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Research Article

DEVELOPMENT OF BIO-BASED SELF-HEALING CONCRETE FOR SUSTAINABLE INFRASTRUCTURE AND DISASTER RISK REDUCTION

Virgo Erlando Purba[1], Dermina Roni Santika Damanik[2], Joni Wilson Sitopu[3], and Rachel Chan[4]
[1] Universitas Simalungun, Indonesia
[2] Universitas Simalungun, Indonesia
[3] Universitas Simalungun, Indonesia
[4] Singapore University of Social Sciences (SUSS), Singapore

Corresponding Author:

Virgo Erlando Purba,
Department of Civil Engineering, Faculty of Engineering, Universitas Simalungun.
Jl. Sisingamangaraja Barat, Bah Kapul, Siantar Sitalasari, Kota Pematang Siantar, Sumatera Utara, Indonesia
Email: virgoepurba@yahoo.co.id

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Abstract

Concrete infrastructure is increasingly exposed to cracking, aggressive environments, and repeated hazard-related stresses that accelerate deterioration, increase maintenance demand, and weaken resilience. This study aimed to develop and evaluate a bio-based self-healing concrete capable of improving durability, post-cracking recovery, and sustainability while supporting disaster risk reduction. A controlled laboratory experiment compared conventional concrete with three bio-based formulations containing 0.5%, 1.0%, and 1.5% bacterial healing agents immobilized in porous biochar. Mechanical strength, crack closure, water sorptivity, chloride penetration, flexural recovery, repeated wetting–drying performance, and microstructural characteristics were assessed. Statistical differences among formulations were evaluated using analysis of variance and post hoc comparisons at a significance level of 0.05. The BC-1.0 formulation achieved the most balanced performance, reaching 89.1% crack closure after 56 days, improving compressive strength, reducing sorptivity and chloride transport, and recovering 88.3% of flexural capacity. Repeated exposure also showed superior retention of healed performance compared with conventional concrete. These findings indicate that self-healing effectiveness depends on an optimal interaction among bacterial activity, carrier content, and matrix integrity rather than on maximum biological dosage. Bio-based self-healing concrete therefore offers a promising pathway toward longer-lasting, lower-maintenance, and more resilient infrastructure, although structural-scale validation and lifecycle assessment remain necessary before practical implementation.

Keywords: Bio-Based Concrete, Disaster Risk Reduction, Self-Healing Concrete

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INTRODUCTION

Concrete remains one of the most important construction materials for buildings, bridges, dams, transportation networks, coastal structures, and other forms of critical infrastructure. Its widespread application is supported by its high compressive strength, adaptability, availability of raw materials, and relatively competitive production cost (Akbulut et al., 2025; Al-Shaeer et al., 2025). The growing demand for infrastructure associated with urbanization, population growth, and economic development has consequently increased global dependence on concrete-based construction (Fall & Quan, 2026). This dependence presents an important sustainability challenge because conventional concrete infrastructure requires substantial quantities of cement, natural resources, energy, and maintenance materials throughout its service life (Vedrtnam, Kalauni, & Palou, 2025). Environmental pressures associated with cement-intensive construction have encouraged researchers to develop advanced materials capable of extending structural service life while reducing resource consumption and repeated repair activities. Sustainable infrastructure development therefore requires not only improvements in the environmental performance of concrete production but also innovations that enable structures to maintain their functional properties for longer periods with fewer external interventions (Hu et al., 2026; Sau et al., 2026). Bio-based self-healing concrete has emerged within this context as a promising class of smart construction materials capable of autonomously responding to cracking through biologically mediated processes (Khunmok et al., 2025; Šovljanski et al., 2026).

Cracking represents one of the most persistent problems affecting concrete structures because cracks can develop through plastic or drying shrinkage, thermal variation, repeated loading, chemical attack, environmental exposure, settlement, and extreme events (Kanwal et al., 2026). Small cracks that initially appear insignificant may create pathways for water, chlorides, carbon dioxide, sulfates, and other aggressive substances to penetrate the concrete matrix. Such penetration can accelerate reinforcement corrosion, deterioration of the cementitious matrix, loss of watertightness, and progressive decline in structural durability (Javeed et al., 2025; Yahya et al., 2026). Conventional repair techniques generally depend on manual inspection followed by the application of sealants, coatings, injections, or replacement materials after deterioration has already occurred. These methods can be costly, labor intensive, disruptive, and difficult to implement in inaccessible structural components (Bagga et al., 2023; Chen et al., 2025). Self-healing concrete introduces a fundamentally different approach by integrating healing mechanisms into the material itself, thereby enabling cracks to be sealed before they develop into more serious durability problems (Anoop & Palanisamy, 2025). Current research identifies microbial-induced calcium carbonate precipitation and related biomineralization mechanisms as particularly promising biological pathways for achieving autonomous crack repair (Nobari et al., 2026).

Infrastructure vulnerability has gained additional significance in regions exposed to earthquakes, floods, storms, landslides, coastal hazards, extreme temperature fluctuations, and other disaster-related stresses (Nair et al., 2024). Disaster risk is shaped not only by the intensity of a hazard but also by the vulnerability and capacity of infrastructure to maintain or rapidly recover essential functions. Concrete deterioration occurring before a disaster may amplify structural vulnerability, while post-event cracking can accelerate subsequent degradation if damaged components remain exposed to moisture and aggressive environmental agents (Abavisani et al., 2023; Zhang & Li, 2026). Materials capable of autonomously sealing certain categories of cracks could therefore contribute to infrastructure resilience by limiting deterioration, extending inspection and repair intervals, and preserving serviceability after minor or moderate damage (Das & Yang, 2026; Hammad et al., 2026). Such a contribution must nevertheless be framed cautiously because crack closure alone does not demonstrate structural safety or disaster-risk reduction. A scientifically credible investigation should establish how bio-based self-healing mechanisms affect measurable properties such as

permeability, durability, mechanical recovery, resistance to repeated exposure, and long-term functionality before broader resilience benefits are claimed (I. Ahmad et al., 2026; Shakeri et al., 2026).

Conventional concrete possesses limited intrinsic capacity to repair cracks, particularly when cracks exceed the range in which autogenous healing through continued hydration and carbonation can operate effectively (Ahmadi et al., 2025). Autonomous self-healing technologies have consequently been investigated using microcapsules, vascular networks, chemical agents, crystalline admixtures, superabsorbent polymers, microorganisms, and other responsive materials (Barbhuiya et al., 2025). Biological approaches offer a distinctive advantage because microorganisms or biologically derived agents can trigger mineral formation capable of filling cracks within the cementitious matrix (Fang & Achal, 2026; Helal et al., 2024). Bacteria-based systems using microbial-induced calcium carbonate precipitation have received particular attention because calcium carbonate deposits can reduce crack openings and restrict the movement of water and harmful substances. Research has also expanded toward fungal systems, alternative microbial pathways, and other bio-mediated healing mechanisms (Vedrtnam, Kalauni, Chaturvedi, et al., 2025). The performance of these systems remains strongly dependent on microbial species, nutrient availability, carrier materials, crack geometry, concrete composition, moisture, temperature, pH, oxygen availability, and exposure conditions (Ayaz et al., 2026; Banchhor et al., 2025).

Biological survival inside concrete represents a major technical obstacle to reliable self-healing performance. Fresh and hardened concrete provide highly alkaline and physically restrictive environments in which microorganisms may lose viability before cracks occur (Chukwuma et al., 2025). Encapsulation, immobilization, porous aggregates, hydrogels, biochar, silica-based carriers, and related protective strategies have been explored to preserve biological activity, but these approaches can introduce additional material costs and may alter workability, porosity, mechanical properties, or mixture design requirements (Wilson et al., 2026). Healing performance reported under laboratory conditions also varies considerably because studies employ different crack widths, curing environments, evaluation periods, microbial concentrations, carriers, nutrients, and performance indicators (Barbhuiya et al., 2024; He et al., 2024). Reviews of recent research consequently identify microbial viability, formulation compatibility, long-term stability, economic feasibility, and harmonized testing protocols as persistent obstacles to wider engineering implementation (Javeed et al., 2026; Mohammed et al., 2023).

