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Review Article

Synergistic Integration of Artificial Intelligence and Microbial Biotechnology for Next-Generation Self-Healing Interlocking Masonry Systems: Towards Sustainable and Intelligent Construction Materials

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Abstract

The convergence of artificial intelligence (AI) and microbial biotechnology is reshaping the development of next-generation construction materials, particularly in self-healing interlocking masonry systems. Interlocking masonry blocks offer mortar-free construction through geometric load transfer, providing improved modularity, seismic resilience, and sustainability. However, their long-term performance is often limited by interface degradation, cracking, and environmental exposure. To address these challenges, microbial-induced calcite precipitation (MICP) has emerged as a promising bio-based strategy for autonomous crack repair, where bacteria precipitate calcium carbonate to restore structural integrity and reduce permeability. In parallel, AI-driven approaches are increasingly being used to model, predict, and optimize material behavior, including strength development, durability performance, and healing efficiency. Machine learning algorithms such as artificial neural networks, random forest, and gradient boosting techniques enable rapid analysis of complex nonlinear relationships between material composition, environmental conditions, and structural response. Furthermore, AI-assisted optimization supports efficient mix design, bacterial selection, and carrier system development, reducing experimental cost and time. Integration of IoT-based sensing and digital twin frameworks further enhances real-time monitoring and lifecycle prediction of self-healing masonry systems. Despite these advancements, challenges remain in data standardization, bacterial survival in alkaline environments, scaling of bio-construction technologies, and lack of unified testing protocols. Addressing these limitations is essential for large-scale adoption. Overall, the integration of AI and microbial biotechnology provides a transformative pathway toward intelligent, durable, and environmentally sustainable interlocking masonry systems capable of autonomous repair and enhanced structural performance.

Keywords: Artificial intelligence; microbial biotechnology; self-healing masonry; interlocking blocks; sustainability

Highlights

a. Integration of AI and MICP enables autonomous crack repair in interlocking masonry systems.

b. Machine learning models improve prediction, optimization, and characterization of construction materials.

c. Bio-AI interlocking systems significantly enhance sustainability, durability, and lifecycle performance.

Introduction

Interlocking masonry block systems have emerged as an innovative and sustainable construction technology that combines structural efficiency, ease of assembly, and enhanced resilience against dynamic loading conditions [1]. Unlike conventional masonry, these dry-stack systems utilize specially designed geometric interlocks that enable mechanical engagement between units without the use of mortar, transferring loads primarily through frictional resistance, contact interaction, and geometric confinement [2]. The growing interest in interlocking blocks is driven by the need for cost-effective, earthquake-resistant, and environmentally sustainable building solutions [3]. Depending on their material composition, interlocking blocks may be manufactured from cement, concrete, recycled plastics, geopolymers, fiber-reinforced composites, or bio-engineered materials incorporating microbial-induced calcite precipitation (MICP), each offering distinct mechanical and durability characteristics [4]. Their structural behavior under seismic loading is governed by interface mechanics, where mechanisms such as sliding, rocking, stiffness degradation, and friction-based energy dissipation play critical roles in mitigating earthquake-induced damage. [5] Recent advances in bio-enhanced and geopolymer interlocking blocks have further expanded their potential by improving crack resistance, self-healing capability, and long-term durability while reducing carbon emissions associated with conventional construction materials [6]. Additionally, the elimination of mortar, reduction in material consumption, and incorporation of recycled or biologically derived components contribute significantly to resource efficiency and circular economy principles [7]. These attributes make interlocking masonry systems particularly attractive for sustainable infrastructure development in seismic-prone regions [8]. As research continues to integrate advanced materials, biotechnology, and performance-based design approaches, interlocking masonry blocks are increasingly recognized as a promising solution for achieving both structural resilience and environmental sustainability in modern construction. Overall, the evolution of interlocking masonry technology highlights its growing importance as a durable, eco-friendly, and earthquake-resistant alternative to traditional masonry systems.

