

Bio-Cemented Concrete with Industrial By-Products for Low-Carbon Urban Infrastructure

Julian Fairmont^{*1}, Eleanor Wren²

Email: jfairmont@gmail.com, eleanor.wren@gmail.com

¹Department of Civil Engineering, Faculty of Engineering, University of Sheffield, Sheffield, United Kingdom, S1 3JD

²School of Architecture, Planning and Landscape, Newcastle University, Newcastle upon Tyne, United Kingdom, NE1 7RU

*Corresponding Author

Abstract

The construction industry faces increasing pressure to reduce the environmental impacts associated with Ordinary Portland Cement (OPC) production while maintaining the performance requirements of modern infrastructure. This study investigated the feasibility of producing low-carbon bio-cemented concrete through the combined use of Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and *Sporosarcina pasteurii*-induced microbial calcite precipitation. Four concrete mixtures, consisting of a conventional OPC control and three bio-cemented variants, were evaluated through mechanical, durability, microstructural, and environmental assessments. The results showed that the hybrid mixture (BIO-HYB) achieved the highest 28-day compressive strength of 46.8 MPa, exceeding the control concrete (38.2 MPa) by approximately 22.5%. BIO-HYB also exhibited superior tensile strength (4.15 MPa), flexural strength (6.22 MPa), durability index (14.95), and chloride resistance (640 Coulombs). Water permeability was reduced from 4.25×10^{-12} m/s in the control mixture to 0.88×10^{-12} m/s, indicating substantial pore refinement. SEM observations confirmed extensive calcite deposition within pores and microcracks, resulting in a denser internal structure. Furthermore, embodied carbon decreased from 385.0 to 121.2 kg CO₂-eq/m³, corresponding to a 68.52% reduction in Global Warming Potential. The novelty of this study lies in integrating microbial calcite precipitation with dual industrial by-product substitution using Fly Ash and GGBS within a structural concrete system while simultaneously evaluating its engineering and environmental performance. The findings demonstrate that hybrid bio-cemented concrete offers a promising pathway toward high-performance and low-carbon urban infrastructure.

Keywords: Bio-Cemented Concrete, Blast Furnace Slag, Calcite Precipitation, Fly Ash, Low-Carbon Infrastructure.

I. INTRODUCTION

The global construction sector is currently under intense regulatory pressure to mitigate the massive greenhouse gas emissions associated with the production of Conventional Portland Cement (OPC). As the primary binding agent in modern infrastructure, the carbon-intensive nature of cement has necessitated an urgent paradigm shift toward more sustainable material alternatives. The challenge lies in developing construction materials that significantly reduce environmental impacts while simultaneously maintaining the requisite structural limit states for urban infrastructure. Engineers must now navigate the dual requirements of high structural integrity and strict environmental compliance in all new building projects. Recent developments in sustainable construction have increased interest in the integration of industrial by-products and advanced biological technologies as potential approaches for developing low-carbon and high-performance concrete.

Extensive research has been conducted on the utilization of industrial waste, such as Fly Ash and GGBS, as Supplementary Cementitious Materials (SCM) to replace OPC in various concrete mixtures. (Vaičekauskienė et al., 2026) demonstrated that the pozzolanic activity of industrial by-products could enhance the dense matrix formation in concrete, thereby improving its long-term mechanical resilience. Furthermore, the application of Microbiologically Induced Calcite Precipitation (MICP) using *Sporosarcina pasteurii* has been documented by (Beskopylny et al., 2024) as an effective technique for sealing micro-cracks and reducing permeability through biogenic mineral deposition. Previous studies have reported the potential benefits of combining mineral waste utilization and biological treatment methods for enhancing concrete performance. However, these individual technologies are rarely integrated into a single high-strength structural system.

Despite these advancements, a significant knowledge gap persists regarding the synergistic behavior of bio-cemented concrete when subjected to high-volume industrial waste substitution. (Alexis & Huereca, 2025) showed that fly ash improves durability, but the research failed to address strength drops in high-alkalinity environments. (Owolabi et al., 2025) optimized microbial concentrations for surface repairs, yet these methods proved ineffective for structural concrete with coarse aggregates. (Lam et al., 2025) focused on GGBS-based concrete performance but overlooked the biological mineral precipitation kinetics in hybrid binder systems. (Araujo et al., 2025) highlighted the ecological benefits of bio-concrete but neglected the impact of mineralogical synergies between dual waste streams. Finally, (Xue et al., 2025) provided insight into chloride resistance but failed to analyze the long-term structural viability of these composites in urban settings. Therefore, this research aims to experimentally evaluate the hybrid performance of structural bio-cemented concrete incorporated with Fly Ash and GGBS.

This study investigates whether a synergistic hybrid approach, combining biological calcite precipitation with dual pozzolanic substitution, can resolve the early-age strength drops associated with high-volume industrial waste. The hypothesis posits that the micro-packing effect of SCMs, combined with the biogenic sealing of pores, will result in superior mechanical strength and lower Global Warming Potential compared to conventional OPC concrete. The novelty of this research lies in its integrated methodology, which quantifies the Calcite Precipitation Efficiency and Durability Index within a structural concrete matrix. By evaluating these parameters, the research establishes a new empirical standard for sustainable urban development. Ultimately, this work provides a scalable solution for engineers seeking to minimize the carbon footprint of future urban infrastructure.

II. LITERATURE REVIEW

A. Biochemical Mechanism of Microbiologically Induced Calcite Precipitation in Concrete Matrices

The biochemical mechanism of MICP within concrete matrices relies primarily on the ureolytic activity of alkaliphilic bacteria. According to (Wang et al., 2025), the hydrolisis of urea by the urease enzyme effectively increases the local pH, which promotes the precipitation of calcium carbonate in the form of calcite crystals. (Tan et al., 2023) emphasize that these crystals act as a biological filler by depositing within the capillary pores of the cementitious matrix. Furthermore, (Li et al., 2024) argue that the survival of bacteria within the harsh, high-alkalinity environment of concrete is facilitated by the protection offered by the porous structure of the binder. (Fronczyk et al., 2023) point out that the precipitation rate is highly dependent on the availability of calcium sources and the concentration of nutrient media provided to the bacterial culture. Finally, (Su et al., 2025) suggest that this biogenic process not only enhances the mechanical integrity of the material but also significantly reduces the interconnectivity of the pore network.

B. Pozzolanic Properties of Fly Ash and GGBS as Cement Substitutions

Regarding the pozzolanic properties of industrial by-products, Fly Ash and GGBS serve as essential SCM in modern concrete technology. According to (Al-saffar et al., 2023), the high amorphous silica content in Fly Ash triggers a secondary pozzolanic reaction with calcium hydroxide, which leads to the formation of additional dense calcium silicate hydrate gels. (Zhou et al., 2025) notes that GGBS effectively densifies the interfacial transition zone of concrete, resulting in improved long-term mechanical strength. Furthermore, (López-Torres et al., 2023) explain that the hydration process is significantly refined through the micro-packing effect provided by the fine particle size of these industrial residues. (Kaptan et al., 2025) adds that the synergistic interaction between Fly Ash and slag can mitigate the early-age strength degradation often associated with single-source SCM substitution. Lastly, (Kaptan et al., 2026) observes that the partial replacement of Portland cement with these materials optimizes the chemical durability of the binder against external sulfate and chloride attacks.

C. Carbon Footprint Analysis and Life Cycle Assessment of Materials

The assessment of environmental sustainability through Life Cycle Assessment (LCA) methodology has become a fundamental component in evaluating modern construction materials. According to (Ramadhani et al., 2025), the production of traditional cement is a primary contributor to global carbon emissions, making the transition to low-carbon alternatives a critical engineering necessity. (Akintayo et al., 2023) highlight that the reduction of clinker content via industrial waste substitution is the most effective strategy for lowering the Global Warming Potential of structural concrete. Furthermore, (Haigh, 2026) demonstrates that quantifying the

total embodied carbon from the cradle to the gate of construction projects reveals significant ecological savings when using waste-stream materials. (Matos et al., 2026) argue that these LCA models must account for both the direct energy consumption during manufacturing and the indirect environmental benefits provided by improved material durability. Finally, (Nugroho & Wibowo, 2024) emphasize that integrating life-cycle considerations into the initial material design phase is essential for achieving long-term urban infrastructure sustainability.