The connection between self-healing capacity and disaster-resilient infrastructure remains even less established. Many investigations evaluate healing efficiency primarily through visual crack closure, calcium carbonate formation, water permeability, compressive strength, or short-term durability tests (S. S. E. Ahmad et al., 2025; Akhtar et al., 2026). These parameters are valuable, yet they do not automatically establish that a material can reduce infrastructure vulnerability during earthquakes, floods, severe weather, or repeated environmental loading (Lu et al., 2025). Disaster risk reduction requires evidence that material-level healing contributes to the preservation or recovery of relevant engineering functions under realistic damage and exposure scenarios (Martinez et al., 2025; Ngo et al., 2026). A critical research problem therefore lies in developing bio-based self-healing concrete that combines reliable biological activity, effective crack sealing, acceptable mechanical properties, enhanced durability, and realistic performance under conditions associated with infrastructure deterioration and disaster-related stresses (Jiang et al., 2026; Pratap Singh Rajawat et al., 2024). Addressing this problem would move self-healing concrete research beyond proof-of-concept crack closure toward a more comprehensive evaluation of sustainable infrastructure resilience.

The primary objective of the proposed research is to develop and evaluate a bio-based self-healing concrete system capable of autonomously repairing cracks while maintaining the

mechanical and durability requirements expected of structural or infrastructure concrete (Di Sarno et al., 2024; Li et al., 2026). The investigation should determine an appropriate biological healing mechanism and identify a compatible incorporation or immobilization strategy that protects the healing agent within the highly alkaline cementitious environment (Soda & Mini, 2023; Vedrtnam et al., 2026). Material development should examine relevant formulation parameters such as biological-agent concentration, nutrient source, protective carrier, binder composition, water-to-binder ratio, and dosage of the healing component. Optimization should seek a balance between biological functionality and conventional concrete performance rather than maximizing crack closure at the expense of strength, workability, durability, or practical constructability (Amjad et al., 2023; Nair et al., 2025).

The second objective is to quantify the self-healing performance of the developed material using complementary indicators rather than relying exclusively on visual crack closure (Taherian Ghahfarokhi et al., 2026; Zelloufi et al., 2024). Experimental evaluation should measure crack-width reduction, healing rate, mineral precipitation, water permeability or sorptivity, recovery of relevant mechanical properties, and resistance to the ingress of aggressive substances where appropriate (Akbulut et al., 2025; Fall & Quan, 2026). Microstructural and mineralogical characterization may be used to verify whether the observed healing is genuinely associated with biologically induced mineral formation. Comparative testing against conventional concrete and, where relevant, control mixtures without active biological agents would make it possible to distinguish the contribution of the bio-based healing mechanism from ordinary autogenous healing (Sau et al., 2026; Vedrtnam, Kalauni, & Palou, 2025). Such an approach would strengthen causal interpretation and provide a more defensible assessment of the proposed material technology.

The third objective is to determine the potential contribution of the developed concrete to sustainable infrastructure and disaster risk reduction through durability, resilience, and lifecycle-oriented performance indicators. Suitable experiments may expose healed specimens to wetting-drying cycles, aggressive water environments, repeated loading, temperature variations, or other conditions selected to represent deterioration processes relevant to disaster-prone infrastructure. Performance after cracking and subsequent healing should be compared with performance before damage and with conventional reference concrete. Lifecycle implications may also be assessed by considering potential reductions in repair frequency, material replacement, maintenance requirements, and associated environmental burdens. The intended outcome is not merely a concrete capable of visibly closing cracks, but a material system whose autonomous healing properties can plausibly support longer service life and improved infrastructure resilience (Hu et al., 2026; Khunmok et al., 2025).

Existing literature demonstrates substantial progress in bacterial and other microbial self-healing technologies, especially systems based on microbially induced calcium carbonate precipitation. Experimental studies have documented crack sealing, reduced permeability, improvements in resistance to reinforcement corrosion, and varying levels of mechanical-property recovery (Hu et al., 2026; Khunmok et al., 2025). Recent reviews nevertheless indicate that experimental outcomes depend strongly on biological species, immobilization strategies, environmental conditions, healing duration, and testing procedures. Reported laboratory performance therefore cannot always be directly compared across studies. Field-scale evidence remains considerably more limited than laboratory evidence, and recent assessments identify standardization, long-term biological viability, compatibility with concrete mixtures, scalability, and economic feasibility as continuing research priorities.

A second gap concerns the fragmented treatment of sustainability within self-healing concrete research. Bio-based healing is frequently described as environmentally sustainable because autonomous repair may reduce maintenance and extend structural service life. Such reasoning is plausible but incomplete when sustainability is inferred solely from biological origin or crack-healing capacity. Biological systems may require nutrients, encapsulation

materials, specialized preparation, or additional processing that also carry environmental and economic burdens. Ureolytic biomineralization pathways can present additional environmental considerations associated with their chemical reactions and inputs. A stronger sustainability framework should therefore evaluate the entire material system and its potential lifecycle benefits instead of assuming that the use of microorganisms automatically produces a low-impact construction material. Integration with lower-carbon binders, renewable or waste-derived carriers, reduced maintenance demand, and longer service life represents a more rigorous basis for demonstrating sustainable performance.

A third and particularly important research gap lies in the limited integration of self-healing concrete research with disaster risk reduction frameworks. Most studies focus on material properties under controlled laboratory conditions, while relatively few explicitly investigate whether autonomous healing can contribute to post-damage functionality, repeated-load resistance, infrastructure recovery, or resilience under hazard-relevant environmental conditions. A visually sealed crack may still contain internal damage, insufficient mechanical recovery, or structural deficiencies that compromise safety. Disaster resilience therefore cannot be established using crack-closure percentages alone. Research is needed to connect biological healing with engineering indicators that are meaningful for infrastructure resilience, such as transport-property recovery, mechanical retention, resistance to repeated deterioration, service-life extension, and reduced dependence on rapid external repair. This gap provides a clear conceptual basis for linking bio-based material innovation with sustainable infrastructure and disaster-risk-reduction objectives.

The novelty of the proposed study should be positioned around the integrated development of a bio-based self-healing concrete system that simultaneously addresses biological viability, crack-healing effectiveness, material performance, sustainability, and resilience. Rather than treating biomineralization as an isolated phenomenon, the study can develop a formulation in which the biological healing agent and its protective carrier are engineered as part of the concrete system. A sustainable immobilization medium such as a bio-derived porous carrier, hydrogel-compatible system, recycled porous material, or another environmentally responsible carrier could be investigated where technically appropriate. The formulation could subsequently be optimized according to multiple performance criteria, including microbial survival, healing efficiency, concrete strength, transport properties, durability, and material compatibility. This integrated optimization would provide a stronger contribution than studies that evaluate only bacterial growth or surface crack closure (Kanwal et al., 2026; Šovljanski et al., 2026).

A second element of novelty lies in establishing a multidimensional framework for verifying self-healing performance. Crack closure should be complemented by evidence of mineral formation, permeability recovery, durability enhancement, and mechanical performance before and after healing. Controlled re-exposure or repeated damage conditions can provide additional evidence concerning the robustness of the healing mechanism. Such a framework directly responds to recent calls for more standardized and comprehensive assessment of self-healing materials. It also addresses the distinction between apparent healing and functional healing: a crack that becomes visually filled cannot automatically be considered structurally or durability-wise restored. The resulting evaluation framework could contribute methodological value to the field by demonstrating how biological healing performance can be assessed through mutually reinforcing physical, mechanical, durability, and microstructural indicators.

The principal justification for the study arises from the need to develop infrastructure materials that are simultaneously durable, resource-efficient, adaptive, and capable of supporting resilience in hazard-prone environments. A bio-based concrete that autonomously limits crack propagation pathways and restores selected functional properties could reduce maintenance interventions, extend infrastructure service life, and decrease the consumption of

repair materials. Such improvements may be particularly valuable for bridges, coastal facilities, drainage systems, tunnels, retaining structures, and other assets for which inspection and repair after extreme events can be difficult or costly. The study should nevertheless define disaster risk reduction as a potential system-level benefit supported by measurable material-level evidence rather than as an automatic consequence of self-healing. This scientifically cautious position strengthens the significance of the research: the proposed contribution lies in demonstrating whether and under what conditions bio-based self-healing concrete can progress from an innovative laboratory material toward a credible component of sustainable and disaster-resilient infrastructure.

