

Microbially Modified Sustainable Cementitious Composites Using Industrial Ash Fillers

Priya Sopan Nikam^{1*}, Pravin Dinkar Nemade²

Abstract

*The growing demand for sustainable, durable construction materials has driven the development of bio-engineered cementitious composites incorporating industrial by-products and self-healing mechanisms. This study investigates a microbially modified cementitious composite that integrates industrial ash fillers with bacteria-based self-healing technology to enhance mechanical performance and microstructural integrity while reducing cement consumption. Cement was partially replaced with industrial ash at 20%, 30%, and 40% replacement levels, and a uratolytic bacterial strain (*Bacillus subtilis*) was introduced at concentrations ranging from 10^5 to 10^7 cells/ml to activate microbial-induced calcite precipitation (MICP). Compressive and flexural strength tests were conducted at 3, 14, and 28 days of curing to evaluate mechanical performance. Microstructural characterisation using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) was performed to analyse hydration products, pore refinement, and elemental composition. The results demonstrate that bacterial cementitious composites incorporating industrial ash exhibit significantly higher compressive and flexural strengths than conventional concrete, with the optimum mix showing up to a 30% increase in compressive strength and a notable improvement in flexural resistance. SEM observations revealed a denser matrix with reduced porosity and effective crack filling due to calcite precipitation, while EDS analysis confirmed the enrichment of calcium- and silicon-rich phases responsible for enhanced calcium-silicate-hydrate formation. The synergistic interaction between bio-mineralisation and pozzolanic reactions contributed to improved matrix continuity and stress transfer efficiency. Overall, the proposed bio-modified cementitious composite presents a promising sustainable alternative for durable construction applications by combining waste utilisation, reduced carbon footprint, and autonomous self-healing functionality.*

Keywords: Cementitious composites; Industrial ash filler; Bio-mineralization; Self-healing composites; SEM-EDS; Sustainable materials, Pond Ash

INTRODUCTION

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Cement-based materials can be understood as particulate-reinforced composite systems, in which hydration products form the continuous matrix, and mineral constituents act as fillers that govern mechanical performance and durability [1]. Despite their widespread use, conventional cementitious composites are inherently brittle and susceptible to microcrack formation arising from shrinkage, thermal stresses, and external loading. These microcracks accelerate permeability, reduce load-transfer efficiency, and ultimately compromise long-term structural integrity. Addressing these limitations has become a central research focus within the field of sustainable and functional composite materials [2].

In recent years, the incorporation of industrial by-products as supplementary fillers has attracted considerable attention as an effective strategy to enhance sustainability and improve composite performance. Industrial ashes, such as pond ash, exhibit pozzolanic properties that promote secondary hydration reactions, leading to matrix densification and improved interfacial bonding [3]. When appropriately integrated, such fillers not only reduce cement consumption and carbon emissions but also refine pore structure and enhance mechanical efficiency. However, filler incorporation alone cannot fully mitigate crack propagation, particularly under service conditions where microcracks continuously evolve [4].

To overcome this limitation, bioengineered self-healing mechanisms have emerged as a promising approach to enhance the functional performance of cementitious composites. Among these, microbial-induced calcite precipitation (MICP) has demonstrated significant potential as an autonomous crack-healing process [5]. In this mechanism, dormant bacterial spores embedded within the composite matrix become activated upon moisture ingress, producing calcium carbonate that seals microcracks and voids. From a composite-materials perspective, this bio-mineralisation process acts as an in situ secondary binder, restoring matrix continuity and improving stress transfer across damaged regions [6].

The integration of bacteria within cementitious systems introduces a functional bio-additive, analogous to polymeric modifiers or healing agents used in advanced composite materials. Precipitated calcium carbonate not only fills cracks but also enhances the filler–matrix interface, leading to reduced porosity, improved stiffness, and greater durability [7]. When combined with industrial ash fillers, a synergistic interaction can be achieved, in which pozzolanic reactions and microbial calcite deposition collectively enhance the microstructural integrity of the composite [8].

Despite growing interest in bio-based self-healing cementitious materials, limited studies have systematically explored the combined effect of industrial ash fillers and bacterial healing agents from a composite-materials viewpoint, particularly with emphasis on microstructural evolution and structure–property relationships. Understanding how bio-mineralisation interacts with filler-modified cement matrices is essential for optimising mechanical performance and long-term durability in sustainable composite systems [9].

Therefore, the present study investigates a bio-engineered cementitious composite incorporating pond ash as a partial cement replacement and bacteria as a self-healing functional agent. The composite performance is evaluated through mechanical testing and detailed microstructural characterisation using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS). The study aims to establish clear correlations between filler content, bacterial activity, microstructural refinement, and mechanical enhancement, thereby contributing to the development of next-generation sustainable cementitious composites suitable for advanced structural applications.

Unlike conventional research that focuses on the use of industrial by-products or bacterial self-healing as separate entities, the current research combines industrial ash fillers and microbially induced calcite precipitation in a systematic manner to simultaneously improve strength, microstructure density, and sustainability. The research is unique in that it links bacterial processes, filler-induced pozzolanic reactions, and microstructural changes using SEM-EDS analysis to provide a clear understanding of structure-property relationships in bio-engineered cement composites.

The current study is well in line with the current trends in research that have been pursued to minimise the ecological footprint of cement-based materials using waste valorisation and bio-engineered functionalisation. By using industrial ash fillers in combination with microbially induced calcite precipitation, the current study has addressed some of the most important sustainability issues, including carbon, resource use, and durability.

LITERATURE SURVEY

Bagga *et al.* (2023) reported that a bacteria-based self-healing Cementitious composite (BBSHC) utilising microbial-induced carbonate precipitation (MICP) holds promise for enhancing Cementitious composite resilience and sustainability. However, current models are still in their infancy, and there is a need for more detailed, predictive simulations that combine biological and mineral processes at the Representative Elementary Volume (REV) level to accelerate progress in the field [10].

Ghatol and Kalurkar (2020) investigated the incorporation of bacteria-based self-healing Cementitious composite, combined with fly ash, to enhance the durability and compressive strength of concrete. The study revealed that the use of *Bacillus megaterium* and *Bacillus subtilis* significantly improved the compressive strength and stiffness, while also reducing water absorption and permeability. The addition of fly ash (10% bacteria and 10% fly ash) showed the highest increase in strength, with a 1.16% improvement. Furthermore, bacterial precipitation of calcium carbonate effectively seals cracks, providing enhanced durability, particularly in hydraulic environments, and thus offers a sustainable solution for Cementitious composite structures [11].

Pannem and Chintalapudi (2019) reviewed the properties of bacterial-based self-healing Cementitious composite. They highlighted the benefits of using urease-producing bacteria, such as *Bacillus pasteurii*, in combination with a calcium source to precipitate calcite and seal micro-cracks. The study emphasised the ability of bio-mineralisation to enhance the durability of cementitious composites, reduce permeability, and improve compressive strength over time. SEM and XRD analyses confirmed that the bacteria-induced CaCO_3 precipitation effectively sealed micro-cracks. Optimising bacterial concentration improved concrete's crack-healing capacity, resulting in reduced chloride penetration and water absorption, and enhanced mechanical performance, thereby increasing the longevity of Cementitious composite structures and reducing maintenance costs [12].

Wong *et al.* (2024) reviewed microbial self-healing Cementitious composite (bioconcrete), focusing on how bacteria and fungi help repair cracks through calcium carbonate precipitation. Environmental factors like pH, temperature, and moisture influence the effectiveness of this process. While bioCementitious composite enhances durability and sustainability, challenges such as microbial viability and cost remain. The review suggests further research into diverse biological agents, improved encapsulation techniques, and the use of AI to optimise self-healing for broader applications [13].

Vishal *et al.* (2025) assessed bacteria-based self-healing Cementitious composite using *Bacillus subtilis* across different grades (M20, M25, M30) and cell counts (10^5 and 10^6 cells/ml). The study found a 25–40% increase in strength compared to the control composite, with bacterial mixes showing superior velocity (above 4.45 km/s) and reduced wear (15–25% less Cantabro loss). Additionally, the bacterial Cementitious composite exhibited improved high-temperature resistance, with specimens showing less strength loss than traditional concrete. The study highlights the potential of bacterial Cementitious composite for specific applications requiring enhanced strength and durability [14].

Elgendy *et al.* (2025) explored bacteria-powered self-healing concrete, where dormant bacteria repair cracks by producing calcium carbonate when activated by moisture. The review discusses challenges like bacterial viability, cost, and environmental impact, while highlighting advancements in genetic engineering and smart technologies. Prospects include using waste materials for bacterial nutrients, enhancing heat resistance, and integrating self-sensing systems for real-time damage detection. These innovations could make the technology more sustainable, cost-effective, and widely adopted for both new and retrofitted structures, revolutionising construction practices [15].

Ghatol and Kalurkar (2020) investigated bacteria-based self-healing Cementitious composite incorporating fly ash. The study found that embedding bacteria like *Bacillus megaterium* and *Bacillus subtilis* improved compressive strength, reduced water absorption, and lowered permeability. The use

of fly ash and bacteria enhances concrete's durability, offering an eco-friendly solution for stronger, more sustainable concrete [16].

Luhar *et al.* (2022) reviewed the application of bacteria-based self-healing concrete, emphasising the use of ureolytic bacteria such as *Bacillus pasteurii* and *Bacillus subtilis*. These bacteria produce calcium carbonate (CaCO_3) precipitations that help seal cracks in concrete, improving its strength and durability. The review highlighted that adding bacteria reduces water penetration and chloride-ion permeability, and enhances concrete's resistance to sulphates and acid rain. SEM, EDS, and XRD analyses confirmed the role of bacteria in improving the concrete's microstructure [17].