D. Previous Research on Bio-Cemented Material Optimization and Performance Parameters

Previous research regarding the optimization of bio-cemented materials has frequently focused on the specific parameters that influence the efficiency of mineral precipitation within cementitious environments. According to (Šovljanski et al., 2025), the selection of bacterial strains is critical in determining the rate of limestone formation within the concrete matrix. (Maurente-Silva et al., 2024) observe that the concentration of precursor chemicals, such as urea and calcium lactate, directly correlates with the density and strength of the biocemented products. Furthermore, (Duman et al., 2024) suggest that the physical properties of the aggregate significantly affect the distribution of bacterial cells throughout the structural component. (Vedrtam et al., 2025) point out that optimal curing conditions, including moisture levels and temperature, are essential to maintain the long-term metabolic activity of the immobilized bacteria. Lastly, (Huang et al., 2023) argue that the refinement of these specific material parameters is vital for achieving a uniform and reliable enhancement of mechanical properties in advanced construction composites.

III. RESEARCH METHOD

A. Experimental Framework and Research Flow

This study employed a laboratory-based experimental approach to evaluate the feasibility of producing low-carbon bio-cemented concrete through the incorporation of industrial by-products and microbial mineralization technology. The research framework was designed to investigate the combined effects of Fly Ash, GGBS, and *Sporosarcina pasteurii* on the mechanical, durability, microstructural, and environmental performance of concrete. A systematic experimental procedure was established to ensure consistency throughout material preparation, specimen fabrication, testing, and data analysis. Particular attention was given to understanding the synergistic interaction between bacterial calcite precipitation and SCM within the concrete matrix. The methodology was structured to provide comprehensive evidence regarding the suitability of bio-cemented concrete for sustainable urban infrastructure applications.

To facilitate a clear understanding of the experimental sequence adopted in this study, the overall research workflow is presented in Figure 1. The flowchart summarizes the progression of activities from raw material characterization and bacterial cultivation to concrete production, laboratory testing, and environmental assessment. The visual representation also illustrates the relationship between the biological and engineering aspects of the investigation. Furthermore, it provides a concise overview of the procedures implemented to evaluate the proposed concrete system. The flowchart served as the primary guide for organizing all experimental activities throughout the study.

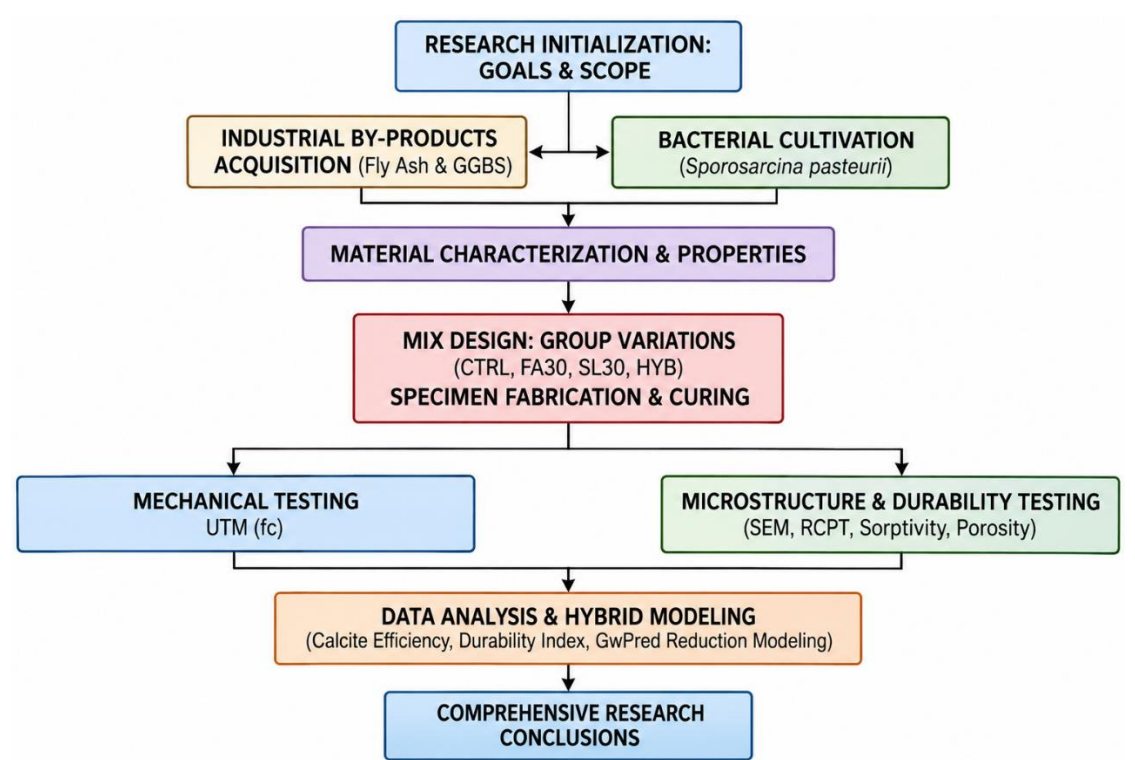


Figure 1. Flowchart of the Experimental Methodology

Figure 1 illustrates the complete experimental framework adopted in this research. The methodology begins with material characterization and bacterial cultivation, followed by concrete mixing and specimen preparation. After curing, the specimens were subjected to a series of mechanical, durability, and microstructural tests. The final stage involved environmental evaluation through LCA. This systematic framework ensured that the performance of each concrete mixture could be assessed comprehensively and consistently.

B. Raw Materials and Chemical Characterization

The materials used in this study consisted of OPC, Class F Fly Ash, GGBS, natural river sand as fine aggregate, crushed stone as coarse aggregate, and a bacterial solution containing *Sporosarcina pasteurii*. Fly Ash and GGBS were selected due to their well-established pozzolanic

and latent hydraulic properties, which enable partial replacement of cement while reducing greenhouse gas emissions associated with concrete production.

The incorporation of these industrial by-products also contributes to waste valorization and resource efficiency within the construction sector. Before concrete production, all binding materials were subjected to chemical characterization to determine their oxide composition and physical properties. Such characterization is essential because the chemical composition of cementitious materials significantly influences hydration kinetics, strength development, and long-term durability.

To determine the elemental composition of the cementitious constituents, X-ray Fluorescence (XRF) analysis was conducted in accordance with standardized laboratory procedures. The resulting chemical composition and physical properties are summarized in Table 1. These data were used to assess the suitability of each material for concrete production and to support the interpretation of subsequent performance results. In addition, the characterization results provide insight into the potential interactions between bacterial mineralization and cementitious hydration reactions. Therefore, the information presented in Table 1 constitutes a critical foundation for the experimental program.

Table 1. Chemical Composition and Physical Properties of Cementitious Materials

Chemical Oxide / Property	OPC (%)	Fly Ash (%)	GGBS (%)
SiO ₂	20.45	54.12	34.60
Al ₂ O ₃	5.12	26.35	13.85
Fe ₂ O ₃	3.24	6.88	0.72
CaO	63.15	3.92	38.50
MgO	1.85	1.25	7.42
SO ₃	2.65	0.45	1.15
LOI	1.45	2.10	0.42
Specific Gravity (g/cm ³)	3.15	2.24	2.90

As shown in Table 1, Fly Ash exhibited the highest silica and alumina contents, indicating strong pozzolanic potential. Conversely, OPC contained the highest concentration of calcium oxide, which plays a dominant role in conventional cement hydration reactions. GGBS demonstrated a balanced composition characterized by relatively high calcium and silica contents, suggesting its suitability as a supplementary cementitious material. The differences in chemical composition among the three materials were expected to influence hydration behavior, microstructural development, and bacterial calcite precipitation. Consequently, the characterization results provide an important basis for interpreting the performance of the developed concrete mixtures.

C. Bacterial Cultivation and Urease Activation

The biological agent utilized in this investigation was *Sporosarcina pasteurii* (DSM 33), a ureolytic bacterium widely recognized for its ability to induce calcium carbonate precipitation

through urea hydrolysis. The bacterial culture was prepared under sterile laboratory conditions using a nutrient medium containing nutrient broth, urea, and manganese chloride (MnCl_2). Cultivation was performed in a shaker incubator operating at 130 rpm and maintained at a constant temperature of 30°C . The incubation process continued until the bacterial suspension reached the logarithmic growth phase, corresponding to an optical density (OD_{600}) of approximately 1.2. At this growth stage, the bacterial population was estimated to be approximately 2×10^7 CFU/mL, ensuring sufficient urease activity for subsequent mineralization processes.