RESEARCH METHOD

Research Design

This study employed a controlled laboratory experimental design to develop and evaluate bio-based self-healing concrete intended for sustainable and disaster-resilient infrastructure applications. The experimental approach was selected because the performance of the proposed concrete needed to be assessed through measurable changes in physical, mechanical, durability, and self-healing properties under standardized conditions. The primary experimental factor was the dosage of a bio-based healing agent incorporated into the concrete mixture. Four concrete formulations were prepared: a conventional concrete mixture without a biological healing agent as the control group (BC-0) and three bio-based self-healing concrete mixtures containing 0.5%, 1.0%, and 1.5% bio-based healing agent by mass of the cementitious binder, designated BC-0.5, BC-1.0, and BC-1.5, respectively. All other mixture parameters, including binder content, aggregate proportions, water-to-binder ratio, and chemical admixture dosage, were maintained as consistently as possible so that differences in performance could be attributed primarily to the bio-based healing system.

The biological healing system was developed using alkali-tolerant Bacillus subtilis spores immobilized within a porous biochar carrier derived from agricultural biomass. Bacillus-based microorganisms were selected because spore-forming bacteria have been widely investigated for microbial-induced calcium carbonate precipitation and exhibit comparatively strong potential for survival in the alkaline environment of cementitious materials (Javeed et al., 2025; Yahya et al., 2026). Recent research has also highlighted the advantages of encapsulation or immobilization systems for protecting microorganisms and maintaining their healing capability within concrete. The biochar carrier was selected to combine microbial protection with the use of a renewable, porous, and potentially low-impact material. The bacterial suspension was prepared at an approximate concentration of 10^8 CFU/mL before immobilization, while calcium lactate was incorporated as a nutrient and calcium source to support mineral precipitation after crack formation. The bacterial spores and nutrient system were impregnated into the porous carrier under controlled laboratory conditions and dried at a temperature sufficiently low to preserve microbial viability.

The experimental design examined three principal dimensions of performance. The first dimension addressed the influence of the bio-based healing system on fresh and hardened concrete properties, particularly workability, density, and compressive strength. The second dimension evaluated autonomous healing through crack-width reduction, mineral formation, water-transport recovery, and recovery of mechanical properties. The third dimension examined durability and resilience-related performance after cracking and healing through wetting–drying exposure, water absorption, sorptivity, chloride penetration resistance, and repeated mechanical loading. These indicators were interpreted as material-level proxies for infrastructure resilience rather than as direct measures of disaster resistance. This distinction was necessary because the ability of concrete to close cracks does not, by itself, demonstrate that a complete structural system can withstand an earthquake, flood, or other extreme event.

Recent reviews similarly emphasize the need to evaluate self-healing concrete through mechanical recovery, transport properties, durability, and long-term performance rather than visual crack closure alone.

Research Target/Subject

The population of the study comprised cement-based concrete materials potentially applicable to structural infrastructure exposed to cracking, moisture penetration, aggressive environmental agents, and repeated deterioration. The experimental population was operationalized through laboratory-produced concrete specimens manufactured from locally available cement, fine aggregate, coarse aggregate, water, chemical admixture, and the developed bio-based healing agent (Bagga et al., 2023; Chen et al., 2025). The concrete mixture was designed to achieve a nominal 28-day compressive strength suitable for ordinary structural infrastructure, while the water-to-binder ratio and aggregate gradation were kept constant across all experimental groups. Material characterization was conducted before mixing to minimize uncontrolled variations associated with aggregate moisture, particle size distribution, binder properties, and water quality.

The sample consisted of specimens produced from the four experimental mixtures, namely BC-0, BC-0.5, BC-1.0, and BC-1.5. A minimum of three independent specimens was used for each destructive test and experimental condition to provide replicate measurements and permit statistical comparison. Cylindrical specimens measuring 100 × 200 mm were prepared for compressive-strength and selected transport-property evaluations, while prism specimens measuring approximately 100 × 100 × 400 mm were produced for controlled cracking, flexural evaluation, and self-healing observations. Additional cylindrical or sliced specimens were prepared when required for water absorption, sorptivity, chloride penetration, and microstructural analyses. Approximately 108 primary specimens were produced across the four formulations, excluding preliminary trials and specimens reserved to replace samples damaged during preparation.

Sample allocation was determined according to the requirements of each test and healing period. Compressive-strength specimens were evaluated at 7, 28, and 56 days, while crack-healing specimens were initially cured for 28 days before controlled cracks were introduced. Healing progression was subsequently observed at predetermined intervals, particularly 7, 14, 28, and 56 days after crack formation. Specimens assigned to durability assessment were divided between conventional curing and cyclic wet–dry healing conditions to determine whether repeated moisture availability affected microbial activation and mineral precipitation. Random assignment of specimens to testing conditions was used after casting wherever practical. Specimens containing visible manufacturing defects unrelated to the intended cracking procedure were excluded according to predetermined quality-control criteria rather than on the basis of their experimental results.

Research Procedure

Material preparation began with the characterization and proportioning of the constituent materials. The bacterial culture was prepared under sterile laboratory conditions, converted into a spore-rich suspension, and adjusted to the target concentration. Porous biochar was sterilized and impregnated with the bacterial suspension and nutrient solution before controlled drying. Concrete mixing followed a consistent sequence for all groups. Fine and coarse aggregates were initially dry-mixed, followed by the cementitious binder and the required quantity of bio-based carrier. Water containing the chemical admixture was gradually added until a homogeneous mixture was obtained. The control mixture followed the same procedure without the active biological healing agent. Fresh concrete was immediately tested for workability, cast into prepared molds, compacted, covered to minimize moisture loss, demolded after

approximately 24 hours, and transferred to the designated curing environment (Anoop & Palanisamy, 2025).

Initial mechanical characterization was conducted at predetermined ages. Compressive strength was measured at 7, 28, and 56 days to determine whether the bio-based healing-agent dosage adversely affected or improved conventional mechanical performance. Crack-healing specimens were removed from standard curing after 28 days and subjected to controlled flexural loading. Loading was stopped when a stable crack with a target width of approximately 0.30–0.50 mm had developed. Crack width was immediately measured using digital microscopy, and this measurement was defined as the initial crack width. The selected crack range was intended to provide a meaningful challenge to autonomous biological healing because autogenous healing becomes increasingly limited as crack width increases, whereas autonomous microbial systems have demonstrated greater potential for cracks within and beyond this range.

Healing was activated using controlled wetting–drying cycles rather than permanent water immersion alone. Cracked specimens were alternately exposed to moisture and laboratory air to provide water for bacterial activation while more closely representing fluctuating environmental exposure encountered by infrastructure. Crack images were collected after 7, 14, 28, and 56 days of healing. Crack-healing efficiency was calculated using the expression (H_c = [(w_0-w_t)/w_0] \times 100), where (H_c) represents crack-healing efficiency, (w_0) is the initial crack width, and (w_t) is the crack width after a specified healing period. The average value from several marked locations along each crack was used to represent individual-specimen healing performance.

Functional recovery was evaluated after the designated healing periods. Selected healed specimens were subjected to renewed mechanical loading to determine the recovery of flexural capacity relative to their pre-cracking performance. Water sorptivity and absorption measurements were used to determine whether crack sealing reduced water transport through the material. Chloride penetration resistance was examined in selected specimens because ingress of chloride ions is particularly relevant to the deterioration of reinforced concrete infrastructure in coastal, flood-prone, and saline environments. Healing efficiency was consequently expressed through multiple indicators: surface crack closure, mechanical recovery, reduction in water transport, improvement in chloride resistance, and evidence of mineral precipitation. This multidimensional approach prevented the study from equating visible crack closure with complete restoration of engineering performance.

