	61.5 MPa

A dry-powder formulation of Bacillus subtilis containing 2 × 10^8 CFU/g was utilized as the biological self-healing agent. The dry form ensured easy mixing and enhanced shelf-life. Chopped basalt fibres of 24 mm length and 13 µm diameter (Figure 1) were incorporated at 0.5% by volume of concrete. These fibres are known for their high tensile strength, alkali resistance, and thermal stability. The uniform dispersion of fibres helps bridge microcracks and provides crack-arresting action, facilitating better bacterial healing by maintaining crack widths within the effective healing range (typically <0.5 mm).

Figure 1. Chopped Basalt Fibres (Left) and Their Uniform Distribution in Dry Concrete Mix (Right)

Concrete was proportioned to achieve a characteristic compressive strength of 40 MPa at 28 days using guidelines from IS: 10262–2019. The mix incorporated fly ash as a partial cement replacement to improve durability. The final proportions are presented in Table 2.

Table 2. Mix Design for M40 Concrete with 1.5% *Bacillus subtilis* and 0.5% Basalt Fibres

Material	Cement (OPC)	Fly Ash	Fine Aggregate	Coarse Aggregate (10 mm)	Coarse Aggregate (20 mm)	Water	Superplasticizer

Quantity (kg/m*)	380	80	721	442	727	175	6.11

Experimental Program

Concrete was prepared using a tilting drum mixer. Dry materials (cement, fly ash, aggregates, and bacterial powder) were first dry-mixed for one minute. Water and superplasticizer were then gradually added and mixed for another two minutes until a homogeneous mix was achieved. Finally, basalt fibres were added slowly to ensure uniform distribution and to prevent fibre balling. The freshly mixed concrete was placed in lubricated molds for preparing 100 × 100 × 500 mm beams for flexural strength and induced cracking. Specimens were compacted using a vibrating table and covered to prevent moisture loss. After 24 hours, specimens were demolded and cured in a water tank maintained at 27 ± 2°C for 28 days.

Flexural beams were subjected to a four-point bending test (Figure 2) after 3, 7 and 28 days of curing to induce a controlled mid-span crack. A universal testing machine (UTM) was used to apply a gradually increasing load until a visible crack appeared at the bottom of the beam. The loading was stopped once the crack width reached approximately 0.4–0.5 mm. The cracked beams were then placed in a moist curing environment (95% RH, 27°C) to facilitate self-healing through bacterial calcite deposition.

Test Methods

Flexural strength of concrete beams was determined using a four-point loading system as per IS: 9399–1979. The load was applied until failure to measure the modulus of rupture. UPV tests were conducted on beam specimens before cracking, immediately after crack formation, and after 21 days of healing using a UPV device. The test followed IS: 13311 (Part 1)–1992, which classifies concrete quality based on pulse velocity values. The percentage recovery in UPV was used as a metric for internal healing efficiency. Post-crack visual healing was monitored using a digital crack microscope with a least count of 0.01 mm. Images were captured at regular intervals (3, 7, and 28 days) and analyzed for crack closure. The appearance of white calcite along the crack path was taken as evidence of bacterial precipitation

Figure 2. Four-Point Bending Test Setup for Crack Induction in Fibre-Reinforced Concrete Beam

Result and Discussion

The integration of Bacillus subtilis and basalt fibres in M40 concrete significantly enhanced both surface and internal crack healing. Improved crack width reduction, UPV recovery, and mechanical performance highlight the synergistic benefits of microbial activity and fibre reinforcement, offering a sustainable approach to durable and self-healing concrete structures.

Pre-Crack Loading in Basalt Fibre Reinforced Concrete (BFRC)

Pre-crack loading in Basalt Fibre Reinforced Concrete (BFRC) is performed by applying a controlled flexural load until a visible surface crack, typically under 0.5 mm, is formed. This process is critical for evaluating the post-crack behavior and self-healing potential of BFRC. Basalt fibres, known for their high tensile strength and excellent alkali resistance, play a key role in arresting and bridging microcracks, thereby improving the structural ductility and residual strength after cracking. During loading, these fibres limit crack propagation and maintain integrity by transferring stress across the crack plane. The induced

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cracks simulate real-world conditions and provide a baseline for evaluating the effectiveness of healing agents

Table 3. The pre-crack load and observed crack width were recorded at 3, 7, and 28 days