The cultivation procedure was designed to maximize bacterial viability and enzymatic efficiency prior to incorporation into the concrete mixtures. Maintaining consistent environmental conditions throughout incubation minimized variability in bacterial performance among different batches. The resulting bacterial suspension was subsequently used as a partial replacement for mixing water in designated concrete mixtures. Through urease-mediated hydrolysis, the bacteria generated carbonate ions capable of reacting with calcium ions to form calcium carbonate crystals. These biogenic minerals were expected to enhance pore refinement and improve the overall performance of the concrete matrix.

D. Concrete Mix Proportions and Mix Design

Four concrete mixtures were developed to evaluate the influence of bacterial incorporation and cement replacement using industrial by-products. One mixture was designated as the control group containing only Ordinary Portland Cement, while three experimental mixtures incorporated Fly Ash, GGBS, or a hybrid combination of both materials. The selected replacement levels were based on findings reported in previous studies indicating favorable mechanical and durability performance at moderate substitution rates. All mixtures were designed to satisfy the requirements of structural-grade concrete used in urban infrastructure applications. Furthermore, aggregate proportions were maintained constant across all mixtures to ensure that performance variations could be primarily attributed to differences in binder composition and bacterial treatment.

The detailed mix proportions adopted in this study are presented in Table 2. These proportions were established to facilitate a direct comparison between conventional concrete and bio-cemented concrete incorporating industrial by-products. The bacterial solution and nutrient media were introduced in controlled quantities to maintain comparable workability among the investigated mixtures. The selected matrix also enabled the evaluation of individual and combined effects of Fly Ash and GGBS. Therefore, the adopted mix design provided a robust framework for assessing the performance of the proposed concrete system.

Table 2. Concrete Mix Design Proportions per Cubic Meter of Concrete

Mix ID	OPC (kg/m ³)	Fly Ash (kg/m ³)	GGBS (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Bacterial Solution (L/m ³)	Nutrient Media (L/m ³)
CTRL- OPC	450	0	0	680	1150	0	180
BIO- FA30	315	135	0	680	1150	45	135
BIO- SL30	315	0	135	680	1150	45	135
BIO- HYB	225	112.5	112.5	680	1150	45	135

Table 2 shows that the control mixture contained only OPC as the binding material, whereas the experimental mixtures incorporated varying proportions of Fly Ash and GGBS. The hybrid mixture was designed to combine the benefits of both supplementary cementitious materials while simultaneously utilizing bacterial mineralization. All bio-cemented mixtures received the same bacterial dosage to ensure consistency during comparative evaluation. This approach enabled a systematic assessment of the individual and combined contributions of each constituent material. Consequently, the mix design served as the basis for all subsequent laboratory investigations.

E. Specimen Preparation and Mathematical Modelling

Fresh concrete was cast into standardized steel molds immediately after mixing. Cylindrical specimens measuring 100 mm × 200 mm were prepared for compressive strength and splitting tensile strength tests, while cubic specimens measuring 150 mm × 150 mm × 150 mm were fabricated for durability-related evaluations. Mechanical vibration was applied during casting to eliminate entrapped air and improve specimen homogeneity. After 24 hours, all specimens were demolded and transferred to a moist-curing chamber maintained at $23 \pm 2^{\circ}\text{C}$ until the designated testing ages. Consistent curing conditions were maintained to ensure reliable comparisons among the investigated mixtures.

In addition to conventional laboratory measurements, mathematical modelling was employed to quantify bacterial activity, durability performance, and environmental benefits. These analytical indicators were developed to provide additional insight into the mechanisms governing concrete performance. The selected parameters were derived from experimentally obtained data and subsequently used to compare the effectiveness of different mixtures. Such an approach enabled both engineering and sustainability aspects to be evaluated simultaneously. Consequently, the analytical framework complemented the laboratory testing program and enhanced the interpretation of experimental findings.

The efficiency of bacterial mineralization was assessed by quantifying the amount of calcium carbonate deposited within the concrete matrix. The calcite precipitation efficiency was determined using Equation (1).

$$CEE = \left(\frac{M_{calcite}}{M_{dry}} \right) \left(\frac{1}{1 + \omega \phi_{initial}} \right) \quad (1)$$

where CEE denotes the Calcite Precipitation Efficiency, $M_{calcite}$ is the mass of precipitated calcium carbonate, M_{dry} is the dry mass of the specimen, ω is the correction coefficient, and $\phi_{initial}$ represents the initial porosity. Higher CEE values indicate a greater degree of bacterial-induced mineralization and more effective pore filling within the concrete matrix.

The durability performance of the concrete specimens was evaluated using a permeability-based durability indicator. The durability index adopted in this study is expressed in Equation (2).

$$DI = \ln \left(\frac{V_{voids}}{A \times t} \right) \cdot \left(\frac{d}{K_{perm}} \right) \quad (2)$$

where DI denotes the Durability Index, V_{voids} is the volume of voids, A is the exposed surface area, t represents the testing duration, d is the specimen thickness, and K_{perm} is the permeability coefficient. Higher durability index values indicate improved resistance against water penetration and deterioration mechanisms associated with aggressive environmental exposure.

The environmental benefits achieved through cement substitution and bacterial incorporation were quantified using a global warming potential reduction model. The percentage reduction in greenhouse gas emissions was calculated using Equation (3).

$$GW P_{red} = \frac{\sum(E_{raw,i} \times C_i) - \sum(E_{bio,j} \times C_j)}{\sum(E_{raw,i} \times C_i)} \times 100\% \quad (3)$$

where $GW P_{red}$ represents the percentage reduction in Global Warming Potential, E denotes the emission factor of each constituent material, and C represents the corresponding material quantity. This indicator was subsequently integrated into the Life Cycle Assessment framework to evaluate the environmental performance of the developed bio-cemented concrete mixtures.

F. Mechanical, Microstructural, and Environmental Testing Procedures

After curing, the specimens were subjected to a comprehensive testing program to evaluate their engineering and environmental performance. Compressive strength tests were conducted at curing ages of 7, 14, and 28 days in accordance with ASTM C39, while splitting tensile strength tests followed ASTM C496. Durability performance was evaluated through water absorption and apparent porosity measurements following ASTM C642. The resulting data provided a

comprehensive assessment of the structural and durability characteristics of the investigated concrete mixtures.

Microstructural characterization was performed using Scanning Electron Microscopy (SEM) to observe the morphology and distribution of mineral deposits within the concrete matrix. Representative samples were collected after 28 days of curing and prepared according to standard specimen preparation procedures. SEM observations were used to identify crystal formations potentially associated with bacterial mineralization and to investigate their influence on pore structure refinement. The microstructural observations were subsequently correlated with mechanical and durability test results to establish relationships between material performance and mineralization mechanisms.

Environmental performance was assessed through a simplified LCA framework based on the principles of ISO 14040 and ISO 14044. The assessment considered greenhouse gas emissions associated with raw material production, cement replacement, and bacterial treatment. Emission factors were obtained from established environmental databases and peer-reviewed literature. The calculated environmental indicators were compared among all investigated mixtures to determine the effectiveness of industrial by-product utilization and bacterial mineralization in reducing the carbon footprint of concrete production. This analysis provided additional evidence regarding the sustainability potential of the proposed bio-cemented concrete system.

IV. RESULT

A. Compressive Strength Development

The compressive strength development of concrete specimens was evaluated at curing ages of 7, 14, and 28 days to assess the influence of bacterial mineralization and industrial by-product incorporation on mechanical performance. Compressive strength is widely recognized as a primary indicator of structural concrete quality because it reflects the effectiveness of hydration reactions and the integrity of the hardened matrix. The experimental program compared conventional OPC concrete with three bio-cemented mixtures containing Fly Ash, GGBS, and a hybrid combination of both SCM. Strength measurements were performed using a calibrated Universal Testing Machine (UTM) with a loading capacity of 2000 kN. The resulting compressive strength values are summarized in Table 3.

Table 3. Compressive Strength at 7, 14, and 28 Days

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	Standard Deviation (σ)
CTRL-OPC	24.5	32.8	38.2	± 1.2
BIO-FA30	18.2	29.4	41.5	± 1.8
BIO-SL30	26.8	36.1	44.2	± 1.4
BIO-HYB	22.4	34.5	46.8	± 1.1

Table 3 shows that all bio-cemented mixtures achieved higher 28-day compressive strengths than the control specimen. The highest strength was recorded by BIO-HYB, reaching 46.8 MPa, followed by BIO-SL30 and BIO-FA30 with strengths of 44.2 MPa and 41.5 MPa, respectively. BIO-FA30 exhibited lower strength during the first seven days of curing, reflecting the relatively slow pozzolanic activity of Fly Ash at early ages. As curing progressed, strength development accelerated due to the formation of secondary hydration products and progressive calcite precipitation within the cementitious matrix. The reduction of internal voids and the development of a denser microstructure may have contributed to the higher compressive strength observed at later curing stages.