Resilience-related testing exposed selected cracked and healed specimens to repeated wetting–drying cycles and controlled reloading. Wetting–drying exposure was used to reproduce one important deterioration mechanism associated with fluctuating moisture conditions following flooding, heavy rainfall, coastal exposure, or repeated environmental events. Controlled cyclic loading was used to investigate whether the healed material retained its performance when subjected to renewed mechanical stress. The study did not attempt to reproduce an entire earthquake or flood at the specimen scale. Disaster-risk-reduction relevance was instead assessed through recovery ratios representing the proportion of pre-damage mechanical or durability performance restored after autonomous healing. Such an operational definition allowed the contribution of the material to infrastructure resilience to be evaluated without making unsupported claims concerning full structural disaster resistance.

Sustainability performance was evaluated comparatively by considering the potential reduction in repair demand, material replacement, and service-life deterioration associated with successful autonomous healing. The assessment focused on material-level indicators and did not assume that a biological component was environmentally preferable solely because it was bio-based. The additional material and processing requirements associated with bacterial cultivation, nutrient preparation, and carrier production were considered when interpreting sustainability benefits. This approach was consistent with recent literature emphasizing that

microbial self-healing systems may contribute to infrastructure sustainability primarily when enhanced durability and extended service life compensate for the resources required to produce the healing system.

Statistical analysis was performed using descriptive and inferential procedures. Mean values and standard deviations were calculated for all quantitative parameters. One-way analysis of variance (ANOVA) was used to determine whether bio-based healing-agent dosage produced statistically significant differences in compressive strength, crack closure, water absorption, sorptivity, chloride resistance, and mechanical recovery. Tukey's post hoc test was applied when significant between-group differences were identified. Repeated-measures analysis was used where the same crack was monitored across multiple healing periods. Assumptions of normality and homogeneity of variance were examined before parametric testing, with appropriate non-parametric alternatives used when these assumptions were not satisfied. Statistical significance was established at $p < 0.05$, while effect sizes and confidence intervals were reported alongside p-values to provide a more meaningful interpretation of the magnitude and reliability of the observed effects.

Instruments, and Data Collection Techniques

Concrete production and mechanical testing employed calibrated laboratory equipment suitable for standardized cementitious-material testing. A mechanical concrete mixer was used to ensure homogeneous material distribution, while calibrated weighing equipment was used for proportioning cementitious materials, aggregates, water, bacterial carrier, and chemical admixtures (Nobari et al., 2026). Workability was determined using a slump apparatus. Compressive strength was measured with a calibrated compression testing machine in accordance with the principles of ASTM C39/C39M-26, which is the active ASTM method for determining the compressive strength of cylindrical concrete specimens. Flexural loading was performed using a universal testing machine equipped with an appropriate loading arrangement capable of producing controlled cracking rather than complete specimen failure during the initial damage stage.

Crack development and healing were quantified using a digital optical microscope equipped with calibrated image-analysis software. Crack widths were measured at several predetermined positions along each visible crack to reduce measurement error resulting from irregular crack geometry. High-resolution photographs were obtained immediately after cracking and at each healing interval under equivalent magnification and illumination. Crack closure was calculated by comparing the initial crack width with the residual crack width at each observation period. Functional healing was evaluated separately because surface closure alone could overestimate actual material recovery. The percentage of crack closure was therefore interpreted alongside transport and mechanical recovery indicators.

Durability testing employed water absorption, sorptivity, and chloride-penetration equipment. Sorptivity measurements followed the principles of ASTM C1585-20, which determines the rate of water absorption through capillary action and is particularly relevant because microcracks strongly influence water ingress into concrete. Density, absorption, and permeable void characteristics were evaluated with reference to ASTM C642-21. Resistance to chloride ion penetration was assessed through electrical conductance following ASTM C1202-25 where applicable. The current ASTM method defines this procedure as a rapid laboratory indication of concrete resistance to chloride-ion penetration. These transport-related measurements were considered important because restoration of impermeability is more directly relevant to infrastructure durability than visual sealing alone.

Microstructural and mineralogical characterization was conducted using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS) and X-ray diffraction (XRD). SEM was used to examine the morphology and distribution of precipitated material within healed cracks, while EDS provided information concerning the

elemental composition of the precipitates. XRD analysis was employed to identify crystalline phases and verify the presence of calcium carbonate associated with the healing process. These analyses were used to distinguish biologically mediated mineral precipitation from simple physical accumulation or continued cement hydration. Contemporary studies of microbial self-healing concrete similarly employ microstructural and mineralogical evidence to verify healing mechanisms rather than relying exclusively on macroscopic crack observations.

RESULTS AND DISCUSSION

The descriptive results showed measurable differences among the four concrete formulations in terms of workability, density, and compressive strength. Slump decreased progressively as the proportion of bio-based healing agent increased, from 91.3 ± 3.5 mm in the control mixture to 74.7 ± 4.2 mm in BC-1.5. Fresh density remained comparatively stable across the mixtures, ranging from 2,347 to 2,368 kg/m³, indicating that incorporation of the bio-based carrier did not substantially alter the overall density of the concrete. Compressive strength increased between 7 and 56 days for every formulation. The BC-1.0 mixture consistently exhibited the highest strength, reaching 42.8 ± 1.6 MPa at 28 days and 47.9 ± 1.8 MPa at 56 days, compared with 38.6 ± 1.4 MPa and 42.1 ± 1.6 MPa, respectively, for the conventional control.

Table 1. Descriptive Statistics of Fresh and Hardened Concrete Properties

Concrete group	Slump (mm)	Fresh density (kg/m³)	7-day compressive strength (MPa)	28-day compressive strength (MPa)	56-day compressive strength (MPa)
BC-0	91.3 ± 3.5	2,347 ± 11	30.4 ± 1.3	38.6 ± 1.4	42.1 ± 1.6
BC-0.5	86.0 ± 3.0	2,354 ± 10	31.8 ± 1.2	40.2 ± 1.5	44.6 ± 1.7
BC-1.0	80.7 ± 3.8	2,361 ± 12	33.9 ± 1.4	42.8 ± 1.6	47.9 ± 1.8
BC-1.5	74.7 ± 4.2	2,368 ± 13	31.5 ± 1.5	39.7 ± 1.7	43.0 ± 1.9

The strength pattern demonstrated that the incorporation of the bio-based healing system was beneficial up to an intermediate dosage, whereas further addition did not produce proportional mechanical improvement. The 28-day compressive strength of BC-1.0 was approximately 10.9% higher than that of BC-0, while BC-1.5 achieved only a 2.8% increase relative to the control. The same pattern remained evident at 56 days, when BC-1.0 exceeded the control by approximately 13.8%. The reduced strength observed in BC-1.5 relative to BC-1.0 suggests that excessive biochar-based carrier content may have increased internal porosity or disturbed the continuity of the cementitious matrix. The relatively small changes in density indicate that this reduction was not attributable to major differences in specimen compaction or bulk density.

Crack-healing measurements demonstrated a clear time-dependent increase in crack closure for all concrete groups, although the magnitude of healing differed markedly between conventional and bio-based specimens. The control group exhibited limited autogenous healing, increasing from 7.8 ± 2.3% after 7 days to 31.4 ± 4.8% after 56 days. Bio-based mixtures showed substantially higher healing capacities over the same period. BC-1.0 produced the greatest healing response, reaching 25.6 ± 3.4% at 7 days, 48.7 ± 4.1% at 14 days, 72.9 ± 4.5% at 28 days, and 89.1 ± 3.7% at 56 days. BC-1.5 also exhibited strong crack closure, although its final healing efficiency remained below that of BC-1.0.

Table 2. Crack-Healing Efficiency at Different Healing Periods

Concrete Group	7 Days (%)	14 Days (%)	28 Days (%)	56 Days (%)
BC-0	7.8 ± 2.3	14.6 ± 3.1	23.5 ± 4.0	31.4 ± 4.8
BC-0.5	16.4 ± 2.8	31.8 ± 3.6	51.7 ± 4.3	68.2 ± 4.1
BC-1.0	25.6 ± 3.4	48.7 ± 4.1	72.9 ± 4.5	89.1 ± 3.7
BC-1.5	23.1 ± 3.2	43.4 ± 3.9	67.2 ± 4.8	82.4 ± 4.2

The observed progression indicates that biological healing became increasingly effective as sufficient moisture and healing time were provided. BC-1.0 closed approximately 2.8 times more crack area than the control after 56 days, demonstrating a substantial contribution from the microbial system beyond ordinary autogenous healing. BC-1.5 did not outperform BC-1.0 despite containing a larger amount of healing agent. This pattern indicates that maximum bacterial-carrier dosage did not correspond to maximum healing efficiency. The intermediate BC-1.0 formulation therefore represented the most balanced condition for microbial activation, calcium carbonate precipitation, and preservation of the surrounding cementitious structure.