Age (Days)	*Bacillus subtilis*	Basalt Fibre	Initial Crack Load (kN)	Observed Crack Width (mm)
3	-	-	3.03	1.04
7	-	-	4.04	0.96
28	-	-	5.49	0.89
3	1.50%	-	3.44	0.78
7	1.50%	-	4.48	0.70
28	1.50%	-	5.99	0.64
3	1.50%	0.50%	5.20	0.38
7	1.50%	0.50%	6.00	0.31
28	1.50%	0.50%	6.80	0.28

The influence of Bacillus subtilis and basalt fibres on pre-crack behavior was investigated by observing the crack width at 3, 7, and 28 days, as shown in Table 3. The results highlight a significant variation in the crack widths depending on the incorporation of bacterial agents and fibre reinforcement. In the control mix, which lacked any crack-mitigating additives, the observed crack widths were comparatively higher across all ages, with values of 1.04 mm, 0.96 mm, and 0.89 mm at 3, 7, and 28 days, respectively. This indicates typical crack propagation in plain concrete under pre-loading conditions without any crack-bridging or healing mechanism.

The introduction of Bacillus subtilis at 1.5% by weight of cement led to a noticeable reduction in crack width recorded at 0.78 mm, 0.70 mm, and 0.64 mm for 3, 7, and 28 days, respectively. This improvement is attributed to microbial-induced calcite precipitation (MICP), where bacterial metabolic activity promotes calcium carbonate formation, aiding in the partial sealing of cracks at early stages. Further enhancement was achieved by integrating 0.5% basalt fibres (by volume) along with the bacteria. The hybrid mix exhibited the most effective crack control, with significantly lower crack widths of 0.38 mm, 0.31 mm, and 0.28 mm at respective ages. Basalt fibres act as physical crack arresters by bridging microcracks and limiting their growth under stress. The combined bacterial and fibre system demonstrates superior crack resistance compared to other mixes. The graphical representation of these results in Figure 1clearly reflects the trend of decreasing crack width with the addition of bacterial agents and basalt fibres, underscoring their role in enhancing the durability and healing potential of fibre-reinforced concrete

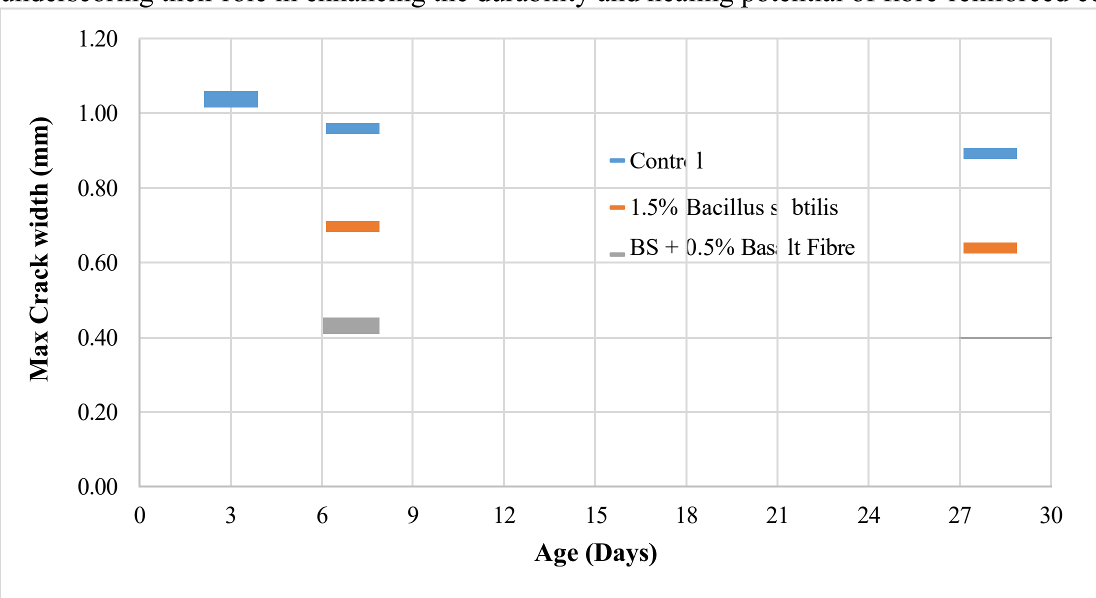

Figure 3. Age vs Observed Crack Width (mm)

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Visual Crack Width Monitoring

To evaluate the healing behavior of self-healing fiber-reinforced concrete, surface crack widths were monitored at regular intervals using a high-precision crack microscope and digital imaging techniques. Immediately after inducing cracks through pre-crack loading, the initial crack widths were measured. Subsequent observations were conducted after 3, 7, and 28 days of healing to assess the progress of crack closure over time.