Wong *et al.* (2024) reviewed advances in microbial self-healing Cementitious composite (bioconcrete), which uses microorganisms such as bacteria and fungi to autonomously repair cracks by producing calcium carbonate (CaCO_3). The review focuses on the biochemical pathways these organisms use for repair and the environmental factors (pH, temperature, moisture) that affect the healing process. Despite its potential to improve structural durability and sustainability, challenges remain, such as maintaining microbial viability and associated costs [18].

Kadamba *et al.* (2024) explored the use of agro-industrial waste, such as coffee husk ash and rice husk ash, as partial cement replacements in self-healing concrete. These materials improve the sustainability of Cementitious composites and enhance their self-healing properties. The review highlights the impact of these wastes on concrete's mechanical and durability performance, emphasising the need for further research into their long-term effectiveness and scalability in self-healing concrete [19].

Previous studies on bacteria-based self-healing cementitious composites have largely focused on strength enhancement or crack-healing efficiency using microbial-induced calcite precipitation, often without incorporating supplementary industrial fillers or providing detailed microstructural correlations. Similarly, investigations on industrial ash fillers primarily emphasise pozzolanic reactivity and sustainability benefits, but do not address autonomous crack-healing mechanisms or long-term matrix restoration. In contrast, the present study advances the field by integrating industrial ash fillers with microbial self-healing agents within a single composite system and systematically evaluating their combined effect. Unlike many earlier works that rely predominantly on mechanical performance indicators, this research establishes direct links between strength development, microstructural densification, and elemental composition through comprehensive SEM–EDS analysis. The findings demonstrate that the synergistic interaction between pozzolanic reactions and biomineralisation leads to improved matrix continuity, reduced porosity, and enhanced stress-transfer efficiency. By addressing both sustainability through waste utilisation and durability through bio-mediated self-healing, the present work provides a more holistic framework for developing next-generation cementitious composites. This integrated approach represents a meaningful advancement over existing studies and contributes toward the practical realisation of sustainable, high-performance construction materials.

MATERIALS AND METHODS

Materials

In this study, Type I Ordinary Portland Cement (OPC), standard quartz sand (0-2mm), and pond ash were used in the mix, in accordance with IS 10262:2019 guidelines. Non-ureolytic bacteria were incorporated in varying proportions to enhance self-healing properties. The Cementitious composite was cured using ponding. SEM and EDAX analyses of Sample-1 (bacterial Cementitious composite with pond ash) revealed calcium carbonate (CaCO_3) precipitation around bacterial cells. EDAX detected calcium (Ca), silicon (Si), and trace amounts of aluminium (Al) and iron (Fe). Compression and flexural strength tests were conducted after 3 and 7 days of curing to compare the bacterial Cementitious composite with the control composite. Table 1 lists the materials used in the ferro-cement mix.

Table 1. Materials Used in Ferro-Cement Mix

Material	Properties / Specifications
Cement	Ordinary Portland Cement (OPC, 53 Grade), Specific Gravity: 3.15, Conforming to IS: 12269
Fine Aggregate (Sand)	River sand, Zone II (IS: 383-2016), Fineness Modulus: 2.65, Specific Gravity: 2.60
Coarse Aggregate	Crushed granite, size: 12 mm, Specific Gravity: 2.70
Water	Potable, free from impurities, pH 7–8
Industrial By-Product (CBA / Fly Ash / GGBS)	Used as a partial cement replacement; improves pozzolanic activity and durability.
Bacteria (for Self-Healing)	Ureolytic type, spore-forming, dosage prepared in liquid culture medium

Mix Proportions

Cementitious composite specimens were prepared in multiple proportions by partially replacing cement with 20%, 30%, and 40% fly ash and GGBS (individually and in combination). Bacterial suspensions at concentrations of 10^5 – 10^7 cells/ml were introduced by mixing with water. A control mix (without bacteria and without by-products) and a reference mix (with by-products but no bacteria) were also cast for benchmarking. Table 2 represents the experimental methods and testing parameters.

Table 2. Experimental Methods and Testing Parameters

Method / Test	Specimen Details	Standards / Parameters	Purpose
Compressive Strength Test	Cubes (150×150×150 mm) and Cylinders (150×300 mm)	IS: 516-1959, Load rate: 140 kg/cm ² /min	To evaluate the load-bearing capacity under axial load at 7, 14, and 28 days.
Flexural Strength Test	Prisms (100×100×500 mm)	IS: 516-1959, Two-point loading method	To determine crack resistance, bending strength, and tensile behaviour.
SEM Analysis	Powdered/fragmented cured samples	Magnification: 4kX–42kX, 10 keV beam energy	To examine surface morphology, pore structure, and hydration products.
EDS Analysis	SEM coupled with an X-ray detector	Elemental analysis of Ca, Si, O, Al, Mg, C	To identify the composition and confirm the presence of hydration compounds.

Selection of Bacteria

A ureolytic bacterial strain, *Bacillus subtilis*, was selected for its ability to survive in alkaline environments and precipitate calcium carbonate (CaCO₃) through microbial induced calcite precipitation (MICP). The strain was cultured in nutrient broth enriched with urea and calcium lactate, then harvested as spores to ensure long-term viability in the Cementitious composite matrix.

EXPERIMENTAL METHOD

Compression Test

The compression test measures the compressive strength of ferro-cement cubes and cylinders. This test determines the material's ability to withstand axial loads, which is essential for evaluating the strength of ferro-cement mixes. The cubes and cylinders were subjected to gradually increasing loads until failure. The results were recorded to assess strength development, load-bearing capacity, and durability under compressive stresses.

Flexural Strength Test

The flexural test evaluates the bending resistance of ferro-cement prisms or beams. It measures the material's ability to resist tensile stresses induced by bending. Specimens were placed on a two-point

loading setup and subjected to increasing loads until fracture occurred. The load–deflection behaviour was studied, and flexural strength was calculated. This test is significant for analysing crack resistance, toughness, and structural performance under flexural loads.

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

SEM analysis was conducted to examine the surface morphology, particle distribution, and hydration product formation in ferro-cement samples. High-magnification images revealed microstructural features, porosity, and the presence of C-S-H gel. EDS was performed simultaneously to determine the elemental composition, including Ca, Si, O, and Al, which are vital to hydration and strength. Together, SEM and EDS analyses provided insights into the correlation between microstructural characteristics and the mechanical performance of ferro-cement mixes.

“For each mix proportion and curing age, a minimum of three specimens were tested. The reported compressive and flexural strength values represent the average of these measurements. Statistical variability is expressed in terms of standard deviation, providing an indication of experimental repeatability and data reliability.”

RESULTS AND DISCUSSION

The combined use of mechanical performance evaluation and SEM–EDS microstructural analysis ensures technical robustness and enables validation of the underlying mechanisms governing strength improvement and matrix densification. Multiple SEM magnifications consistently reveal a loosely packed microstructure with unreacted particles and higher porosity in the conventional composite, confirming weaker matrix continuity than in the bio-modified mixes. All strength results are presented as mean values with associated standard deviations to account for experimental variability. Microbial-induced calcite precipitation (MICP) plays a critical role in governing the performance of bio-modified cementitious composites by directly influencing microstructural evolution. Upon activation in the alkaline cementitious environment, bacterial activity leads to the precipitation of calcium carbonate within pores, microcracks, and interfacial transition zones. This bio-mineralisation process reduces pore connectivity, enhances matrix densification, and restores local continuity across damaged regions. From a composite-materials perspective, the precipitated calcite acts as a secondary binding phase that improves filler–matrix interaction and enhances stress transfer efficiency under mechanical loading. The refinement of pore structure and sealing of microcracks delay crack propagation, resulting in increased compressive strength, improved flexural resistance, and enhanced durability. When combined with pozzolanic reactions from industrial ash fillers, MICP synergistically contributes to the formation of a denser, more cohesive microstructure, thereby directly linking microbial activity to macroscopic composite performance. The results and discussion section presents experimental findings from mechanical testing, SEM analysis, and EDS elemental mapping to evaluate the microstructural and strength characteristics of concrete. Compressive and flexural strength tests at varying curing ages highlight the influence of CBA and bacterial activity on performance improvement. SEM micrographs provide insight into surface morphology, hydration products, and porosity, while EDS analysis confirms the elemental composition and distribution. Together, these analyses establish the relationship between microstructural features and the enhanced mechanical properties of concrete. Figure 1 represent the 3-day compressive strength.

At 3 days, conventional Cementitious composites show an average strength of 10.45 N/mm², whereas BC mixes with CBA substitution exhibit higher values. Strength increases with the percentage of CBA, reaching 13.68 N/mm² at 30% CBA replacement. This indicates that early-age strength is enhanced in bacterial Cementitious composite (BC) and CBA due to accelerated hydration and possible microbial activity that facilitates calcium carbonate precipitation, improving the pore structure and matrix densification. Figure 2 represent the 14- days compressive strength.