Durability measurements confirmed that crack closure was accompanied by measurable recovery in transport-related properties. Water absorption after healing was highest in BC-0 at 5.72 ± 0.24% and lowest in BC-1.0 at 4.11 ± 0.19%. The initial sorptivity coefficient followed a comparable pattern, declining from 0.184 ± 0.013 mm/min^0.5 in the control group to 0.098 ± 0.009 mm/min^0.5 in BC-1.0. Chloride-ion penetration also decreased substantially in the bio-based mixtures. The mean electrical charge passed through BC-1.0 specimens was 1,820 ± 143 C, compared with 3,246 ± 216 C for the control group. Mechanical recovery after controlled cracking reached 88.3 ± 4.1% in BC-1.0, substantially exceeding the 54.6 ± 5.3% observed in BC-0.

Table 3. Durability and Functional Recovery after the 56-Day Healing Period

Concrete Group	Water Absorption (%)	Sorptivity (Mm/Min^0.5)	Chloride Charge Passed (C)	Flexural Recovery (%)	Reduction In Water Transport (%)
BC-0	5.72 ± 0.24	0.184 ± 0.013	3,246 ± 216	54.6 ± 5.3	8.4 ± 3.1
BC-0.5	4.86 ± 0.21	0.137 ± 0.011	2,487 ± 184	72.7 ± 4.8	30.8 ± 4.5
BC-1.0	4.11 ± 0.19	0.098 ± 0.009	1,820 ± 143	88.3 ± 4.1	49.6 ± 4.2
BC-1.5	4.34 ± 0.20	0.109 ± 0.010	2,034 ± 157	80.6 ± 4.4	43.1 ± 4.4

The durability results indicate that visible crack closure was accompanied by functional restoration of the concrete matrix. The 46.7% lower sorptivity observed in BC-1.0 relative to BC-0 suggests that mineral precipitation reduced interconnected transport pathways through the cracked material. The chloride charge passed through BC-1.0 was approximately 43.9% lower than that of the control, indicating improved resistance to ionic transport after healing. Flexural recovery followed the same general order as crack-healing efficiency, with BC-1.0 producing the highest post-healing recovery. These results indicate that the healing process was not limited to surface-level crack filling but also contributed to measurable restoration of properties relevant to durability.

One-way ANOVA identified statistically significant differences among the concrete groups for the principal mechanical, healing, and durability parameters. The effect of mixture formulation on 28-day compressive strength was significant, $F(3, 32) = 11.84$, $p < 0.001$, with an eta-squared value of 0.53. Crack-healing efficiency after 56 days showed a substantially larger between-group effect, $F(3, 32) = 64.21$, $p < 0.001$, $\eta^2 = 0.86$. Significant formulation effects were also identified for sorptivity, $F(3, 32) = 28.33$, $p < 0.001$, $\eta^2 = 0.73$; chloride

penetration, $F(3, 32) = 31.76$, $p < 0.001$, $\eta^2 = 0.75$; and flexural recovery, $F(3, 32) = 35.42$, $p < 0.001$, $\eta^2 = 0.77$.

Table 4. Inferential Statistics for Major Performance Indicators

Dependent Variable	F-Value	Df	P-Value	Effect Size (H^2)	Statistical Interpretation
28-day compressive strength	11.84	3, 32	<0.001	0.53	Significant, large effect
56-day crack healing	64.21	3, 32	<0.001	0.86	Significant, very large effect
Sorptivity	28.33	3, 32	<0.001	0.73	Significant, large effect
Chloride penetration	31.76	3, 32	<0.001	0.75	Significant, large effect
Flexural recovery	35.42	3, 32	<0.001	0.77	Significant, large effect

Tukey post hoc comparisons showed that BC-1.0 differed significantly from BC-0 for compressive strength, crack-healing efficiency, sorptivity, chloride penetration, and flexural recovery, with adjusted p-values below 0.01. Differences between BC-1.0 and BC-0.5 were also significant for 56-day crack healing and durability-related parameters. The comparison between BC-1.0 and BC-1.5 showed a smaller but statistically meaningful difference in crack-healing efficiency and mechanical recovery. Repeated-measures analysis of crack closure produced significant main effects for healing time, $F(3, 96) = 142.57$, $p < 0.001$, mixture group, $F(3, 32) = 61.48$, $p < 0.001$, and the group × time interaction, $F(9, 96) = 8.92$, $p < 0.001$. The significant interaction confirms that the rate of healing over time depended on the formulation used rather than representing a uniform temporal effect across all specimens.

Correlation analysis revealed strong relationships between crack-healing efficiency and functional durability indicators. The 56-day crack-closure percentage showed a strong positive correlation with flexural recovery, $r = 0.79$, $p < 0.001$, indicating that specimens with greater crack closure generally recovered a larger proportion of their mechanical capacity. Crack closure was also positively associated with reduction in water transport, $r = 0.84$, $p < 0.001$. An inverse relationship was observed between crack closure and chloride charge passed, $r = -0.76$, $p < 0.001$, meaning that higher healing efficiencies were associated with lower ionic transport through the concrete.

Table 5. Correlation among Self-Healing, Mechanical, and Durability Variables

Variables	Correlation Coefficient (R)	P-Value	Relationship
Crack healing × flexural recovery	0.79	<0.001	Strong positive
Crack healing × reduction in water transport	0.84	<0.001	Strong positive
Crack healing × chloride charge passed	−0.76	<0.001	Strong negative
Flexural recovery × sorptivity	−0.71	<0.001	Strong negative
Compressive strength × crack healing	0.48	0.006	Moderate positive

The relationship between compressive strength and crack-healing efficiency was weaker than the associations involving durability parameters, with $r = 0.48$, $p = 0.006$. This finding indicates that mixtures exhibiting higher initial mechanical strength did not necessarily show proportionally greater self-healing performance. Functional healing appeared more closely related to mineral sealing and restoration of transport resistance than to compressive strength alone. The strong correlations among crack closure, water-transport reduction, chloride resistance, and flexural recovery support the interpretation that the biological healing process

affected several interconnected performance dimensions rather than producing a purely cosmetic closure of visible cracks.

A representative BC-1.0 specimen with an initial crack width of 0.42 mm was examined in greater detail to illustrate the progression of autonomous healing under cyclic wetting–drying exposure. The crack width decreased to 0.34 mm after 7 days, 0.23 mm after 14 days, 0.12 mm after 28 days, and 0.04 mm after 56 days. The resulting crack-closure efficiency reached 90.5% at the end of the observation period. Water sorptivity decreased from 0.191 mm/min^0.5 immediately after controlled cracking to 0.096 mm/min^0.5 after healing. Flexural reloading showed that the specimen recovered 89.2% of its pre-cracking capacity.

Table 6. Performance Evolution of a Representative BC-1.0 Specimen

Indicator	Initial Cracked Condition	14-Day Healing	28-Day Healing	56-Day Healing
Crack width (mm)	0.42	0.23	0.12	0.04
Crack closure (%)	0.0	45.2	71.4	90.5
Sorptivity (mm/min^0.5)	0.191	0.152	0.118	0.096
Flexural capacity recovery (%)		64.7	78.6	89.2

Microstructural examination of the same specimen showed progressive accumulation of crystalline material along the crack walls and within the crack cavity. SEM images indicated the formation of dense rhombohedral deposits bridging parts of the crack after the 56-day healing period. EDS analysis detected strong calcium, carbon, and oxygen signals within these deposits, while XRD analysis confirmed calcium carbonate as the dominant crystalline healing product. The mineral phase was considerably less evident in the conventional control specimens, where healing products were mainly restricted to localized areas near the crack surface.