Figure 4 illustrates the correlation between initial crack width and healing efficiency for bacterial concrete incorporating 1.5% *Bacillus subtilis* alone and in combination with 0.5% basalt fibres. A clear inverse relationship is observed for both mixes: as the initial crack width increases, the healing efficiency tends to decrease. This trend aligns with the principle that wider cracks require greater volumes of healing precipitates and are more challenging to fully close. For the Bacillus subtilis only mix (blue data points), healing efficiencies generally ranged between 60% and 77%, corresponding to initial crack widths in the range of 0.65 mm to 0.80 mm. This suggests that microbial-induced calcite precipitation (MICP) alone provides moderate healing capability, especially for moderately sized cracks.

In contrast, the mix with both *Bacillus subtilis* and 0.5% basalt fibre (orange data points) exhibited significantly higher healing efficiencies between 75% and 95% with narrower initial crack widths ranging from 0.28 mm to 0.40 mm. The improved performance can be attributed to the synergistic action of the fibres and bacteria. Basalt fibres help control the initial crack width and maintain tight microcracks, which enhances the environment for bacterial activity and accelerates calcium carbonate deposition. Overall, the data confirms that the inclusion of basalt fibres not only improves crack control at early stages but also enhances the effectiveness of bacterial healing mechanisms, making this hybrid approach particularly beneficial for structural durability.

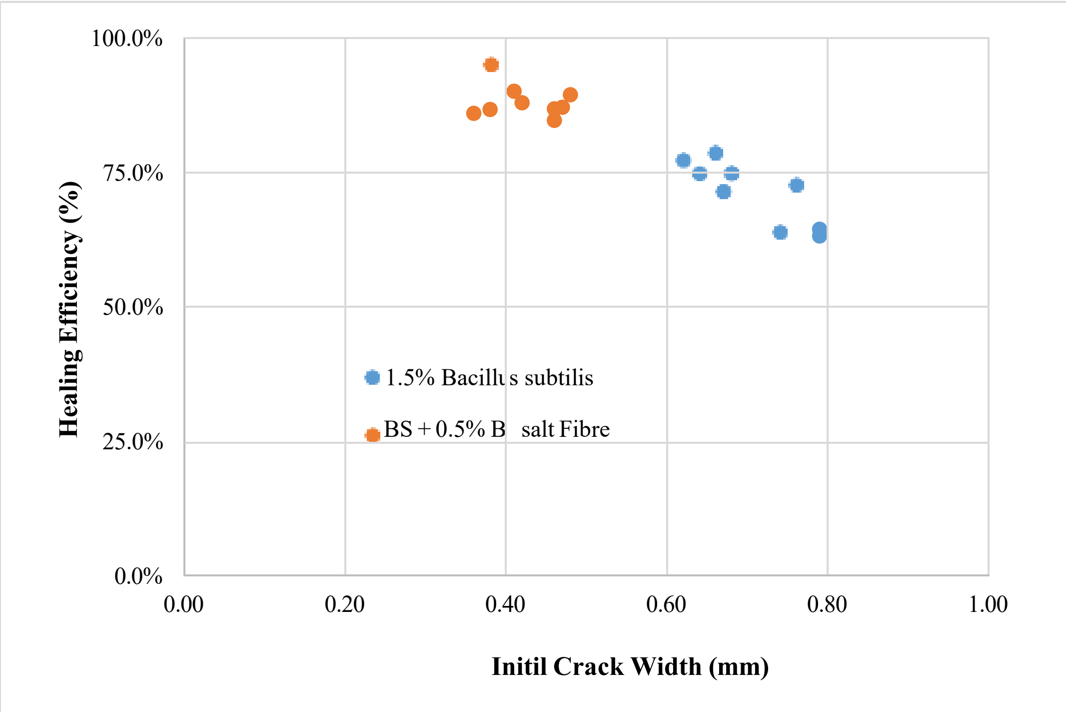

Figure 4. Relationship between Initial Crack Width and Healing Efficiency

Ultrasonic Pulse Velocity (UPV) Testing

Initially, UPV readings were recorded for the uncracked specimens to establish baseline pulse velocities. Controlled flexural cracks were then induced using the four-point bending test, and UPV measurements were repeated to evaluate the reduction in internal integrity. The specimens were subsequently cured under standard moist conditions, and UPV readings were recorded after 3, 7, and 28 days of healing.