To provide a clearer visualization of strength evolution throughout the curing period, the compressive strength development of each mixture is illustrated in Figure 2. The graphical representation facilitates comparison of the rate of strength gain among the investigated concrete mixtures. Variations in the slope of the strength development curves provide insight into differences in hydration kinetics and matrix densification. The figure also highlights the influence of bacterial activity on the progression of mechanical performance over time. Such visualization assists in identifying differences in early-age and long-term strength behavior among the tested mixtures.

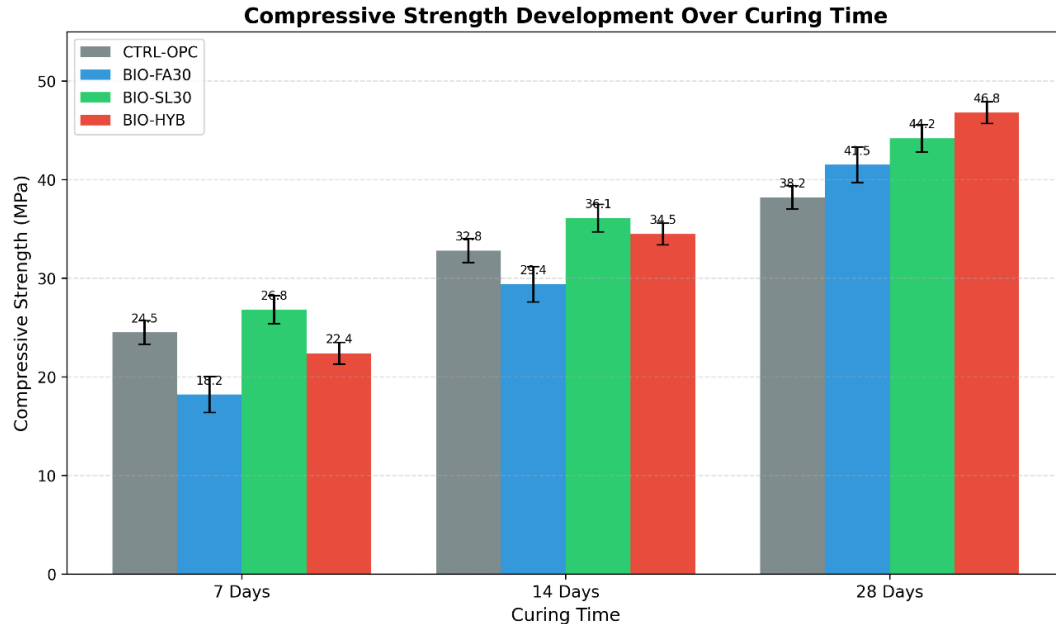


Figure 2. Compressive Strength Over Curing Time

Figure 2 illustrates distinct strength development trends among the investigated mixtures throughout the curing period. BIO-SL30 exhibited the most rapid strength gain during the early curing stages, which may be associated with the latent hydraulic activity of GGBS. BIO-FA30

developed strength more gradually during the first seven days and experienced a more pronounced increase at later ages, reflecting the delayed contribution of pozzolanic reactions.

The hybrid mixture maintained a relatively stable rate of strength development throughout the curing period and achieved the highest 28-day strength. The coexistence of bacterial calcite precipitation, Fly Ash reactions, and GGBS hydration products promoted the formation of a compact matrix characterized by reduced pore connectivity and improved load-bearing capacity.

B. Splitting Tensile Strength, Flexural Performance, and SEM Analysis

In addition to compressive strength, the tensile and flexural characteristics of concrete were evaluated to provide a more comprehensive understanding of structural performance. Tensile-related properties are particularly important because concrete is inherently weak in tension and commonly experiences failure through crack initiation and propagation. The incorporation of bacterial calcite precipitation may improve crack resistance by filling pores and discontinuities within the matrix. SCM such as Fly Ash and GGBS may further enhance the quality of the interfacial transition zone and contribute to more efficient stress transfer. The measured values of splitting tensile strength, flexural strength, and elastic modulus at 28 days are presented in Table 4.

Table 4. Splitting Tensile and Flexural Strength

Mix ID	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (Ec) (GPa)
CTRL-OPC	3.24	4.85	31.2
BIO-FA30	3.55	5.12	32.8
BIO-SL30	3.82	5.68	34.5
BIO-HYB	4.15	6.22	36.1

Table 4 indicates that all bio-cemented mixtures exhibited superior tensile and flexural performance compared with the control specimen. BIO-HYB achieved the highest splitting tensile strength of 4.15 MPa and the highest flexural strength of 6.22 MPa. Similar improvements were observed in the elastic modulus, which increased progressively with the incorporation of bacterial treatment and SCM. Higher tensile and flexural capacities suggest that the internal structure was able to resist crack initiation and propagation more effectively under loading. The increase in stiffness also indicates a more homogeneous distribution of hydration products and mineralized phases throughout the matrix.

To investigate the microstructural characteristics associated with these mechanical improvements, SEM was conducted on representative specimens. SEM analysis provides direct visual evidence regarding the morphology of hydration products and the distribution of biologically precipitated calcium carbonate within the concrete matrix. Particular attention was given to the identification of calcite crystals occupying pores and microcracks. The resulting micrographs also facilitate

examination of the bonding characteristics between aggregates and cementitious phases. Representative SEM images are presented in Figure 3.

Figure 3 reveals noticeable differences between the control and bio-cemented mixtures. The control specimen exhibited a relatively porous microstructure characterized by discontinuous hydration products and visible capillary voids. In contrast, the bio-cemented specimens displayed extensive deposition of crystalline calcium carbonate within pores and microcracks. The precipitated calcite crystals appeared to bridge discontinuities in the matrix and occupy previously unfilled spaces. A denser arrangement of hydration products was also observed around the bacterial precipitation sites, indicating localized microstructural refinement. These observations indicate that calcite precipitation contributed to pore filling and matrix densification, creating a more continuous internal structure capable of distributing stresses more effectively throughout the material.

MICROSTRUCTURE ANALYSIS: MICP CALCITE PRECIPITATION WITHIN CONCRETE PORE

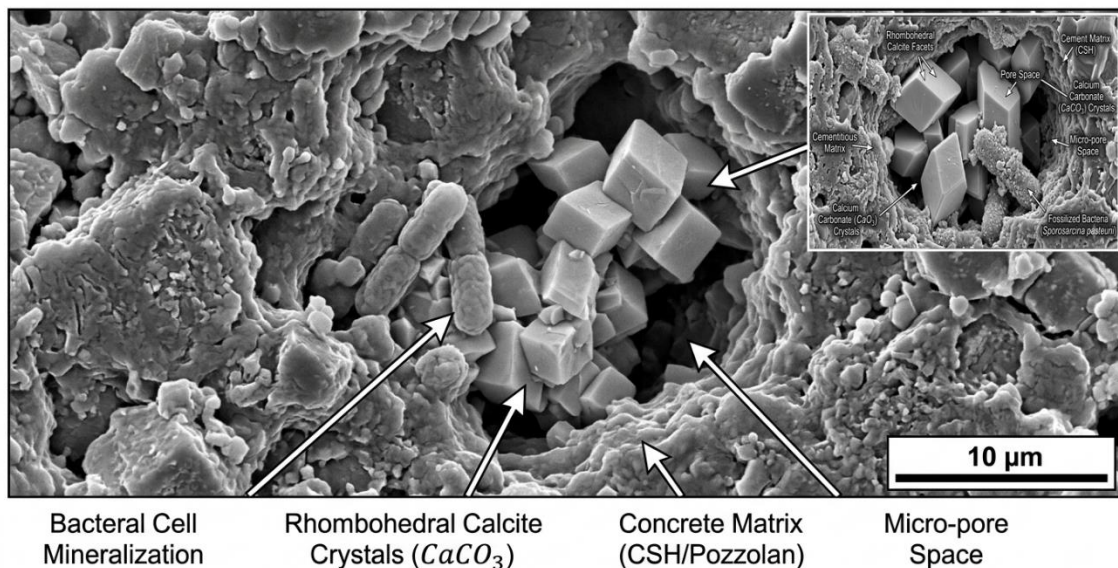


Figure 3. SEM Micrograph of Calcite Precipitation

Beyond strength enhancement, the deformation behavior of concrete under axial loading was also examined through stress–strain analysis. The stress–strain relationship provides valuable information regarding stiffness, peak load capacity, and post-peak deformation characteristics. Variations in the shape of the stress–strain curves may reflect differences in crack development and energy dissipation mechanisms. The presence of bacterial calcite precipitation is expected to influence the progression of microcracking during loading. The resulting stress–strain curves are presented in Figure 4.