Repeated wetting–drying exposure produced a clear distinction between conventional and bio-based concrete after the initial healing period. BC-1.0 retained 92.1 ± 3.6% of its healed flexural capacity after ten additional wetting–drying cycles, whereas BC-0 retained 71.4 ± 5.8%. BC-0.5 and BC-1.5 recorded intermediate retention values of 84.6 ± 4.5% and 87.2 ± 4.1%, respectively. Repeated exposure caused a moderate increase in water sorptivity in all groups, but the deterioration was smallest in BC-1.0. Sorptivity increased by only 8.2% in BC-1.0 after repeated exposure, compared with 22.7% in the control concrete.

Table 7. Performance Retention after Repeated Wetting–Drying Exposure

Concrete Group	Flexural Capacity Retained (%)	Increase In Sorptivity (%)	Crack Reopening After Cyclic Loading (Mm)	Overall Recovery Index (%)
BC-0	71.4 ± 5.8	22.7 ± 3.8	0.19 ± 0.04	59.8 ± 4.7
BC-0.5	84.6 ± 4.5	14.3 ± 3.1	0.12 ± 0.03	75.6 ± 4.2
BC-1.0	92.1 ± 3.6	8.2 ± 2.5	0.07 ± 0.02	87.9 ± 3.6
BC-1.5	87.2 ± 4.1	10.9 ± 2.8	0.09 ± 0.03	82.3 ± 3.9

The cyclic-exposure results provide additional evidence that the benefit of bio-based healing extended beyond the initial healing event. BC-1.0 displayed the smallest degree of crack reopening during subsequent mechanical loading, with a mean residual opening of 0.07 ± 0.02 mm compared with 0.19 ± 0.04 mm in the conventional concrete. The overall recovery index, calculated from normalized mechanical retention, water-transport recovery, and crack stability, reached 87.9 ± 3.6% for BC-1.0. This value was approximately 28 percentage points higher than the control. The results therefore indicate that the optimized bio-based formulation maintained a greater proportion of recovered functionality when subjected to repeated environmental and mechanical stress.

The complete dataset identifies BC-1.0 as the best-performing formulation among the mixtures investigated. This formulation combined the highest 28- and 56-day compressive strengths with the greatest crack-healing efficiency, lowest sorptivity, lowest chloride charge, highest flexural recovery, and strongest resistance to repeated wetting–drying exposure. Increasing the healing-agent dosage from 1.0% to 1.5% did not produce additional performance benefits and resulted in moderate reductions in strength and healing efficiency. The response therefore followed an optimum-dosage pattern rather than a simple linear relationship between the amount of biological agent and concrete performance.

The results indicate that bio-based self-healing concrete can provide measurable functional benefits relevant to long-term infrastructure performance when an appropriate healing-agent dosage and carrier system are used. Crack closure was strongly associated with restoration of transport resistance and mechanical performance, while repeated-exposure tests showed that the healed specimens retained a larger proportion of their recovered properties than conventional concrete. These findings support the potential contribution of the developed material to sustainable and resilient infrastructure through reduced crack permeability, improved durability, enhanced post-damage recovery, and potentially lower repair demand. The evidence should be interpreted at the material level, because the laboratory results demonstrate improved resilience-related properties rather than direct proof that the concrete alone can prevent structural failure during earthquakes, floods, or other disasters.

The present study demonstrated that incorporating a bio-based bacterial healing system into concrete produced measurable improvements in mechanical performance, autonomous crack closure, transport resistance, and post-damage recovery. Among the four formulations examined, BC-1.0 consistently produced the most balanced performance. Its 28-day compressive strength reached 42.8 MPa compared with 38.6 MPa for conventional concrete, while the difference became slightly greater after 56 days. The improvement indicates that the bacterial-biochar system did not merely function as a dormant healing component activated after cracking but also influenced the development of the cementitious matrix before damage. The reduced slump observed with increasing bio-based agent dosage shows, at the same time, that improvements in hardened performance were accompanied by changes in fresh-state behavior that would require consideration during mixture optimization.

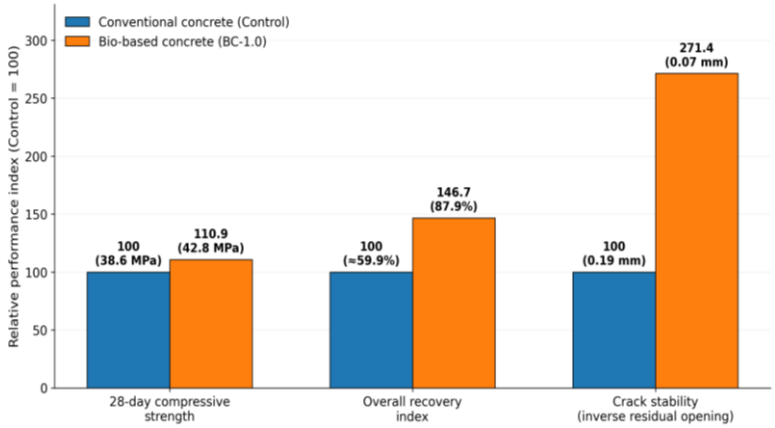


Figure 1. Combined Performance Comparison of Conventional Concrete and BC-1.0
Note: The control recovery index (≈59.9%) is inferred from the reported ~28 percentage-point difference. Crack stability is expressed as the inverse of residual crack opening so that higher values indicate better performance.

The crack-healing results provided the clearest evidence of the effectiveness of the developed system. BC-1.0 achieved approximately 89.1% crack closure after 56 days, substantially exceeding the 31.4% recorded for conventional concrete. The progression from 25.6% healing after 7 days to almost complete crack closure after 56 days indicates that

autonomous repair was strongly time dependent. BC-1.5 also demonstrated high healing efficiency, but increasing the healing-agent content beyond 1.0% did not generate a proportional improvement. The existence of an optimum formulation is an important finding because it challenges the assumption that greater bacterial or carrier content automatically produces greater self-healing capacity.

Durability-oriented results showed that the benefits of biological healing extended beyond visible crack sealing. BC-1.0 reduced sorptivity to approximately 0.098 mm/min^0.5 compared with 0.184 mm/min^0.5 in the control group and decreased chloride charge passed from approximately 3,246 C to 1,820 C. Flexural recovery reached 88.3%, compared with only 54.6% in conventional concrete. Strong relationships between crack closure, water-transport reduction, chloride resistance, and flexural recovery indicate that the deposited healing products partially restored functional properties within the damaged cementitious matrix. Such findings are particularly relevant because contemporary reviews emphasize that the effectiveness of microbial concrete should be evaluated using permeability, durability, and mechanical-recovery indicators rather than crack closure alone.

Repeated-exposure testing further showed that the improved performance was not restricted to a single healing period. BC-1.0 retained approximately 92.1% of its healed flexural performance following additional wetting–drying exposure and experienced less crack reopening than the control concrete. The overall recovery index of 87.9% suggests that the optimized system possessed a meaningful capacity to maintain recovered functionality when subjected to renewed environmental and mechanical stresses. These findings are significant for the proposed infrastructure-resilience application because real structures rarely experience only one isolated cracking event. Repeated moisture fluctuations, traffic loads, thermal stresses, and environmental deterioration require healing systems that remain functional after their initial activation.

The findings are broadly consistent with the rapidly expanding literature on microbial self-healing concrete. Recent systematic and critical reviews report that *Bacillus*-based systems can improve crack closure, reduce water absorption and chloride penetration, and preserve or enhance mechanical performance through microbially induced calcium carbonate precipitation. A meta-analysis of bio-concrete studies concluded that bacteria-incorporated concrete exhibits substantially greater self-healing efficiency than conventional control concrete, while contemporary reviews identify permeability reduction and durability enhancement as some of the most reproducible benefits of microbial healing. The present results therefore reinforce a broader body of evidence suggesting that microbial mineralization can convert crack repair from an externally applied maintenance action into a partially autonomous material response.