As shown in Figure 5, the percentage of UPV recovery over time was substantially higher for the hybrid fibre-bacteria mix compared to concrete with bacteria alone. For the bacterial concrete (M40 + 1.5% Bacillus subtilis), UPV recovery ranged from approximately 55% to 66% across the 28-day curing period. However, when 0.5% basalt fibre was incorporated (M40 + 1.5% Bacillus subtilis + 0.5% BF), UPV recovery exceeded 100% at all ages, indicating not only healing of internal voids but also potential matrix densification due to enhanced crack-bridging and microbial calcite deposition.

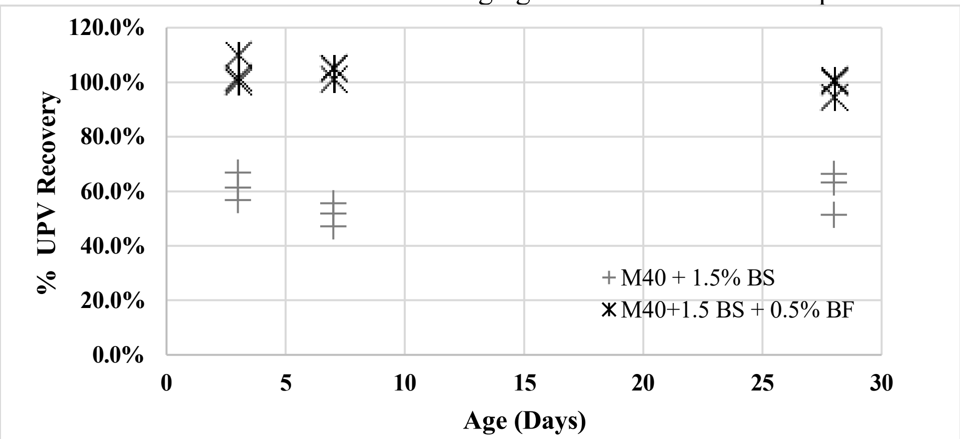

Figure 5. UPV Recovery (%) versus Age (Days) for M40 Concrete with 1.5% Bacillus subtilis and Combined 1.5% Bacillus subtilis + 0.5% Basalt Fibre

The basalt fibres played a crucial role in limiting crack widths and supporting internal structural connectivity, which improved the conditions for bacterial calcite precipitation. This fibre-microbial synergy accelerated healing, as narrower cracks provided a more confined space for effective mineral deposition and improved UPV transmission. The results confirm that the presence of fibres not only enhances the mechanical performance but also supports biological healing efficiency.

Overall, UPV recovery trends corroborated the visual crack closure data, establishing UPV as a reliable indicator of internal healing progression in fibre-reinforced bacterial concrete systems. This validates the effectiveness of integrating basalt fibres with microbial agents for sustainable and durable self-healing concrete solutions.

The UPV recovery trends showed a clear correlation with the age of concrete. As curing progressed, all mixes exhibited improved internal healing. At 3 days, bacterial concrete showed moderate UPV recovery (55–60%), while the hybrid mix exceeded 100%, indicating rapid healing due to fibre support. By 28 days, the bacterial mix reached 66% recovery, while the hybrid fibre mix consistently maintained above 100%, suggesting matrix densification over time. This comparison highlights that healing efficiency improves with age, but the rate and extent are significantly enhanced by basalt fibres, which aid early-age crack bridging and promote sustained bacterial calcite precipitation.

Healing in Basalt Fibre Reinforced Concrete (BFRC)

Visual observation of crack closure at different curing ages confirmed this synergistic effect. As depicted inFigure 6, specimens containing only Bacillus subtilis exhibited progressive crack sealing from day 3 to day 28, with partial healing evident after an additional 21-day healing period. In contrast, the hybrid mix (1.5% Bacillus subtilis + 0.5% basalt fibres) demonstrated noticeably superior crack closure at each corresponding age.