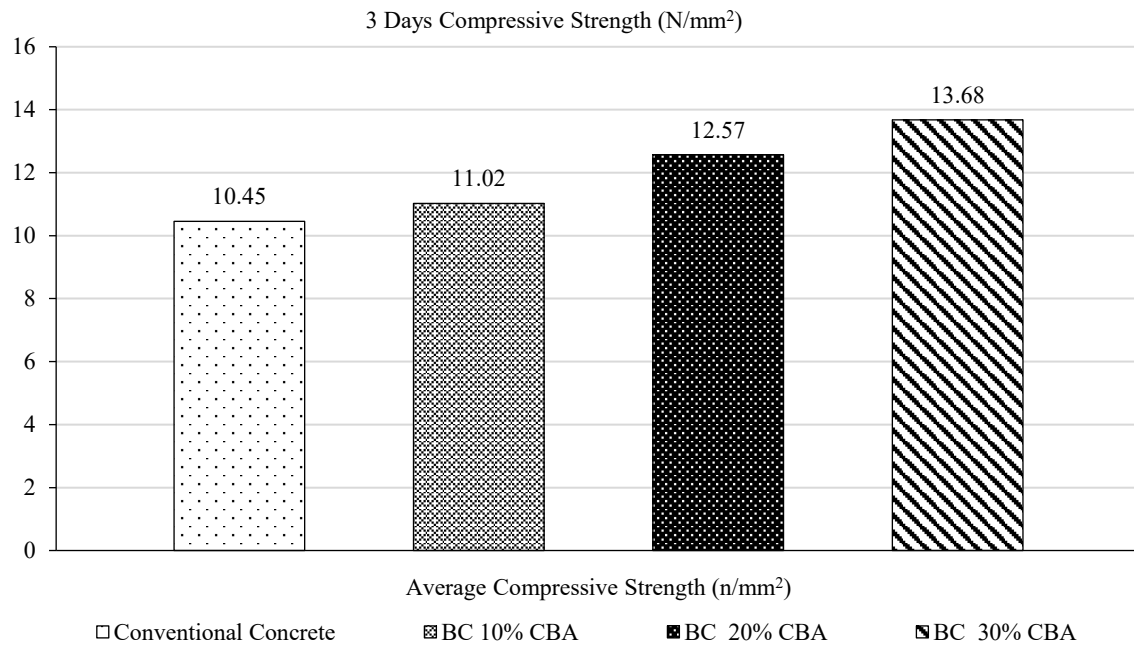


Figure 1. 3 Days Compressive Strength (N/mm²)

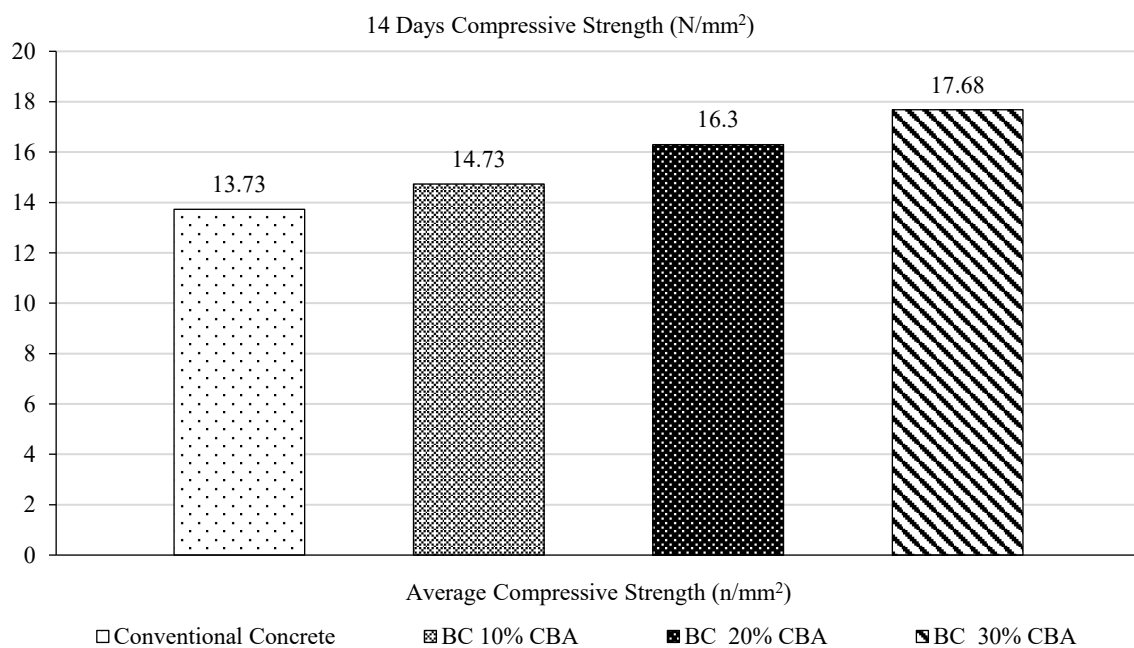


Figure 2. 14 Days Compressive Strength (N/mm²)

At 14 days, compressive strength improves across all mixes. The conventional cementitious composite records a strength of 13.73 N/mm², while BC with 30% CBA shows the maximum strength of 17.68 N/mm². The trend toward increased strength with CBA content suggests an effective pozzolanic reaction and biomineralisation. The results demonstrate that CBA improves binding, fills micro-voids, and contributes to a progressive increase in compressive strength at the medium curing stage compared to the control composite. Figure 3 represent the 28-day compressive strength.

After 28 days, the strength gain is significant, with conventional Cementitious composite at 27.1 N/mm² and BC with 30% CBA reaching 35.2 N/mm². The gradual increase in CBA replacement at higher CBA levels indicates long-term pozzolanic reactivity and microbial-induced calcite

precipitation. The improved strength performance reflects the synergistic effect of bacterial activity and CBA, leading to a denser microstructure and reduced porosity. This shows the potential of BC with CBA as a superior alternative to control composite. Figure 4 represents the 7-day flexural strength.

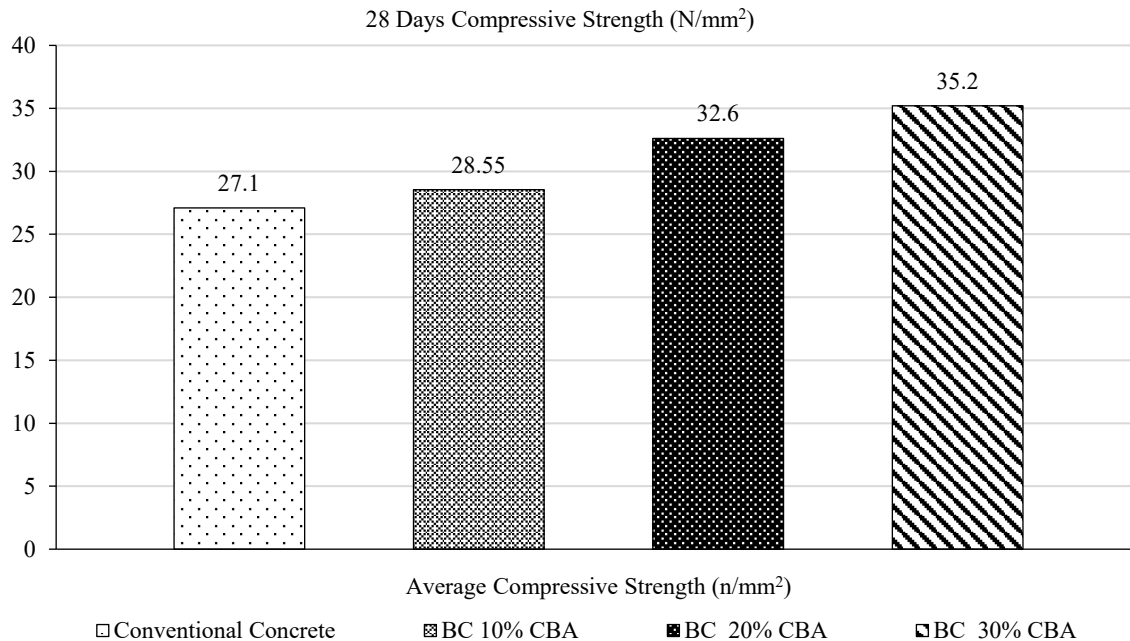


Figure 3. 28 Days Compressive Strength (N/mm²)

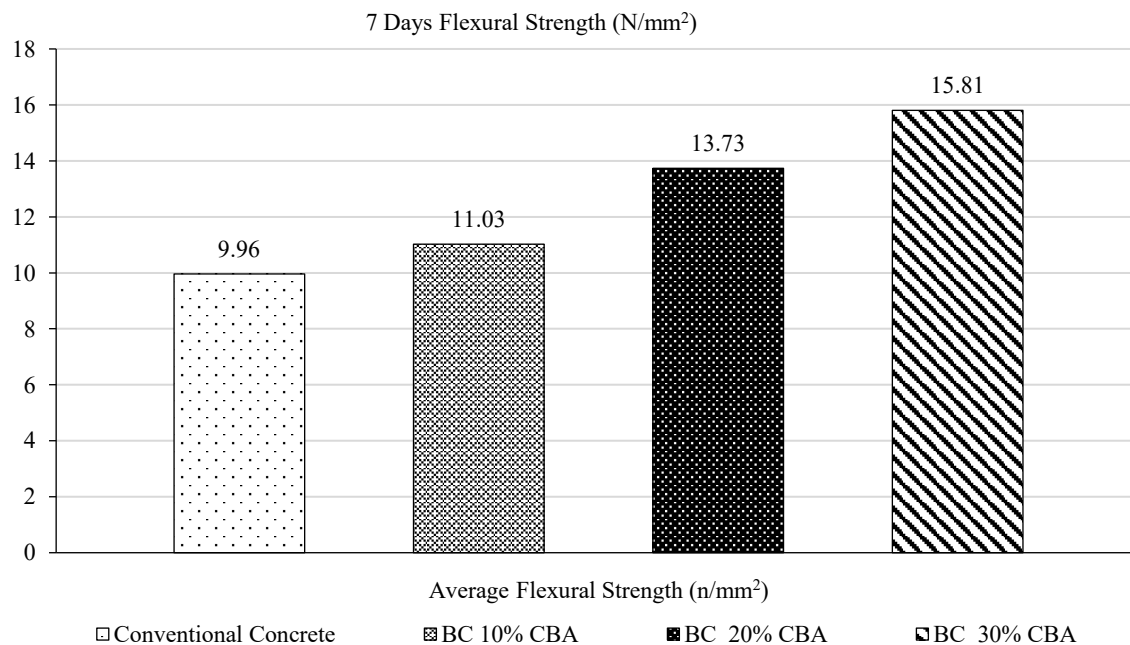


Figure 4. 7 Days Flexural Strength (N/mm²)