The observed optimum performance at the intermediate BC-1.0 dosage also agrees with evidence showing that bacterial self-healing performance is governed by an optimum biological concentration rather than an unrestricted dose-response relationship. Research on bacteria-based cementitious materials has reported effective microbial concentrations generally within approximately 10^5–10^8 cells/mL, while recent reviews warn that excessive biological additives or carrier materials may modify hydration, pore structure, workability, or matrix continuity. A recent investigation using *Bacillus subtilis* similarly found that bacterial concentration materially affected mechanical and healing performance and cautioned that excessive concentration could interfere with cementitious processes. The reduced performance of BC-1.5 relative to BC-1.0 is therefore scientifically plausible rather than anomalous.

Comparable evidence has been reported for biochar-supported microbial systems. Research using carbonized agricultural waste to immobilize *Bacillus subtilis* documented substantial crack sealing, reduced sorptivity, calcium carbonate formation, and mechanical-strength recovery. More recent work using non-reactive coconut-shell biochar as a bacterial carrier demonstrated prolonged bacterial viability, healing of cracks approaching 0.80 mm after 56 days, and substantial restoration of impermeability. These studies support the interpretation

that porous carbonaceous carriers can perform multiple functions by protecting bacterial spores, retaining moisture, providing nucleation surfaces, and facilitating mineral precipitation after cracking.

One distinction between the present findings and portions of the existing literature concerns the relationship between healing-agent dosage and maximum performance. Some reviews report that higher bacterial concentrations can generate the greatest crack closure or impermeability within the dosage ranges examined. The present results instead showed a decline when the bio-based agent increased from 1.0% to 1.5%. This difference is not necessarily contradictory because bacterial concentration cannot be interpreted independently from carrier content, nutrient concentration, pore structure, water availability, and cement chemistry. The present system incorporated microorganisms through a porous biochar carrier; consequently, increasing the healing agent also increased the amount of a physically distinct phase within the cement matrix. The resulting trade-off between microbial availability and matrix integrity provides a credible explanation for the non-linear response.

The pattern observed in this study represents evidence that self-healing performance should be understood as a coupled biological–material phenomenon rather than simply as a bacterial process occurring inside concrete. Bacterial activity alone cannot explain the overall performance because the microorganisms must survive mixing and curing, remain sufficiently protected during dormancy, receive water and nutrients after cracking, precipitate minerals at appropriate locations, and interact with a cementitious matrix capable of retaining the newly formed deposits. Reviews of microbial concrete consistently identify pH, moisture, temperature, oxygen, nutrient availability, crack width, microbial viability, and encapsulation method as interdependent determinants of healing success. The high performance of BC-1.0 therefore signals successful integration of these conditions rather than the isolated effect of bacterial presence.

The strong relationship between crack closure and reduced sorptivity represents another important signal. Surface crack closure becomes engineeringly meaningful only when it reduces the pathways through which water, chlorides, carbon dioxide, and other aggressive agents penetrate concrete. The strong positive association between crack healing and water-transport recovery, together with the negative association between healing and chloride penetration, suggests that calcium carbonate precipitation generated sufficient densification to alter transport behavior (Nair et al., 2024; Zhang & Li, 2026). Recent reviews similarly conclude that reductions in permeability and sorptivity are among the clearest durability advantages associated with microbial self-healing systems. The finding consequently shifts the interpretation from “a crack was filled” toward “a deterioration pathway was partially interrupted.”

The retention of post-healing performance after repeated exposure signals a potentially more important property than initial crack closure itself. Infrastructure resilience requires materials that can tolerate damage, recover selected functions, and continue operating when subsequent disturbances occur. The smaller crack reopening and higher flexural retention of BC-1.0 suggest that the deposited mineral phase contributed to some degree of persistent functional stabilization. This property should not be confused with complete restoration of the original structural state because microbial precipitation cannot necessarily re-establish reinforcement continuity, recover severe fracture damage, or restore all tensile-transfer mechanisms across a major structural crack. The findings instead indicate a material capacity for partial recovery that may complement conventional structural-resilience strategies.

At a broader conceptual level, the results signal a transition from passive durability design toward adaptive material design. Conventional concrete durability relies predominantly on preventing deterioration through adequate cover, low permeability, appropriate mixture proportions, reinforcement protection, and periodic maintenance. Bio-based self-healing introduces a second layer of defense in which the material responds after microdamage occurs.

Contemporary literature increasingly describes this capacity as a promising pathway toward longer-lasting and more resource-efficient infrastructure, while continuing to identify long-term microbial viability, cost, scalability, and standardization as unresolved barriers. The present findings therefore represent progress toward adaptive infrastructure materials rather than a replacement for established durability engineering.

The practical significance of the findings lies first in the possibility of reducing the consequences of early and moderate cracking. Cracks frequently become problematic not because their initial dimensions immediately threaten structural collapse but because they accelerate water ingress, reinforcement corrosion, chemical attack, and progressive material degradation. A concrete formulation capable of autonomously closing such cracks and reducing permeability may delay the transition from minor damage to costly deterioration. Infrastructure assets that are difficult to inspect or repair, including tunnels, bridge components, retaining structures, marine infrastructure, drainage facilities, dams, and underground construction, may particularly benefit from this capability (Abavisani et al., 2023; Das & Yang, 2026). Recent evidence of field and large-scale applications of self-healing technologies in tunnels, retaining structures, and marine works supports the technical relevance of moving research beyond laboratory specimens.

The implications for infrastructure maintenance are equally important. Conventional maintenance strategies are predominantly reactive: damage is identified through inspection, evaluated, and repaired using external intervention. Autonomous healing could shift part of this burden toward preventive material-level recovery occurring before extensive deterioration develops. The potential benefit is not the elimination of inspection or maintenance, which would be an unrealistic conclusion, but a reduction in repair frequency or severity. This distinction matters for infrastructure management because even partial reductions in emergency repairs, lane closures, specialized labor, replacement materials, and associated service disruption can produce meaningful economic and social benefits over a long service life (I. Ahmad et al., 2026; Hammad et al., 2026).

The sustainability implication requires more caution than is often acknowledged in bio-concrete literature. A material cannot be classified as environmentally superior merely because its healing mechanism is biological. Life-cycle research has shown that bacteria-based self-healing concrete can have a higher initial environmental footprint than conventional concrete because of bacterial cultivation, nutrients, encapsulation materials, and carrier production. One published life-cycle assessment found higher embodied impacts for bacteria-based self-healing concrete at the material-production stage while also showing that strategic application and reduced reinforcement or maintenance requirements could offset part of those burdens. A 2025 whole-life assessment of self-healing systems similarly demonstrated that higher initial embodied emissions may be compensated through reductions in repair and maintenance over the service life.

The disaster-risk-reduction implication should also be defined precisely. The present laboratory findings do not establish that BC-1.0 will prevent collapse during an earthquake, protect a bridge during extreme flooding, or guarantee structural functionality after a severe disaster. Such claims would require structural-scale experiments, hazard-specific loading, reinforcement interaction, component testing, and system-level reliability analysis. The results instead indicate that bio-based self-healing may reduce one component of vulnerability by improving post-cracking durability and retaining selected mechanical and transport properties. Disaster risk reduction should therefore be conceptualized as a potential consequence of reduced deterioration and enhanced recovery capacity within a larger resilience framework rather than as an intrinsic property of the concrete itself.

The superior performance of BC-1.0 can primarily be explained by the interaction between microbial biomineralization and the porous carrier system. Crack formation created pathways for moisture and oxygen to reach dormant bacterial spores. Reactivation of the

microorganisms in the presence of an available calcium source promoted carbonate precipitation, allowing calcium carbonate to accumulate within crack spaces. SEM–EDS and XRD observations showing calcium-rich carbonate deposits support this mechanism. Contemporary reviews describe MICP as the principal process through which many *Bacillus*-based systems fill cracks and densify damaged cementitious microstructures. The increasing crack closure between 7 and 56 days is consistent with a progressive biological-mineralization process rather than instantaneous physical sealing.

The weaker performance of BC-0.5 can be explained by an insufficient quantity or distribution of active healing components within the matrix. Fewer bacterial spores and nucleation sites would reduce the probability that newly formed cracks intersect areas containing viable microorganisms and available nutrients. Mineral precipitation could therefore occur locally without producing sufficient deposits to bridge the complete crack cross-section. The 68.2% healing efficiency recorded after 56 days still demonstrates substantial biological activity, but the lower performance relative to BC-1.0 indicates that the concentration did not provide the optimum spatial distribution of healing agents.