Microbial biotechnology has emerged as a transformative approach for developing next-generation self-healing construction materials capable of autonomously repairing damage and enhancing long-term structural performance [9]. Among various bio-based strategies, Microbial-Induced Calcite Precipitation (MICP) has gained significant attention due to its ability to utilize metabolically active microorganisms to precipitate calcium carbonate within cracks, pores, and voids of masonry and cementitious materials [10]. The effectiveness of this technology largely depends on the use of robust spore-forming bacterial species, such as Bacillus and Sporosarcina, which can survive the highly alkaline and nutrient-limited conditions of construction environments and become activated upon crack formation [11]. Once activated by moisture ingress, these microorganisms initiate biomineralization processes that generate calcite crystals, gradually sealing cracks, restoring structural continuity, and reducing pathways for water and aggressive ion penetration [12]. Compared with conventional autogenous healing, bio-mediated healing demonstrates superior crack closure capacity, improved durability, and the ability to repeatedly respond to damage over extended service periods [13]. The incorporation of carrier systems such as hydrogels, lightweight aggregates, biochar, and encapsulation technologies further enhances bacterial viability and healing efficiency by providing protection and nutrient reservoirs [14]. In addition to crack repair, microbial self-healing significantly improves compressive and tensile strength, reduces porosity and permeability, and enhances resistance against chloride attack, freeze–thaw cycles, and chemical degradation [15]. Advanced characterization and performance evaluation techniques have confirmed the effectiveness of biomineralization in improving both microstructural integrity and mechanical behavior of masonry materials [16]. These developments highlight the growing potential of microbial biotechnology as a sustainable and low-maintenance solution for enhancing the resilience and longevity of interlocking masonry systems and other construction materials. Therefore, the integration of self-healing microbial technologies represents a major advancement toward durable, intelligent, and environmentally sustainable infrastructure for future construction applications.

Artificial Intelligence (AI) and microbial biotechnology are emerging as complementary technologies that are revolutionizing the development of intelligent, sustainable, and self-healing construction materials for future infrastructure systems [17]. The increasing demand for durable and environmentally responsible construction solutions has accelerated research into bio-based materials capable of autonomously repairing damage while minimizing maintenance requirements and resource consumption [18]. Microbial biotechnology, particularly Microbial-Induced Calcite Precipitation (MICP), enables the formation of calcium carbonate within cracks through bacterial biomineralization, facilitating crack closure, strength recovery, and enhanced durability of masonry and cementitious materials [19]. The effectiveness of these self-healing systems depends on multiple factors, including bacterial species selection, nutrient availability, carrier systems, environmental conditions, and crack characteristics, creating complex interactions that are difficult to optimize using conventional approaches [20]. In this context, AI technologies such as Artificial Neural Networks (ANN), Random Forest (RF), XGBoost, and deep learning algorithms provide powerful tools for predicting material performance, optimizing mix designs, selecting efficient bacterial strains, and evaluating healing efficiency [21]. Furthermore, AI-driven material characterization, smart monitoring systems, and predictive modeling enable real-time assessment of crack healing, durability enhancement, and long-term structural behavior [22]. The integration of AI with microbial biotechnology also supports the development of advanced digital twins capable of simulating microbial activity, crack evolution, and infrastructure performance throughout the service life of structures [23]. These innovations contribute to reduced experimental costs, accelerated material development, improved resource efficiency, and enhanced sustainability in construction practices [24]. By combining autonomous biological repair mechanisms with intelligent data-driven decision-making, AI-assisted microbial systems offer a transformative pathway toward resilient, low-carbon, and self-sustaining construction materials [25]. Therefore, the convergence of artificial intelligence and microbial biotechnology represents a significant advancement in the creation of smart self-healing

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masonry systems and sustainable infrastructure for future generations.