At 7 days, the flexural strength of conventional Cementitious composite is 9.96 N/mm², while bacterial Cementitious composite with 30% CBA reaches 15.81 N/mm². The increasing trend with higher CBA content highlights improved tensile capacity and crack resistance. The enhanced flexural strength can be attributed to bacterial activity, which fills microcracks with calcite, and to the presence of CBA, which contributes to the microstructure. This combination enhances early-age durability and bending load-bearing capacity. Figure 5 represent the 28 Days Flexural Strength (N/mm²)

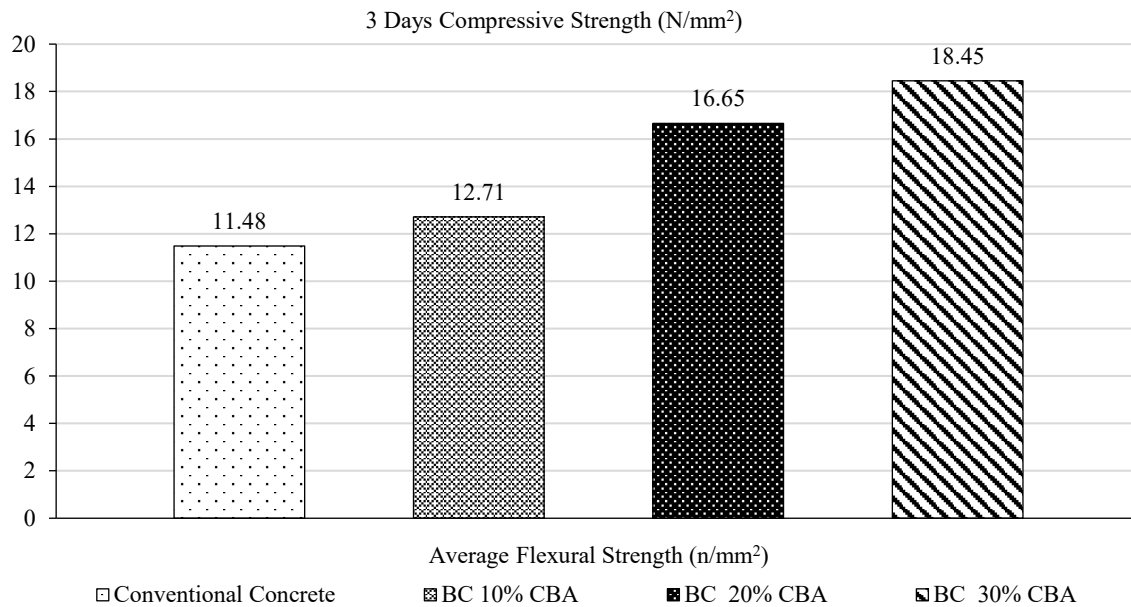


Figure 5. 28 Days Flexural Strength (N/mm²)

Flexural strength continues to rise at 28 days, with conventional Cementitious composite at 11.48 N/mm² and BC with 30% CBA at 18.45 N/mm². The steady improvement emphasises the beneficial role of bacterial self-healing and the pozzolanic reaction of CBA, which refines the pore structure. This strengthens the bond between aggregates and cement paste, significantly improving the concrete's flexural resistance compared to conventional mixes. The results confirm the superior performance of BC-CBA mixes under flexural stresses. Figure 6 represents the SEM Image of the conventional cementitious composite at 20.9kX Magnification.

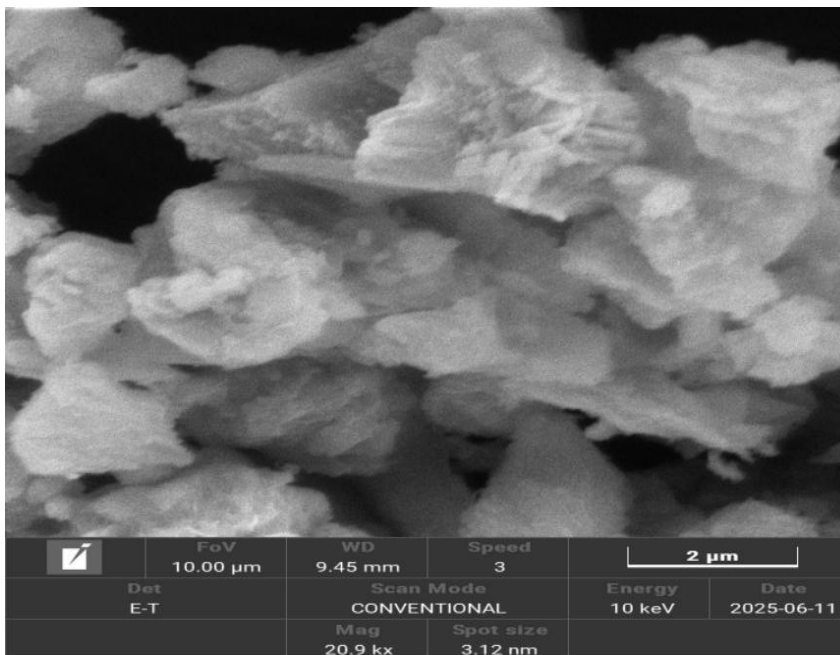


Figure 6. SEM Image of Conventional Cementitious composite at 20.9kX Magnification (2 µm scale) Scanning Electron Microscope (SEM) figure showing the surface morphology of a material, magnified at 20.9kX with a spot size of 3.12 nm. The figure was captured in a conventional scanning mode at 10 keV. The field of view (FoV) is 10.00 µm, with a working distance (WD) of 9.45 mm. Figure 7 represents the SEM Image of the conventional cementitious composite at 4.19kX Magnification

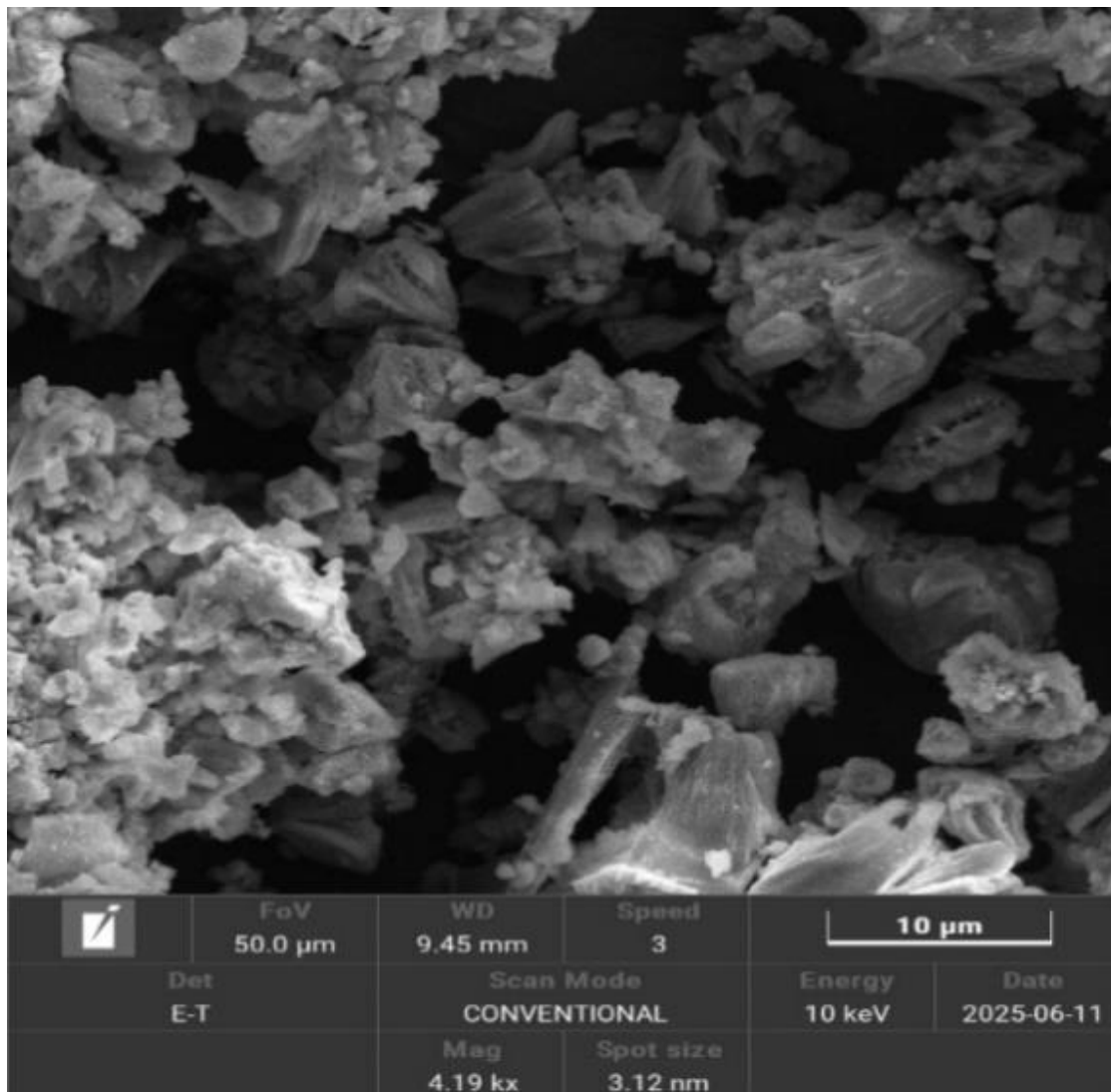


Figure 7. SEM Image of Conventional Cementitious composite at 4.19kX Magnification