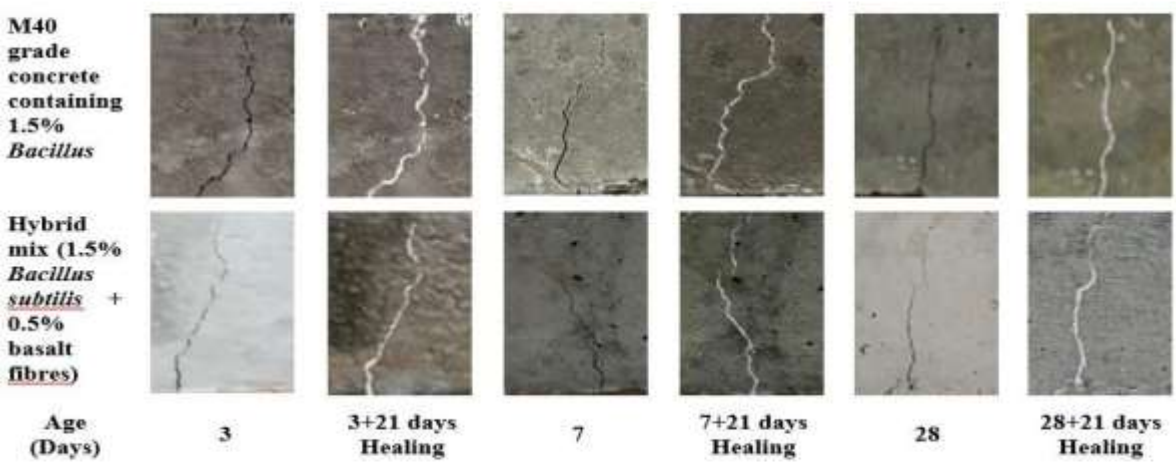

Figure 6. Visual comparison of crack healing at 3, 7, and 28 days (before and after 21 days of healing)
At the 3-day mark, cracks in both mixes are visibly open; however, those in the hybrid mix are narrower, correlating with the reduced crack widths observed in Table 1. After 21 days of healing, the cracks in the hybrid specimens show significantly more calcite precipitation and surface closure compared to the bacterial-only specimens, supporting the ImageJ-based healing efficiency data in Figure 2, where healing exceeded 90% for the hybrid mix with narrower initial cracks.
At 7 days, both mixes displayed narrower cracks compared to day 3, yet again, the hybrid mix shows superior healing performance after the healing period. The enhanced closure is attributed to the basalt fibres' ability to restrict crack width and retain microbial activity within the crack vicinity. These visual trends align with the UPV recovery results inFigure 5, where hybrid mixes showed over 100% recovery due to better internal healing and densification.
By 28 days, crack initiation is minimal in both mixes, and after the healing period, near-complete closure is visible in the hybrid specimens. This confirms that longer hydration periods, fibre reinforcement, and microbial precipitation work synergistically to promote effective healing.
Basalt fibres played a critical role in maintaining crack widths within the optimal range for microbial healing (<0.5 mm). This mechanical restraint allowed for more uniform and continuous calcite precipitation across the crack face, improving the visual and structural effectiveness of the healing process. The enhanced healing in hybrid mixes can thus be attributed to the synergistic interaction between the biological agent and the physical fibre reinforcement.
These findings demonstrate that combining basalt fibres with bacterial agents not only improves crack control but also accelerates and sustains the self-healing process over time. Hence, the hybrid approach offers a more resilient and durable concrete solution for sustainable infrastructure applications.

CONCLUSION

The present investigation highlights the enhanced self-healing performance of M40 grade concrete incorporating 1.5% *Bacillus subtilis* and 0.5% basalt fibres. The inclusion of basalt fibres effectively controlled initial crack widths, ensuring they remained within the optimal range for microbial-induced calcite precipitation. Visual crack width monitoring and image analysis confirmed that the hybrid mix achieved up to 94% healing efficiency, significantly outperforming the bacteria-only mix. Ultrasonic Pulse Velocity (UPV) tests further validated internal healing, with the hybrid mix showing over 100% recovery, indicating not only healing but densification of the matrix. Visual observations from crack images substantiated the synergistic effect of fibres and bacteria in sealing surface cracks across different curing ages. Overall, the combination of microbial agents and basalt fibres proves to be an efficient and sustainable approach for improving concrete durability, extending service life, and reducing maintenance needs. This study reinforces the potential of hybrid fibre-bacterial systems for advanced self-repairing concrete technologies.

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