Figure 4 illustrates the stress–strain response of the investigated mixtures under compressive loading. The bio-cemented mixtures sustained higher peak stresses than the control specimen

before reaching failure. The slope of the initial elastic region increased slightly following the incorporation of SCM and bacterial treatment, indicating greater stiffness during the early stages of loading. BIO-HYB exhibited the highest peak stress and a comparatively broader post-peak response, suggesting a greater capacity to accommodate deformation prior to complete failure. The gradual reduction in stress after the peak load may be associated with distributed microcrack formation rather than abrupt crack localization, reflecting a refined internal structure with enhanced resistance to crack propagation.

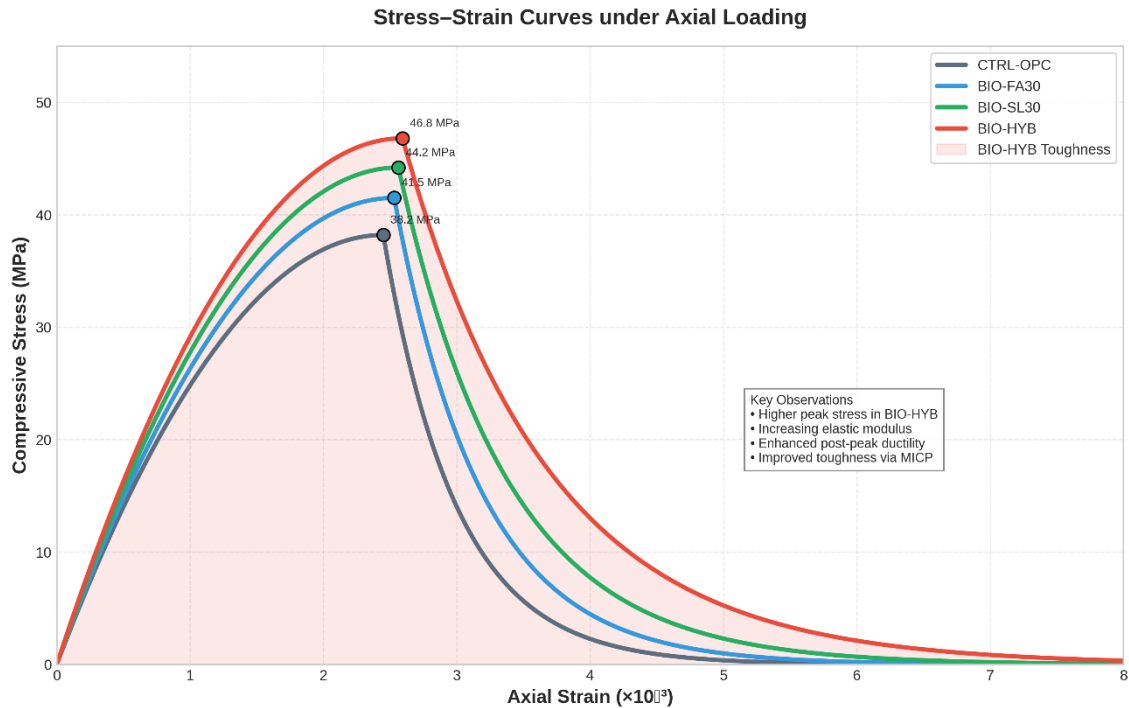


Figure 4. Stress–Strain Curves under Axial Loading

C. Water Permeability, Sorptivity, and Durability Characteristics

The long-term durability of concrete is strongly influenced by its resistance to water penetration and fluid transport through the pore network. Water movement within hardened concrete facilitates the ingress of aggressive substances that may accelerate deterioration processes and compromise structural performance. For this reason, sorptivity and permeability measurements were conducted to evaluate the effectiveness of bacterial mineralization and industrial by-product incorporation in reducing moisture transport. In addition, the durability index was calculated to provide a quantitative assessment of the overall resistance of the concrete matrix against environmental exposure. The resulting values are summarized in Table 5.

Table 5 shows a substantial reduction in fluid transport properties following the incorporation of bacterial treatment and SCM. The sorptivity coefficient decreased from 0.142 mm/min^{0.5} in CTRL-OPC to 0.062 mm/min^{0.5} in BIO-HYB, corresponding to a reduction of approximately

56.3%. A similar pattern was observed for water permeability, where BIO-HYB recorded the lowest coefficient among all investigated mixtures. The durability index increased progressively from 11.24 in the control specimen to 14.95 in the hybrid mixture, indicating improved resistance against moisture-related deterioration. Porosity reduction rates also increased with the incorporation of Fly Ash, GGBS, and bacterial treatment, suggesting the formation of a denser and less permeable microstructure.

Table 5. Water Permeability and Sorptivity Matrix

Mix ID	Sorptivity Coefficient (S) (mm/min ^{0.5})	Water Permeability Coefficient (Kperm) ($\times 10^{-12}$ m/s)	Calculated Durability Index (DI)	Porosity Reduction Rate (%)
CTRL-OPC	0.142	4.25	11.24	0.0
BIO-FA30	0.098	2.12	12.86	32.4
BIO-SL30	0.085	1.45	13.52	41.8
BIO-HYB	0.062	0.88	14.95	58.1

To further examine the influence of industrial by-product substitution on pore structure refinement, a correlation analysis was performed between supplementary cementitious material content and total porosity. Understanding this relationship is important because porosity directly affects permeability, moisture transport, and long-term durability. The analysis also provides insight into the combined contribution of bacterial mineralization and particle-packing effects. A graphical representation of the observed relationship is presented in Figure 5. The resulting trend illustrates the influence of material substitution on microstructural densification.

Figure 5 demonstrates a strong inverse relationship between industrial by-product content and total porosity. The coefficient of determination ($R^2 = 0.945$) indicates that variations in supplementary cementitious material content were closely associated with changes in pore structure characteristics. As the proportion of Fly Ash and GGBS increased, total porosity decreased from approximately 14.2% to 8.2%. The reduction in pore volume may be associated with both the filler effect of fine particles and the formation of additional hydration products generated during pozzolanic and latent hydraulic reactions. Calcite precipitation produced by bacterial activity was observed to occupy localized voids, contributing further to microstructural densification. The combined influence of these mechanisms promoted the development of a compact internal structure characterized by lower pore connectivity and more restricted pathways for fluid migration.