SEM Image of Conventional Cementitious composite at 4.19kX Magnification (10 μm scale)

The figure is an electron microscopy scan of a material's surface, magnified at 4.19kX. It reveals crystalline structures with irregular shapes and sharp edges. The sample's scale bar is set at 10 μm, indicating the size of the particles within the field of view. The scanning parameters include an accelerating voltage of 10 keV and a spot size of 3.12 nm. Figure 8 represents the SEM Image of the conventional cementitious composite at 10.5kX Magnification

The figure shows a scanning electron microscope (SEM) image of a sample at 10.5 kx magnification and a spot size of 3.12 nm. The figure was captured at an energy of 10 keV in conventional scan mode. The scale bar at the bottom indicates a 5 μm scale, highlighting the sample's surface morphology. Figure 9 represents the SEM Image of the conventional cementitious composite at 10.5kX Magnification

The figure displays a high-resolution SEM (scanning electron microscope) micrograph of a material at 5 μm scale. The figure shows complex structures resembling granular or crystalline formations. The magnification is 10.5kX, with an electron beam energy of 10 keV. This detailed view highlights the sample's surface morphology, revealing fine particles and textures that likely indicate its composition. The scale bar indicates that the features are 5 μm in size. Figure 10 represents the SEM Image of the conventional cementitious composite at 41.9kX Magnification.

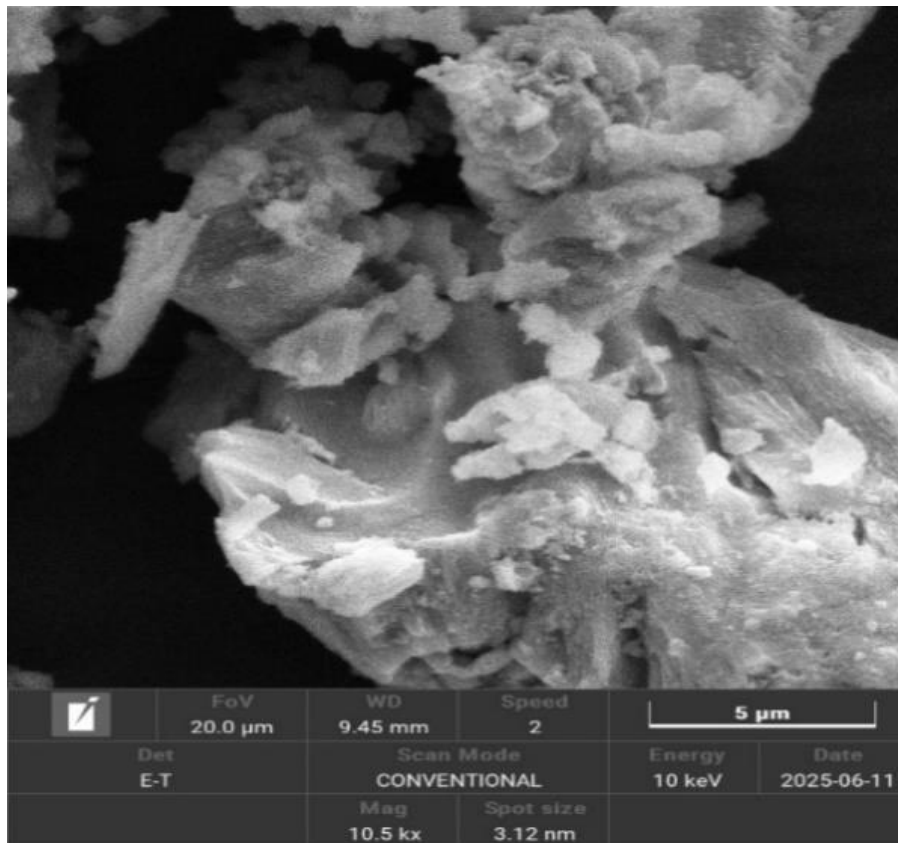


Figure 8. SEM Image of Conventional Cementitious composite at 10.5kX Magnification (5 µm scale)

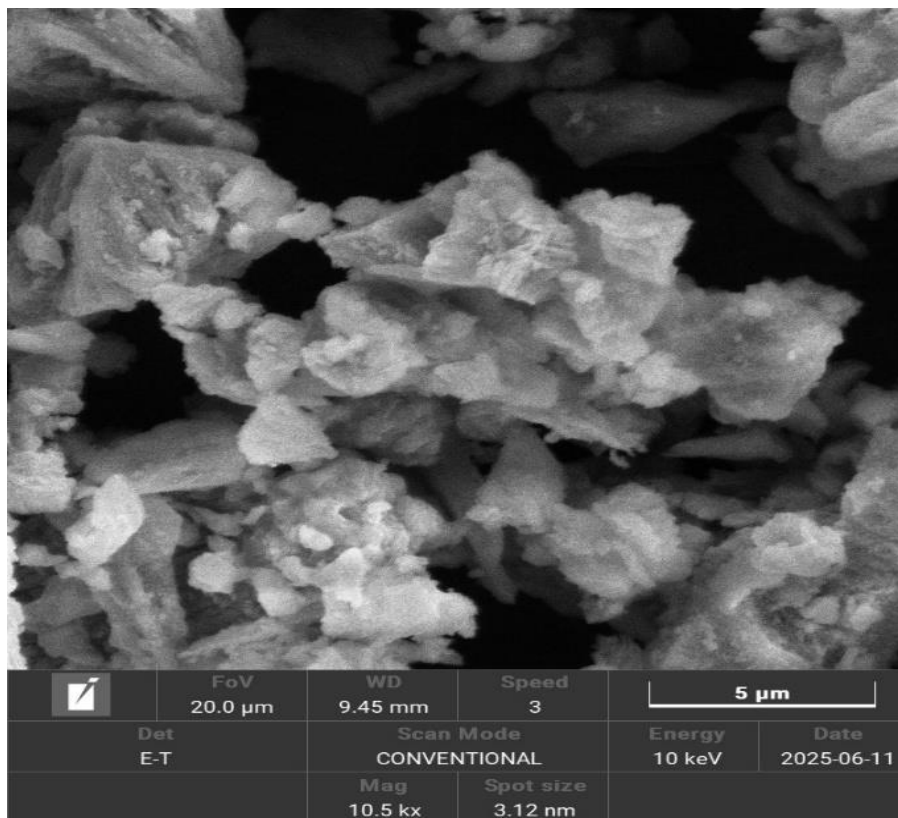


Figure 9. SEM Image of Conventional Cementitious composite at 10.5kX Magnification (5 µm scale)