The high dosage in BC-1.5 appears to have crossed the point at which additional biological-carrier material provided diminishing benefits. Porous biochar can assist bacterial protection, water retention, and mineral nucleation, yet excessive carrier content may create additional pores, increase water demand, reduce workability, interfere with particle packing, or weaken local interfacial zones. Research on bacterial self-healing systems consistently shows that dosage optimization is necessary because the healing system can influence the properties of uncracked concrete as well as post-cracking recovery. The lower slump, compressive strength, and healing efficiency of BC-1.5 relative to BC-1.0 are compatible with such a balance between positive biomineralization and negative matrix modification.

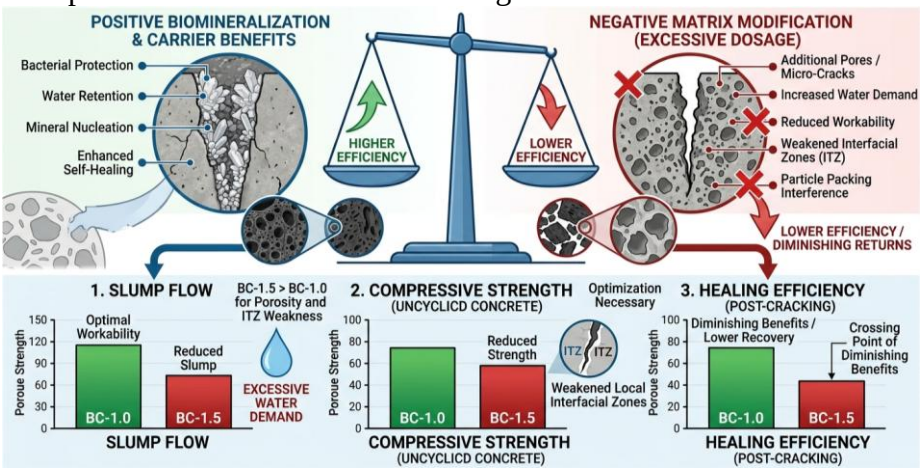


Figure 2. Optimizing Bacterial-Carrier (BC) Dosage for Concrete Self-Healing

The decline in water and chloride transport can be attributed to physical obstruction and microstructural densification produced by mineral precipitation. Calcium carbonate deposited within cracks reduces the effective cross-sectional area available for fluid movement, while precipitation around connected pores can increase tortuosity and interrupt capillary pathways. Biochar may have provided additional nucleation sites for mineral growth, contributing to a denser crack-filling layer. Recent biochar-based self-healing studies have reported the same combination of mineral deposition, reduced permeability, and improved crack closure, supporting this mechanistic explanation. The strong relationship observed between crack closure and durability recovery is therefore consistent with a pore-blocking and crack-bridging mechanism.

Future research should first verify the present laboratory findings using larger specimens and structural components. Concrete beams, reinforced slabs, bridge-deck elements, retaining-wall panels, and precast components would provide more realistic information concerning how

bio-based healing interacts with reinforcement, stress redistribution, crack branching, and multiple-crack development. Structural-scale cyclic loading should be particularly important for the disaster-resilience argument because earthquakes, traffic, settlement, and repeated environmental loading produce damage patterns that cannot be adequately represented by a single laboratory crack. Large-scale validation would make it possible to determine whether the strong material-level recovery observed in BC-1.0 persists when structural complexity increases.

Field validation should examine bacterial survival and healing performance over periods of years rather than weeks. Existing reviews continue to identify long-term microbial viability, field exposure, carrier stability, compatibility with different cement chemistries, and scale-up as major barriers to commercialization. Future experiments should expose bio-based concrete to tropical humidity, coastal salinity, prolonged drying, flooding cycles, elevated temperatures, sulfate-rich environments, and combinations of environmental stresses. Such investigations would be particularly relevant for disaster-prone tropical regions, where high moisture, heat, intense rainfall, coastal exposure, and aggressive environmental conditions may either promote or inhibit microbial healing depending on the formulation.

Life-cycle and techno-economic assessment should become an integral component of subsequent research rather than an optional sustainability claim. Recent evidence demonstrates that the environmental advantage of self-healing concrete is strongly dependent on damage severity, repair strategy, system composition, and the number of healing events achieved during service. A 2026 life-cycle study comparing biological healing approaches with conventional crack repair found that environmental performance varied substantially according to crack severity and repair alternative; biological systems could be advantageous for some moderate-to-severe repair scenarios but were not automatically superior for every crack condition. Future assessment of BC-1.0 should therefore quantify bacterial cultivation, biochar production, calcium-source consumption, transportation, maintenance savings, service-life extension, and end-of-life implications using a transparent functional unit and realistic infrastructure scenarios.

Standardization represents the final requirement for translating the current findings into practical engineering applications. Existing studies use widely different bacterial concentrations, crack-generation techniques, healing periods, curing conditions, crack-width thresholds, and definitions of healing efficiency, making direct comparison difficult. Recent reviews repeatedly identify standardized testing and reporting as critical barriers to industrial adoption. Future work should combine surface crack closure with permeability recovery, mechanical recovery, durability retention, microbial viability, repeated-healing capacity, and long-term structural indicators. Such a multidimensional framework would allow bio-based self-healing concrete to be evaluated not merely as an experimental material capable of producing calcium carbonate, but as a credible engineering technology whose contribution to sustainable infrastructure and disaster risk reduction can be objectively quantified.

CONCLUSION

The most important finding of this study is that the bio-based self-healing concrete did not exhibit a simple linear relationship between healing-agent dosage and engineering performance. The BC-1.0 formulation produced the most balanced results, combining the highest crack-healing efficiency, improved compressive strength, lower water sorptivity, reduced chloride penetration, stronger flexural recovery, and better performance retention under repeated wetting–drying exposure. This finding distinguishes the study from approaches that emphasize maximum biological content as the primary route to improved healing. The results indicate that effective self-healing depends on achieving an optimum interaction between microbial activity, carrier content, pore structure, and cementitious matrix integrity. The study also demonstrates that visible crack closure alone is insufficient to define successful

healing, because functional recovery in transport resistance and mechanical performance provides a more meaningful indication of the material's contribution to long-term infrastructure durability and resilience.

The principal contribution of this research lies in both its conceptual and methodological dimensions. Conceptually, the study positions bio-based self-healing concrete as an adaptive infrastructure material whose value is not limited to autonomous crack sealing but extends to durability recovery, maintenance reduction, and potential enhancement of infrastructure resilience. The research also clarifies that disaster risk reduction should not be interpreted as a direct consequence of crack closure, but as a potential system-level benefit arising from reduced deterioration vulnerability and improved post-damage functionality. Methodologically, the study proposes a multidimensional assessment framework that combines crack-healing efficiency, mechanical recovery, water-transport resistance, chloride penetration, microstructural characterization, and repeated-exposure performance. This integrated approach provides a more robust basis for evaluating self-healing concrete than studies relying predominantly on visual crack measurements and offers a potentially transferable framework for future research on smart and sustainable construction materials.

The study remains limited by its laboratory scale, relatively short healing period, controlled exposure conditions, and reliance on material-level rather than structural-scale resilience indicators. The experimental specimens did not reproduce the complexity of reinforced structural elements subjected to real earthquakes, floods, long-term fatigue, temperature extremes, chemical attack, or combined environmental hazards. Long-term bacterial viability, repeated healing over multiple damage cycles, field-scale constructability, economic feasibility, and whole-life environmental performance were also outside the present scope. Future research should therefore validate the optimized bio-based formulation in reinforced beams, slabs, bridge components, coastal structures, and other full-scale infrastructure systems under realistic cyclic loading and environmental exposure. Additional studies should integrate life-cycle assessment, techno-economic analysis, long-term microbial monitoring, and standardized resilience indicators to determine whether the observed laboratory benefits can translate into measurable reductions in maintenance demand, lifecycle emissions, infrastructure vulnerability, and recovery time after damaging events.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used BlackBox AI to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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