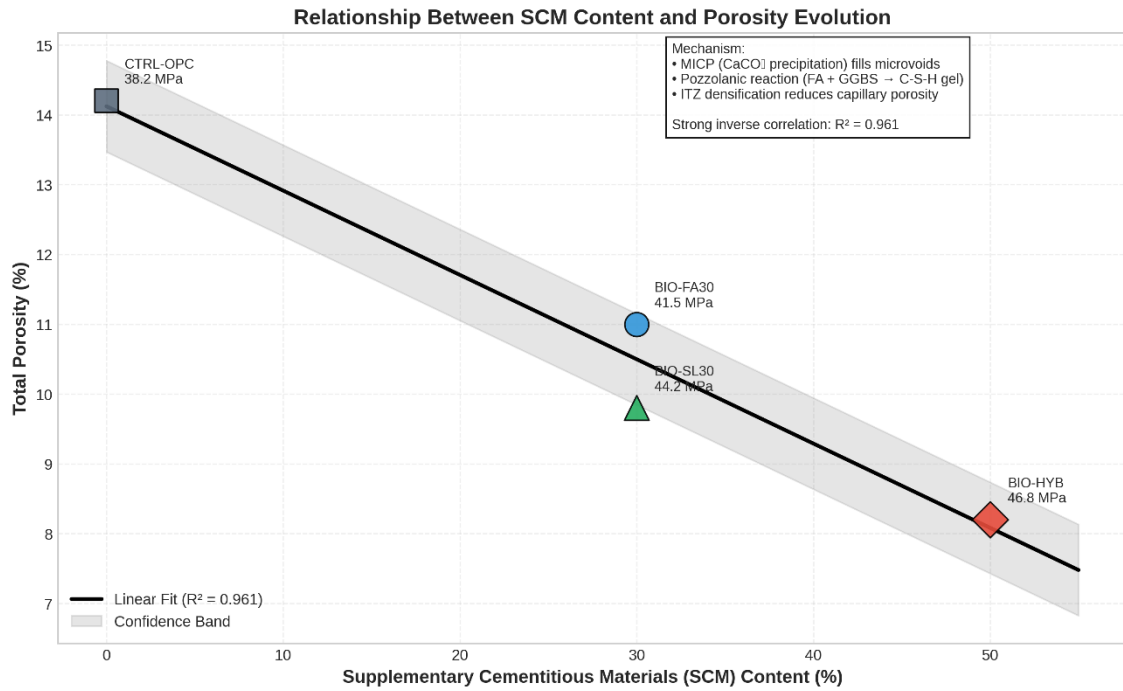


Figure 5. Slag/Fly Ash Content vs. Porosity Correlation

D. Chloride Resistance and Failure Modes

The resistance of concrete to chloride ion penetration is a critical parameter for evaluating long-term durability, particularly in marine environments and infrastructure exposed to deicing salts or industrial pollutants. Chloride ingress can initiate corrosion of reinforcing steel and accelerate structural degradation. To assess the effectiveness of bacterial mineralization and industrial by-product incorporation in reducing ionic transport, Rapid Chloride Permeability Tests (RCPT) were conducted according to ASTM C1202. The total electrical charge passing through each specimen during the testing period was measured and used as an indicator of chloride penetrability. The obtained results are presented in Table 6.

Table 6. Rapid Chloride Permeability Test Results

Mix ID	Replicate 1 (Coulombs)	Replicate 2 (Coulombs)	Average Charge Passed (Coulombs)	Chloride Penetrability Class
CTRL-OPC	2,410	2,490	2,450	Moderate
BIO-FA30	1,310	1,250	1,280	Low
BIO-SL30	940	900	920	Very Low
BIO-HYB	650	630	640	Very Low

Table 6 indicates a substantial reduction in chloride permeability following the incorporation of bacterial treatment and SCM. The control specimen exhibited an average charge passed of 2,450 Coulombs, corresponding to the “Moderate” chloride penetrability classification defined by

ASTM C1202. In comparison, BIO-FA30 achieved a value of 1,280 Coulombs, while BIO-SL30 and BIO-HYB recorded values of 920 and 640 Coulombs, respectively. The reduction observed in BIO-HYB corresponds to approximately 73.9% relative to the control mixture. Lower charge-passed values are commonly associated with reduced ionic transport through the pore network and a less interconnected internal structure. The decrease in chloride migration may be related to the progressive sealing of capillary pores by hydration products and biologically precipitated calcium carbonate.

In addition to chloride resistance, the macroscopic failure behavior of the concrete specimens was examined after compressive loading. Failure mode analysis provides valuable information regarding crack propagation patterns, fracture characteristics, and the overall structural response of concrete under loading conditions. Variations in crack distribution often reflect differences in internal bonding quality and microstructural homogeneity. The presence of bacterial calcite precipitation may influence crack initiation and propagation by reducing internal defects and strengthening weak zones within the matrix. Representative failure patterns observed after destructive testing are presented in Figure 6.

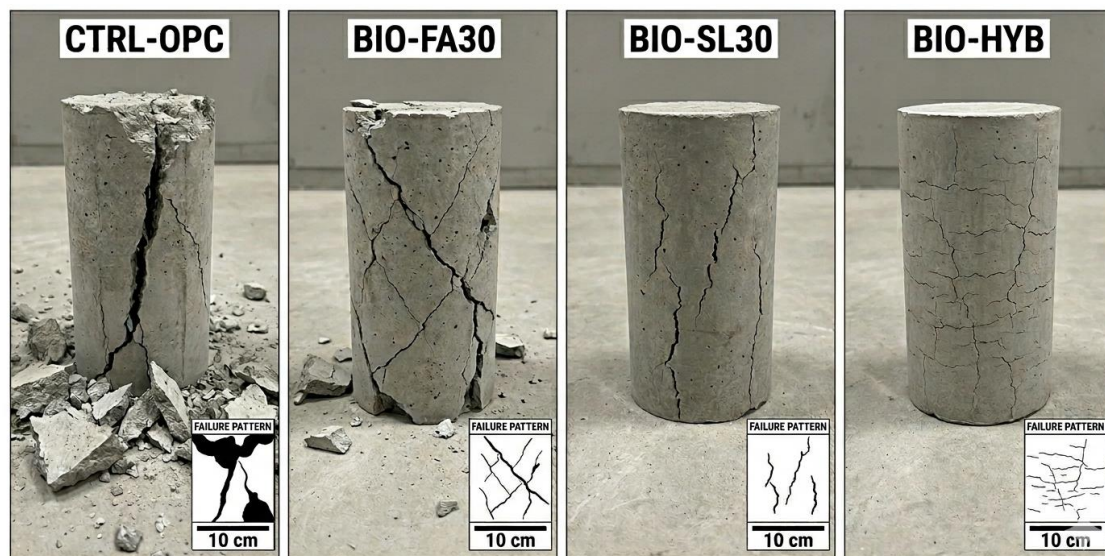


Figure 6. Concrete Failure Modes Post-Testing

Figure 6 reveals distinct differences between the control and bio-cemented specimens. The CTRL-OPC specimens exhibited pronounced vertical cracking accompanied by large detached fragments near the loading zones, characteristics commonly associated with brittle compressive failure. In contrast, the bio-cemented mixtures displayed a more distributed crack pattern with reduced fragmentation of the specimen surface. The BIO-HYB specimens, in particular, showed finer crack widths and a more uniform distribution of microcracks throughout the specimen body. Such crack development suggests that stress redistribution occurred more gradually during

loading. The presence of calcite deposits within pores and microcracks may have delayed crack coalescence, while the denser matrix generated by Fly Ash and GGBS provided additional resistance against crack propagation and localized failure.

E. Life Cycle Assessment and Environmental Performance

In addition to mechanical and durability performance, the environmental impact of the developed concrete mixtures was evaluated through a LCA. The assessment was conducted using a cradle-to-gate system boundary that considered raw material production, transportation, and concrete manufacturing processes. Particular emphasis was placed on quantifying embodied carbon emissions, energy consumption, and water demand associated with each mixture. The incorporation of industrial by-products and bacterial treatment was expected to influence these environmental indicators by reducing Portland cement consumption. The calculated environmental performance metrics are presented in Table 7.

Table 7. LCA and Carbon Footprint Analysis

Concrete Variant ID	Embodied Carbon (CO ₂ -eq/m ³)	Energy Consumption (MJ/m ³)	Water Footprint (L/m ³)	Calculated GWPred (%)
CTRL-OPC	385.0 kg	2,850 MJ	180 L	0.00
BIO-FA30	272.5 kg	2,040 MJ	225 L	29.22
BIO-SL30	268.0 kg	1,980 MJ	225 L	30.39
BIO-HYB	121.2 kg	1,150 MJ	230 L	68.52

Table 7 shows substantial reductions in embodied carbon and energy consumption following cement replacement with industrial by-products. The control mixture exhibited the highest carbon footprint at 385.0 kg CO₂-eq/m³, whereas BIO-HYB recorded the lowest value at 121.2 kg CO₂-eq/m³. This difference corresponds to a reduction of approximately 68.5%, reflecting the significant decrease in Portland cement content within the hybrid mixture. Similar trends were observed for energy consumption, which decreased from 2,850 MJ/m³ in CTRL-OPC to 1,150 MJ/m³ in BIO-HYB. Although the bio-cemented mixtures required slightly higher water consumption due to bacterial cultivation and nutrient preparation, the increase in water footprint remained relatively small compared with the reductions achieved in carbon emissions and energy demand.