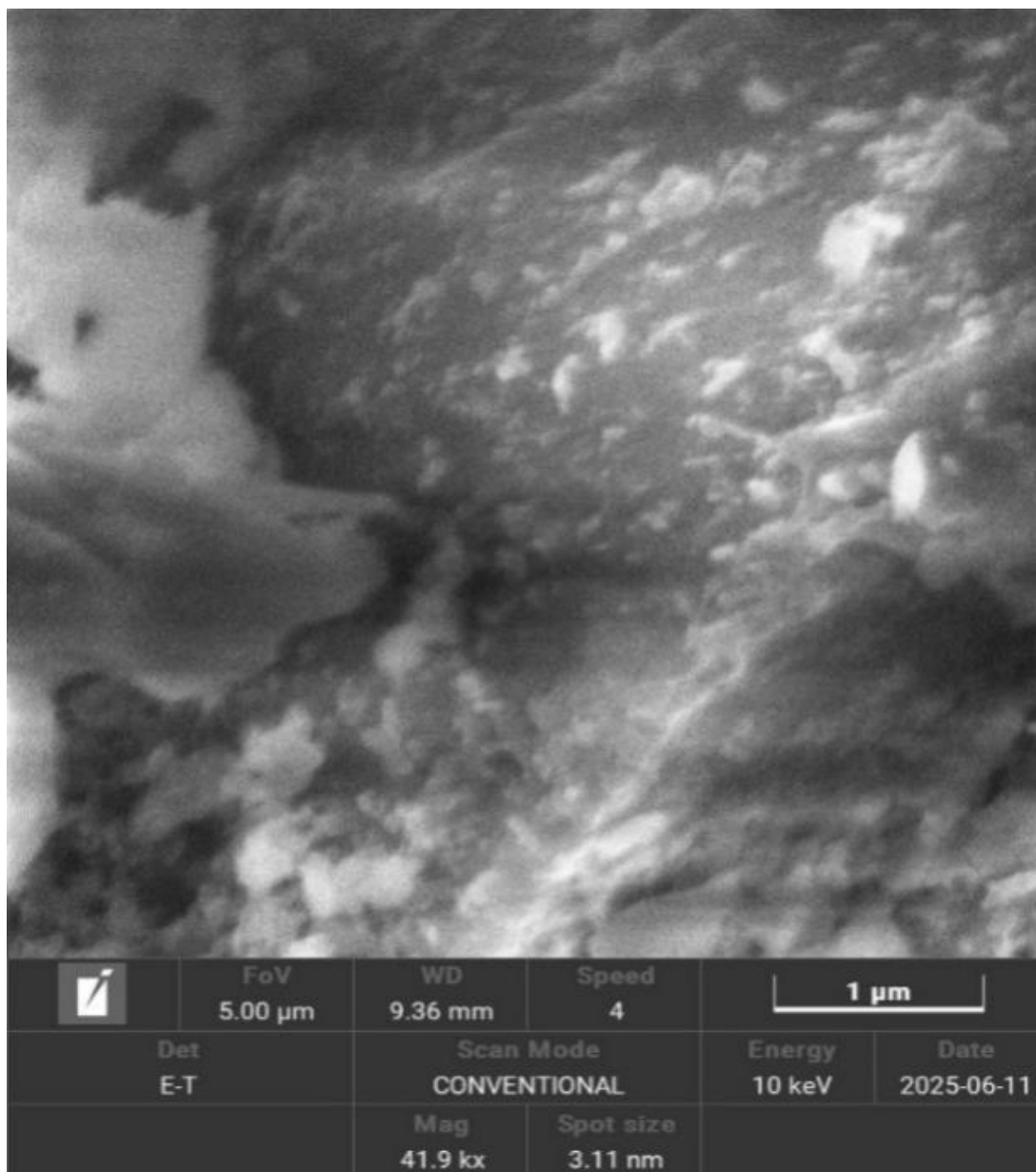


Figure 10. SEM Image of Conventional Cementitious composite at 41.9kX Magnification (1 μm scale)

The figure above shows an electron microscope scan at 41.9kX magnification, providing a detailed view of the surface. The scanning parameters used are 10 keV and a 3.11 mm spot size. The figure captured with a field of view (FoV) of 5.00 μm, at a working distance (WD) of 9.36 mm, and a scanning speed of 4. The scale bar represents 1 μm, providing high-level detail for analysis at micro- and nanoscales. Figure 11 represents the SEM image of a material at 10.5 kx Magnification.

The figure shows a detailed scanning electron microscope (SEM) image of a material at 10.5 kx magnification with a spot size of 3.11 mm. The energy used for scanning is 10 keV, and the figure resolution is 5 μm. The specimen, displayed at a working distance of 9.37 mm, shows surface features, including small particles and a rough texture, which may indicate structural or surface damage. The scanning mode used is conventional. Figure 12 represents the SEM image of a material at 10 keV Magnification.



Figure 11. Electron microscope (SEM) image of a material at 10.5 kx

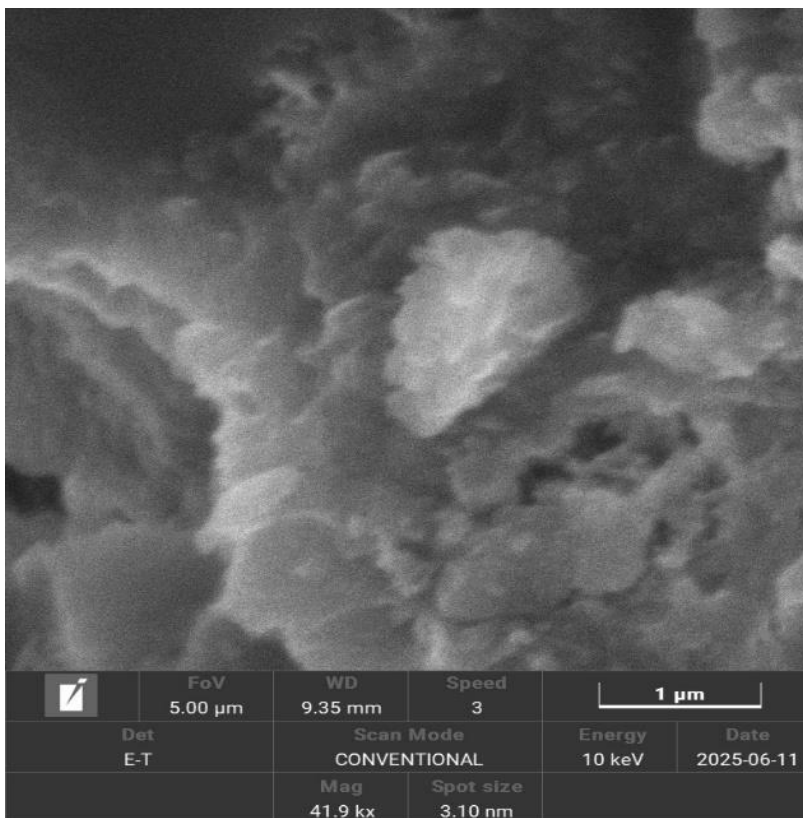


Figure 12. Scanning Electron Microscope (SEM) image captured at 10 keV

The figure above shows a Scanning Electron Microscope (SEM) image captured at 10 keV, revealing high-resolution details of a material's surface. The magnification is 41.9kX, and the spot size is 3.10 nm, revealing delicate structures within a 1 μm scale. The working distance (WD) is 9.35 mm, with an electron beam speed of 3. Figure 13 represents the SEM micrograph surface morphology and particle agglomeration of the material at a 2 μm scale

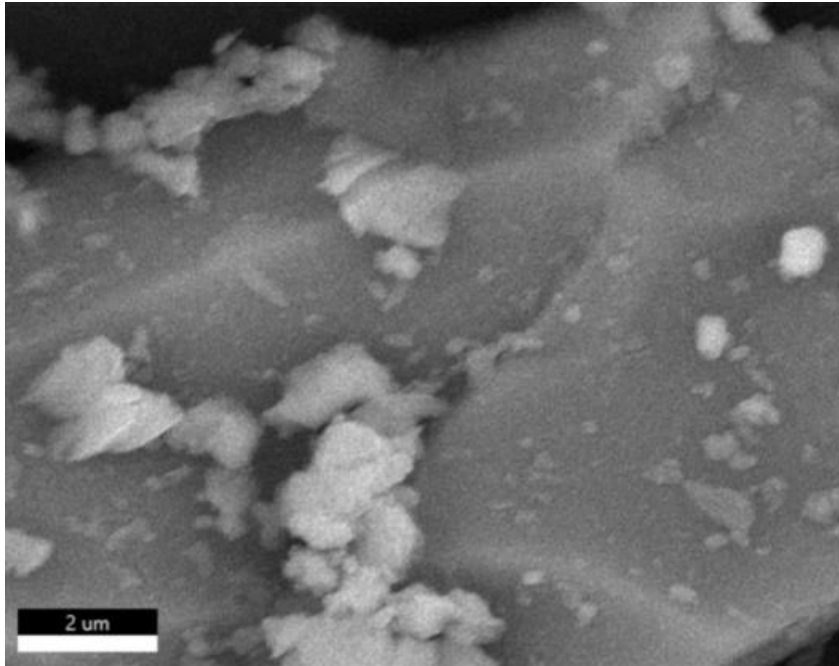


Figure 13. SEM micrograph surface morphology and particle agglomeration of the material at 2 μm scale

This SEM figure shows crystalline particles loosely attached to flat surfaces. The weak bonding and high surface roughness indicate poor hydration and weak cementitious gel. The presence of loosely held particles suggests structural vulnerability under stress. This morphology increases susceptibility to crack formation and reduces overall strength. Compared to treated or modified concrete, this conventional mix exhibits less dense and less durable microstructural properties. Figure 14 shows the SEM micrograph of the sample, revealing a heterogeneous surface morphology with irregularly shaped micro-particles and agglomerates.

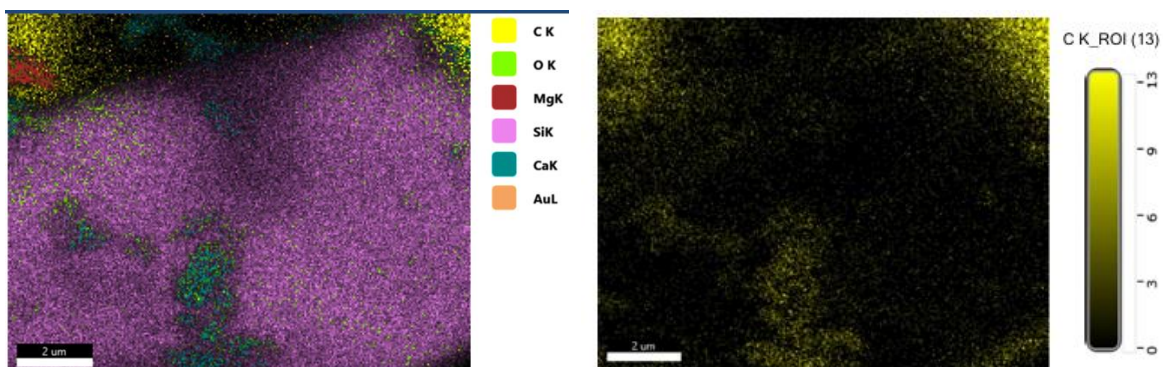


Figure 14. SEM micrograph of the sample showing heterogeneous surface morphology with irregularly shaped micro-particles and agglomerates

Elemental Mapping of Cementitious Composite Matrix (EDS Analysis) The EDS elemental mapping reveals a matrix dominated by Si and Ca, confirming extensive C-S-H gel formation.