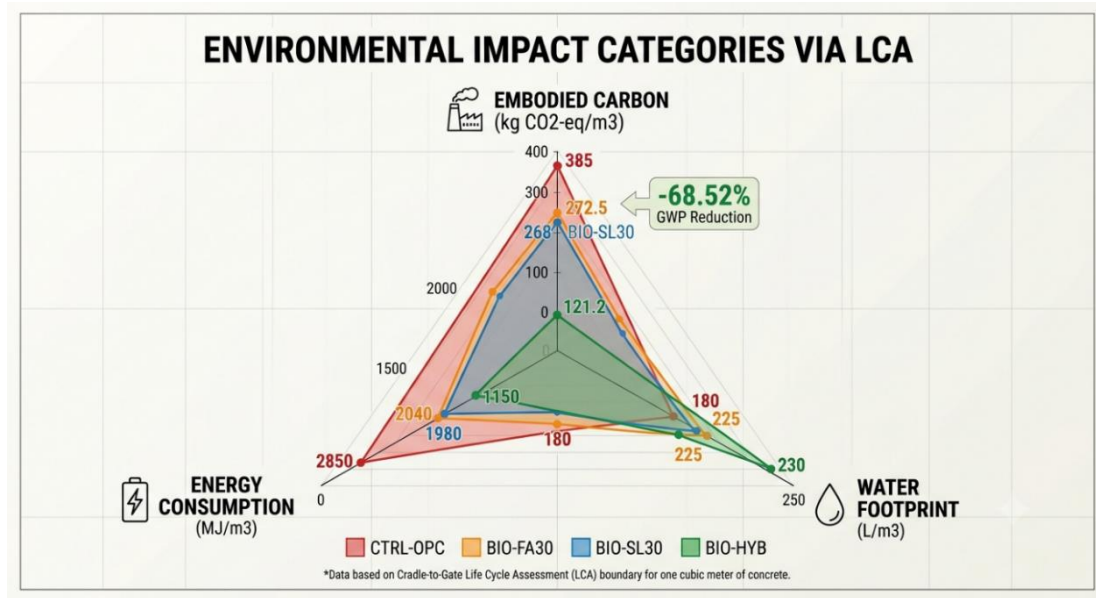


Figure 7. Environmental Impact Categories via LCA

To facilitate a multidimensional comparison of environmental performance, the major sustainability indicators were visualized using a radar chart. The graphical representation enables simultaneous evaluation of carbon emissions, energy consumption, and water demand across all investigated mixtures. Such visualization highlights the relative environmental burden associated with each concrete formulation. Differences among the mixtures become more apparent when multiple environmental indicators are considered simultaneously. The comparative environmental profile is presented in Figure 7.

Figure 7 illustrates clear differences between the environmental profiles of conventional and bio-cemented concrete mixtures. The control specimen occupies the largest area in categories related to embodied carbon and energy consumption, reflecting its greater dependence on Portland cement. The BIO-FA30 and BIO-SL30 mixtures exhibit moderate reductions across these indicators, corresponding to their partial replacement of cement with industrial by-products. The BIO-HYB mixture displays the smallest environmental footprint in terms of carbon emissions and energy demand while maintaining comparable water consumption characteristics.

The reduction in embodied carbon is closely associated with the utilization of Fly Ash and GGBS, both of which require substantially less energy-intensive processing than conventional cement production. The hybrid mixture achieved the lowest overall environmental burden among all investigated formulations through the combined utilization of industrial waste materials and reduced cement consumption.

V. DISCUSSION

The findings demonstrate that the integration of bacterial mineralization with Fly Ash and GGBS significantly improved the mechanical performance of concrete, particularly in the BIO-HYB mixture, which achieved the highest compressive, tensile, and flexural strengths. These results indicate that the combined action of pozzolanic reactions, latent hydraulic activity, and microbial calcite precipitation effectively enhanced matrix densification and load-bearing capacity. The observed strength development supports the hypothesis that biogenic calcium carbonate can compensate for the early-age strength limitations commonly associated with high-volume cement replacement.

This outcome is consistent with the findings of (Vaičekauskienė et al., 2026), who reported that industrial by-products contribute to improved long-term mechanical performance through microstructural refinement. Moreover, the present study extends the work of (Beskopylny et al., 2024) by demonstrating that bacterial mineralization can be successfully integrated into structural-grade concrete systems rather than being limited to crack-healing applications.

The microstructural and durability results further confirm the synergistic interaction between biological and cementitious processes within the hybrid concrete matrix. SEM observations revealed extensive calcite deposition in pores and microcracks, while the reductions in sorptivity, permeability, and porosity indicate the formation of a more compact and less interconnected pore structure. These findings align with the mechanism proposed by (Tan et al., 2023) and (Su et al., 2025), who suggested that biologically precipitated calcite acts as an effective filler capable of reducing pore connectivity. The substantial decrease in chloride penetrability also supports previous observations by (Xue et al., 2025) regarding the importance of microstructural refinement in restricting ionic transport. However, unlike the study of (Xue et al., 2025), which primarily focused on chloride resistance, the present research demonstrates that enhanced durability can be achieved simultaneously with significant gains in structural performance through a hybrid bio-cemented system.

An important observation concerns the different strength development patterns among the investigated mixtures, particularly the lower early-age compressive strength recorded for BIO-FA30. This behavior may be attributed to the slower pozzolanic reactivity of Fly Ash during the initial curing period, which delays the formation of secondary cementitious products. Similar trends were reported by (Alexis & Huereca, 2025), who identified strength reductions in fly ash-based systems during early hydration stages. Nevertheless, the continued strength gain observed at 28 days suggests that bacterial calcite precipitation and ongoing pozzolanic reactions gradually compensated for the initial performance deficit. Consequently, the present findings challenge the

assumption that high-volume supplementary cementitious material substitution inevitably results in inferior structural performance, particularly when combined with biologically induced mineralization processes.

From an environmental perspective, the hybrid bio-cemented concrete exhibited substantial reductions in embodied carbon and energy consumption while maintaining superior engineering performance. The 68.52% reduction in Global Warming Potential achieved by BIO-HYB supports the argument of (Akintayo et al., 2023) and (Ramadhani et al., 2025) that clinker reduction represents one of the most effective pathways toward low-carbon construction materials. These results also address the research gap identified in previous studies such as (Lam et al., 2025) and (Araujo et al., 2025), which evaluated environmental or material performance separately without investigating the synergistic interaction between biological mineralization and dual industrial waste utilization.

Nevertheless, the findings should be interpreted with consideration of several limitations, including the laboratory-scale nature of the experiments, the evaluation period restricted to 28 days, and the use of a single bacterial concentration and curing regime. Despite these constraints, the results provide strong evidence that hybrid bio-cemented concrete incorporating Fly Ash and GGBS can simultaneously enhance structural performance, durability, and environmental sustainability for low-carbon urban infrastructure applications.

VI. CONCLUSION AND RECOMMENDATION

This study experimentally evaluated the performance of bio-cemented concrete incorporating Fly Ash, GGBS, and *Sporosarcina pasteurii* as a sustainable alternative for low-carbon urban infrastructure. The results demonstrated that the hybrid mixture (BIO-HYB) achieved the highest compressive strength, tensile strength, flexural strength, and elastic modulus among all investigated mixtures. Significant improvements in durability were also observed through reductions in porosity, sorptivity, water permeability, and chloride ion penetration, indicating the development of a denser and more resilient concrete matrix. SEM observations confirmed that bacterial calcite precipitation contributed to pore filling and microstructural refinement, while the combined effects of Fly Ash and GGBS enhanced hydration and matrix densification. Furthermore, the hybrid bio-cemented concrete exhibited the lowest embodied carbon and energy consumption, demonstrating its potential to simultaneously improve structural performance and environmental sustainability.

Future research is recommended to investigate the long-term performance of bio-cemented concrete under various environmental exposure conditions, including marine, sulfate-rich, and freeze–thaw environments. Additional studies should evaluate different bacterial concentrations,

nutrient compositions, and supplementary cementitious material replacement ratios to further optimize the synergistic effects observed in this study. Advanced characterization techniques may also be employed to provide deeper insight into the interaction between microbial calcite precipitation and cement hydration products at multiple scales. Moreover, large-scale field applications are needed to verify the practical feasibility and durability of the proposed concrete system under real service conditions. Such efforts would support the broader adoption of bio-cemented concrete as an environmentally responsible construction material for future infrastructure development.

AI Use Declaration

The authors declare that artificial intelligence tools, including ChatGPT, were used only for editorial and linguistic enhancement of the manuscript, including improvements to grammar, readability, wording, and clarity. No AI technologies contributed to the research itself. The study conception, experimental design, data gathering, analytical procedures, methodological development, interpretation of outcomes, and formulation of conclusions were performed exclusively by the authors. Full accountability for the authenticity, accuracy, validity, and integrity of the manuscript remains with the authors.