Additionally, scattered carbon deposition indicates carbonation and microbial activity, which aid in micro-crack healing and overall densification of the Cementitious composite structure. Figure 15 (a,b) represents the Oxygen (O K) Elemental Distribution Map and Magnesium (Mg K) Elemental Distribution Map

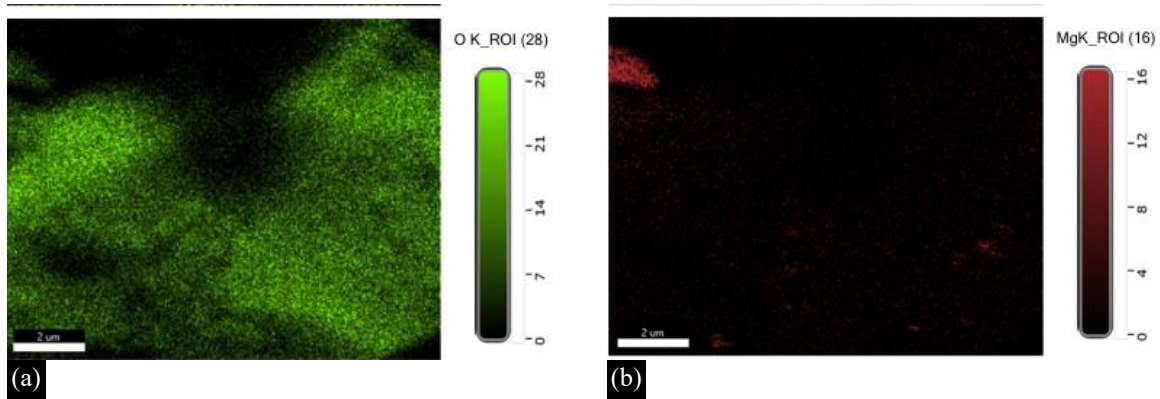


Figure 15. (a) Oxygen Elemental Distribution Map and (b) Magnesium Elemental Distribution Map

The oxygen map shows abundant oxides, such as CaO, SiO₂, and MgO, which drive hydration and strengthen the matrix. In contrast, the magnesium map indicates minor Mg phases that contribute to durability, stability, and improved sulfate resistance in concrete. Table 3 represents the EDS Quantitative Analysis of Sample 1. Figure 16 is the graphical representation of the EDS Quantitative Analysis of Sample 1.

Table 3. EDS Quantitative Analysis of Sample 1

Element	Weight %	MDL	Atomic %	Net Int.	Error %	R	A	F
C K	23.4	0.20	33.0	163.7	11.2	0.9100	0.0543	1.0000
O K	49.2	0.05	52.1	1927.0	9.9	0.9202	0.1188	1.0000
Mg K	0.5	0.02	0.2	78.9	4.0	0.9354	0.0852	1.0008
Si K	21.5	0.01	13.0	5178.6	4.4	0.9418	0.0670	1.0041
Ca K	3.1	0.03	1.3	401.4	3.9	0.9678	0.8946	1.0006
Au L	2.3	0.36	0.2	19.5	20.3	0.9881	0.9958	1.0583

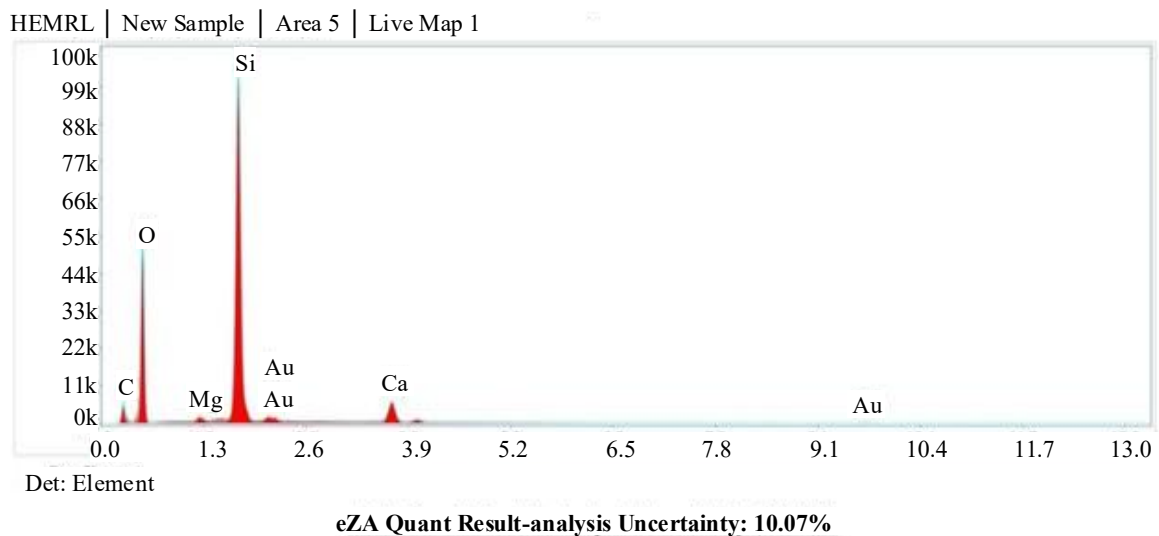


Figure 16. EDS Quantitative Analysis of Sample 1

From Figure 16, the EDS spectrum of Sample 1 shows a dominant presence of oxygen (49.2 wt%) and silicon (21.5 wt%), confirming the presence of high-silicate phases, which are essential for C-S-H gel formation in concrete. Carbon (23.4 wt%) is also significant, likely from carbonation effects or microbial activity. The presence of Ca (3.1 wt%) contributes to the formation of portlandite and C-S-H. Minor Mg and Au traces are observed. The high O/Si ratio confirms the presence of hydration products, while firm C peaks suggest matrix densification. This elemental composition indicates good binding phases but a higher carbon content than the control composite. Figure 17 represents the SEM Micrograph of Cementitious composite Surface Elemental Overlay Mapping of Cementitious composite Matrix

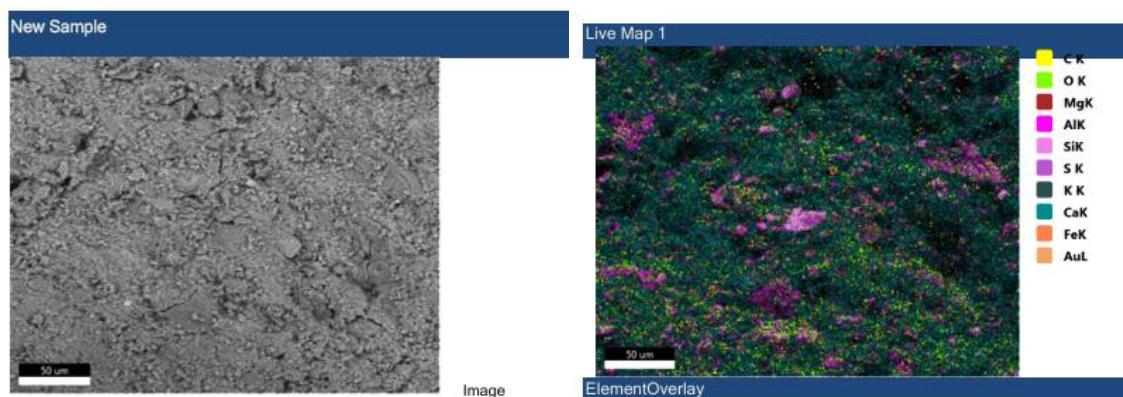


Figure 17. SEM Micrograph of Cementitious composite Surface Elemental Overlay Mapping of Cementitious composite Matrix

The SEM and elemental overlay mapping together reveal a heterogeneous Cementitious composite surface with fine particles, indicating incomplete hydration and porosity. Simultaneously, strong Si and Ca distributions confirm the formation of C-S-H gel and a calcium-rich phase, enhancing matrix strength. Figure 18 (a,b) represents the Aluminium Elemental Distribution Map and Silicon Elemental Distribution Map

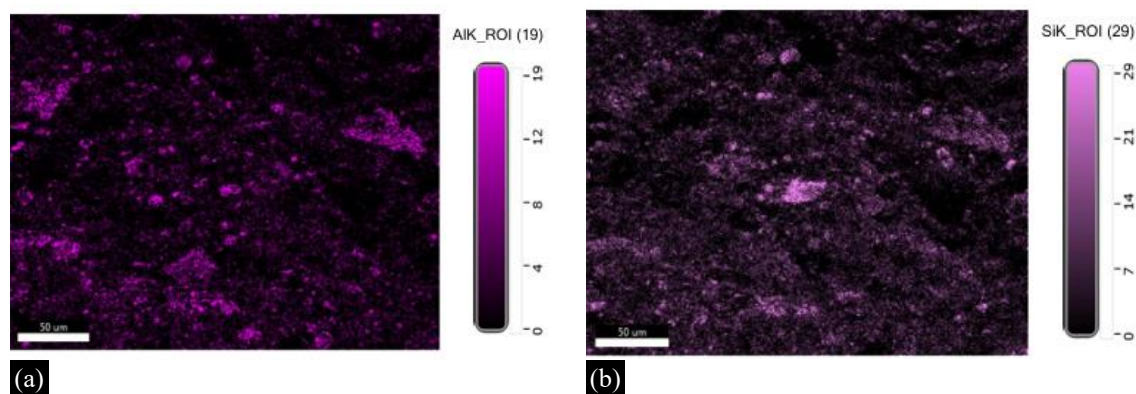


Figure 18. (a) Aluminium Elemental Distribution Map and (b) Silicon Elemental Distribution Map

The elemental mapping indicates dispersed aluminium contributing to aluminosilicate phases and secondary hydration, while abundant silicon confirms the formation of C-S-H gel. Together, Al and Si enhance matrix densification, chemical resistance, and overall mechanical strength of the concrete. Figure 19 represents the Sulfur Elemental Distribution Map

The elemental map indicates minimal sulfur distribution. Trace sulfur may form gypsum or ettringite phases, thereby influencing setting time, expansion control, and durability under sulfate-exposure

conditions. Table 4 represents the EDS Quantitative Analysis of Sample 2. Figure 20 is the graphical representation of the EDS Quantitative Analysis of Sample 2.