REFERENCES

- Akintayo, B. D., Akintayo, D. C., & Olanrewaju, O. A. (2023). Material Substitution Strategies for Energy Reduction and Greenhouse Gas Emission in Cement Manufacturing. *Atmosphere*, 14(8), 1200. <https://doi.org/10.3390/atmos14081200>
- Al-saffar, F. Y., Wong, L. S., & Paul, S. C. (2023). An Elucidative Review of the Nanomaterial Effect on the Durability and Calcium-Silicate-Hydrate (C-S-H) Gel Development of Concrete. *Gels*, 9(8), 613. <https://doi.org/10.3390/gels9080613>
- Alexis, R., & Huereca, C. (2025). Valorization of Industrial Ash Waste as Eco-Friendly Binder for Pavement Applications: Experimental Study on Strength and Permeability Properties. *Civil Engineering Science and Technology*, 1(2), 110–134. <https://doi.org/10.51903/fd9z5952>
- Araujo, A. F., Caldas, L. R., Hasparyk, N. P., & Toledo Filho, R. D. (2025). Low-Carbon Bio-Concretes with Wood, Bamboo, and Rice Husk Aggregates: Life Cycle Assessment for Sustainable Wall Systems. *Sustainability*, 17(5), 2176. <https://doi.org/10.3390/su17052176>
- Beskopylny, A. N., Shcherban', E. M., Stel'makh, S. A., Shilov, A. A., Chernil'nik, A., El'shaeva, D., & Chistyakov, V. A. (2024). Analysis of the Current State of Research on Bio-Healing Concrete (Bioconcrete). *Materials*, 17(18), 4508. <https://doi.org/10.3390/ma17184508>
- Duman, H., Eker, F., Akdaşçi, E., Witkowska, A. M., Bechelany, M., & Karav, S. (2024). Silver Nanoparticles: A Comprehensive Review of Synthesis Methods and Chemical and Physical Properties. *Nanomaterials*, 14(18), 1527. <https://doi.org/10.3390/nano14181527>

- Fronczyk, J., Marchelina, N., Pyzik, A., & Franus, M. (2023). Assessment of the Composition Effect of a Bio-Cementation Solution on the Efficiency of Microbially Induced Calcite Precipitation Processes in Loose Sandy Soil. *Materials*, 16(17), 5767. <https://doi.org/10.3390/ma16175767>
- Haigh, R. (2026). Environmental and Mechanical Trade-Off Optimization of Waste-Derived Concrete Using Surrogate Modeling and Pareto Analysis. *Sustainability*, 18(2), 1119. <https://doi.org/10.3390/su18021119>
- Huang, X., Su, S., Xu, Z., Miao, Q., Li, W., & Wang, L. (2023). Advanced Composite Materials for Structure Strengthening and Resilience Improvement. *Buildings*, 13(10), 2406. <https://doi.org/10.3390/buildings13102406>
- Kaptan, K., Cunha, S., & Aguiar, J. (2025). The Effect of Activation Methods on the Mechanical Properties of Cement Mortars with Recycled Powder from Concrete Waste as a Cement Partial Replacement: A Review. *Sustainability*, 17(10), 4502. <https://doi.org/10.3390/su17104502>
- Kaptan, K., Cunha, S., & Aguiar, J. (2026). Durability Behavior of Portland Cement Mortars with Recycled Powder from Concrete Waste as a Cement Partial Replacement: A Review. *Sustainability*, 18(5), 2561. <https://doi.org/10.3390/su18052561>
- Lam, A., Hamzaoui, R., Kindinis, A., Idir, R., Lamberet, S., & Patrix, S. (2025). Thermal, Hygrothermal, Mechanical and Environmental Study of Stabilized Earth with GGBS-Based Binders. *Buildings*, 15(4), 594. <https://doi.org/10.3390/buildings15040594>
- Li, S., Yin, J., Xu, W., Liu, S., & Liu, X. (2024). Alkalinity Regulation and Optimization of Cementitious Materials Used in Ecological Porous Concrete. *Materials*, 17(8), 1918. <https://doi.org/10.3390/ma17081918>
- López-Torres, O., Rodríguez-Longobardo, C., Escribano-Tabernero, R., & Fernández-Elías, V. E. (2023). Hydration, Hyperthermia, Glycogen, and Recovery: Crucial Factors in Exercise Performance—A Systematic Review and Meta-Analysis. *Nutrients*, 15(20), 4442. <https://doi.org/10.3390/nu15204442>
- Matos, J., Caneve, E., Silva, A., & Pedrosa, P. (2026). Life Cycle and Circularity: The Assessment of Conventional and Additive Manufacturing Injection Molds. *Environments*, 13(3), 169. <https://doi.org/10.3390/environments13030169>
- Maurente-Silva, D. G., Borowski, J. V., Cappellesso, V. G., Vainstein, M. H., Masuero, A. B., & Dal Molin, D. C. (2024). Effect of Exposure Environment and Calcium Source on the Biologically Induced Self-Healing Phenomenon in a Cement-Based Material. *Buildings*, 14(12), 3782. <https://doi.org/10.3390/buildings14123782>
- Nugroho, A. S., & Wibowo, M. C. (2024). Design and Implementation of Animated Stickers as an Educational Tool for Adolescent Drug Awareness Using the MDLC Method. *International Journal of Graphic Design*, 2(2), 195–206. <https://doi.org/10.51903/ijgd.v2i2.2114>

- Owolabi, D. O., Shokouhian, M., Ahmad, I., Jenkins, M., & McLemore, G. L. (2025). Comparative Analysis of Autogenous and Microbial-Based Calcite Precipitation in Concrete: State-of-the-Art Review. *Buildings*, 15(18), 3289. <https://doi.org/10.3390/buildings15183289>
- Ramadhani, S., Siregar, J. K., Suzita, S., & Mayanti, M. (2025). Seismic Resilience of 3D Printed Concrete Structures Parametric Optimization and Real-Scale Experimental Validation. *Jurnal Rekayasa Sipil Dan Arsitektur*, 1(2), 20–38. <https://doi.org/10.51903/zg90qr45>
- Šovljanski, O., Tomić, A., Milović, T., Bulatović, V., Ranitović, A., Cvetković, D., & Markov, S. (2025). Construction Biotechnology: Integrating Bacterial Systems into Civil Engineering Practices. *Microorganisms*, 13(9), 2051. <https://doi.org/10.3390/microorganisms13092051>
- Su, N., Yan, Q., Li, Y., Xu, H., Fang, C., & Su, W. (2025). A Multiscale and Integrative Review of Bamboo Permeability: Structural Mechanisms, Detection Techniques, and Enhancement Approaches. *Forests*, 16(11), 1744. <https://doi.org/10.3390/f16111744>
- Tan, Y., Zhao, B., Yu, J., Xiao, H., Long, X., & Meng, J. (2023). Effect of Cementitious Capillary Crystalline Waterproofing Materials on the Mechanical and Impermeability Properties of Engineered Cementitious Composites with Microscopic Analysis. *Polymers*, 15(4), 1013. <https://doi.org/10.3390/polym15041013>
- Vaičekauskienė, V., Nagrockienė, D., & Pundienė, I. (2026). The Effect of Combining Waste-Derived Pozzolanic and Fibrous Materials with Functional Admixtures on Performance and Corrosion Resistance of Concrete. *Buildings*, 16(4), 767. <https://doi.org/10.3390/buildings16040767>
- Vedrtnam, A., Kalauni, K., & Palou, M. T. (2025). Ranking Bacteria for Carbon Capture and Self-Healing in Concrete: Performance, Encapsulation, and Sustainability. *Sustainability*, 17(12), 5353. <https://doi.org/10.3390/su17125353>
- Wang, X., Hu, W., Chen, K., & Wang, W. (2025). Effects of Ion-Regulated Mechanisms on Calcite Precipitation in the Enzyme-Induced Carbonate Precipitation Treatment of Loess. *Buildings*, 15(17), 3222. <https://doi.org/10.3390/buildings15173222>
- Xue, Q., Zheng, T.-Y., Wang, J., Zhang, J.-J., Xia, W., & Cui, S.-A. (2025). Study on Chloride Permeability and Chloride Ion Transport of Fiber-Reinforced Cementitious Composite Repair System. *Buildings*, 15(6), 975. <https://doi.org/10.3390/buildings15060975>
- Zhou, J., Dong, Y., Qiu, T., Lv, J., Guo, P., & Liu, X. (2025). The Microstructure and Modification of the Interfacial Transition Zone in Lightweight Aggregate Concrete: A Review. *Buildings*, 15(15), 2784. <https://doi.org/10.3390/buildings15152784>