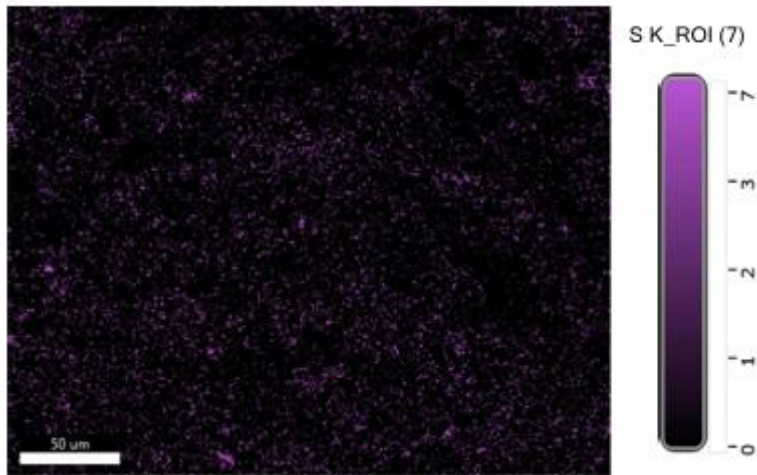
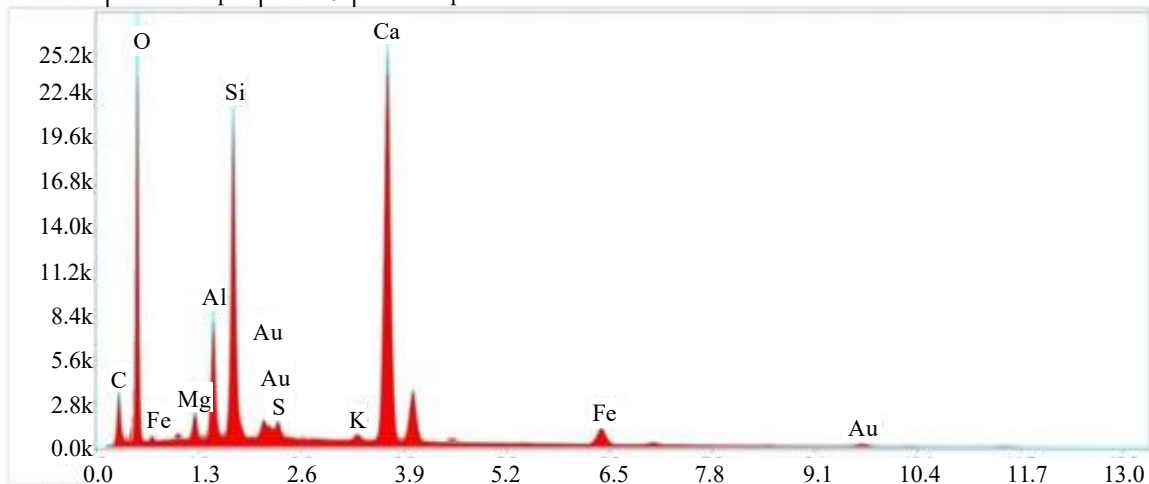


Figure 19. Sulfur Elemental Distribution Map

Table 4. EDS Quantitative Analysis of Sample 2

Element	Weight %	MDL	Atomic %	Net Int.	Error %	R	A	F
C K	11.4	0.44	18.6	65.8	11.8	0.8902	0.0712	1.0000
O K	49.7	0.10	61.1	925.2	10.3	0.9019	0.0893	1.0000
Mg K	0.9	0.03	0.7	82.7	9.0	0.9194	0.3514	1.0060
Al K	3.2	0.03	2.4	377.5	6.7	0.9233	0.4839	1.0091
Si K	7.9	0.03	5.5	1058.7	5.4	0.9270	0.5853	1.0096
S K	0.5	0.03	0.3	59.7	8.1	0.9338	0.7067	1.0226
K K	0.2	0.04	0.1	24.3	13.2	0.9430	0.8685	1.0779
Ca K	21.0	0.05	10.3	1714.3	2.4	0.9459	0.8995	1.0164
Fe K	2.0	0.08	0.7	88.2	4.5	0.9620	0.9554	1.0657
Au L	3.2	0.59	0.3	17.1	25.6	0.9839	0.9909	1.0418

HEMRL | New Sample | Area 6 | Live Map 1



Det: Element

Figure 20. EDS Quantitative Analysis of Sample 2

The EDS spectrum of Sample 2 shows high oxygen (49.7 wt%) and calcium (21 wt%) contents, confirming the presence of significant portlandite and hydration phases. Silicon content (7.9 wt%) is lower compared to Sample 1, while Al (3.2 wt%) and Fe (2 wt%) suggest minor alumino-silicate and ferrite phases. Carbon (11.4 wt%) is lower, indicating reduced carbonation. The presence of sulfur (0.5 wt.%) and potassium (0.2 wt.%) indicates the presence of alkali sulfates, which are typical in cementitious systems. The Ca/Si ratio indicates a well-formed C-S-H matrix, contributing to enhanced strength and durability.

While the experimental results demonstrate notable improvements in mechanical performance and microstructural refinement, the present study does not comprehensively address long-term durability under aggressive service conditions. Durability aspects such as repeated cracking–healing cycles, freeze–thaw exposure, chloride ingress, sulphate attack, and long-term retention of bacterial activity require further investigation. From a scalability perspective, challenges related to bacterial cultivation, survivability during mixing, and uniform distribution within large-volume concrete production must be addressed before field-scale implementation. Additionally, optimising bacterial encapsulation methods and nutrient delivery systems is necessary to ensure consistent self-healing performance in real-world construction environments. Practical implementation of bio-modified cementitious composites will also depend on cost-effectiveness, compatibility with conventional construction practices, and compliance with existing material standards. Future research should therefore focus on pilot-scale studies, life-cycle cost assessments, and performance validation under real-world exposure conditions to facilitate the translation of laboratory-scale investigations into practical infrastructure applications.

CONCLUSION

This study demonstrates that integrating industrial ash fillers with microbial self-healing agents yields a high-performance bio-engineered cementitious composite with enhanced mechanical and microstructural properties. Partial replacement of cement with pond ash contributed to secondary pozzolanic reactions, refining the composite matrix and improving filler–matrix compatibility. The incorporation of bacteria as a functional bio-additive enabled microbially induced calcite precipitation, which served as an autonomous crack-sealing mechanism and promoted matrix continuity.

Mechanical performance evaluation revealed significant improvements in both compressive and flexural behaviour, with optimised composite formulations exhibiting markedly higher strength compared to the control system. These enhancements are attributed to the synergistic interaction between ash fillers and bio-mineralisation products, which collectively improved stress transfer efficiency and reduced microstructural defects. The observed strength gains highlight the effectiveness of combining particulate fillers with biologically activated healing mechanisms in cementitious composite systems.

Microstructural analyses using SEM confirmed the formation of a dense and compact matrix characterised by reduced porosity and well-developed hydration products. The presence of calcium carbonate deposits within pores and microcracks indicates effective bacterial activity and confirms the role of bio-mineralisation in structural restoration. EDS results further validated the enrichment of calcium- and silicon-rich phases, supporting the development of stable calcium–silicate–hydrate networks responsible for the improved mechanical performance. Overall, the findings establish that bio-modified, filler-enhanced cementitious composites can achieve superior functional performance while simultaneously addressing sustainability challenges by reducing cement consumption and utilising industrial by-products. The proposed composite system offers a promising pathway toward durable, self-healing, and environmentally responsible construction materials. Future research should focus on long-term durability, cyclic loading behaviour, and scalability of bio-functional composite formulations to facilitate broader practical implementation.

LIMITATION AND FUTURE SCOPE

Despite the encouraging results, the present study has certain limitations. The experimental investigation was primarily limited to short- and medium-term curing periods, and long-term durability aspects such as cyclic loading behaviour, freeze–thaw resistance, sulphate and chloride attack, and sustained self-healing efficiency were not examined. In addition, bacterial viability and activity were evaluated under controlled laboratory conditions, which may differ from field exposure environments. Future research should therefore focus on long-term durability performance, optimisation of bacterial encapsulation techniques to enhance survivability, and quantitative assessment of self-healing efficiency under repeated cracking. Further studies on scale-up feasibility, cost–benefit analysis, and environmental life-cycle assessment are also required to facilitate the practical adoption of bio-modified cementitious composites in real-world construction applications

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