The sustainability and long-term environmental performance of construction materials have become central concerns in modern infrastructure development, particularly in the context of climate change and resource depletion [26]. The construction sector significantly contributes to global carbon emissions, primarily through cement production, which drives the need for alternative low-carbon and resource-efficient materials such as AI-integrated microbial self-healing interlocking masonry systems [27]. These systems offer substantial carbon reduction potential by eliminating or minimizing mortar usage, extending service life through microbial-induced calcite precipitation (MICP), and reducing repair and maintenance-related emissions over the lifecycle of structures [28]. In addition, the incorporation of recycled materials, industrial by-products, and bio-based carriers further enhances resource efficiency while supporting circular economy principles [29]. Life Cycle Assessment (LCA) studies indicate that such bio-mediated systems demonstrate lower environmental burdens due to reduced material consumption, improved durability, and decreased transportation and reconstruction demands [30]. Resource efficiency is further strengthened through modular interlocking design, AI-driven optimization of material composition, and minimized experimental waste during development [31]. Moreover, these technologies strongly contribute to multiple Sustainable Development Goals (SDGs), including climate action, sustainable cities, responsible consumption, and resilient infrastructure, by integrating environmental performance with structural functionality [32]. Despite these advantages, challenges such as limited large-scale data, bacterial survival constraints, lack of standardized testing methods, and commercialization barriers continue to hinder widespread adoption [33]. However, future directions involving smart bio-interlocking blocks, AI-driven autonomous materials, IoT-enabled monitoring, and digital twin integration are expected to overcome these limitations and enable real-time performance optimization [34]. Overall, the convergence of microbial biotechnology, artificial intelligence, and sustainable construction principles presents a transformative pathway for reducing environmental impact while enhancing structural durability, making it a highly promising approach for next-generation green infrastructure systems.

Table 1: Types of Interlocking Masonry Blocks and Their Characteristics [22-36].

Type of Interlocking Block	Manufacturing Material	Key Mechanical Characteristics	Structural & Seismic Behavior	Sustainability Aspect
Cement-Based Interlocking Blocks	Cement, sand, coarse aggregates	High compressive strength, moderate tensile resistance, brittle failure tendency	Good load-bearing capacity; limited ductility under cyclic seismic loading; friction-based sliding at interfaces	Moderate sustainability; high cement content increases carbon footprint
Concrete Interlocking Blocks	Cement + aggregates + admixtures	Uniform strength distribution, improved durability, higher stiffness	Better structural predictability; stiffness degradation under strong seismic excitation	Moderate sustainability; improved lifespan reduces maintenance demand
Plastic Interlocking Blocks	Recycled polymers (HDPE, PP, etc.)	Lightweight, high ductility, low stiffness, high deformation capacity	Excellent energy dissipation via controlled sliding and rocking; reduced seismic inertia forces	High sustainability due to recycling and reduced material weight
Geopolymer Interlocking Blocks	Fly ash, slag, alkali activators	High compressive strength, chemical resistance, low shrinkage	Improved stiffness retention; reduced brittle cracking under seismic loads	Very high sustainability; low CO_2 emission alternative to cement
Hybrid Fiber/Bio-Enhanced Blocks	Cement/concrete + fibers or microbial additives	Enhanced tensile strength, crack resistance, improved toughness	Delayed crack propagation; improved ductility and damping under cyclic loading	High sustainability with bio-additives and reduced material demand
Bio-Engineered (MICP-Based) Blocks	Microbial calcite precipitation systems	Self-healing microstructure, improved porosity control, enhanced bonding	Crack sealing capability improves long-term seismic resilience and interface stability	Extremely high sustainability; biologically driven self-repair and low environmental impact

1. Interlocking Masonry Blocks: Concepts and Materials

Interlocking masonry block systems represent an advanced form of dry-stack construction in which individual units are designed with complementary geometric profiles that enable mechanical engagement without the need for mortar. These systems rely on frictional resistance, geometric confinement, and interface compatibility to transfer loads across structural members [1]. As highlighted in recent experimental and numerical studies on mortar-free interlocking assemblies, the absence of mortar significantly shifts the load-resisting mechanism from cohesion-based bonding to contact-driven interaction, where stiffness, damping, and energy dissipation are governed by interface behavior and cyclic sliding mechanisms [3]. In the context of seismic performance, particularly in cross-junction configurations, these systems demonstrate nonlinear dynamic response characterized by progressive stiffness degradation, controlled sliding, and friction-based energy dissipation under cyclic excitation, as observed in shake-table investigations of interlocking plastic block masonry.

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The classification of interlocking blocks is primarily based on material composition and structural functionality, ranging from conventional cementitious units to emerging bio-engineered and polymer-based systems (Table 1). Cement and concrete interlocking blocks remain widely used due to their high compressive strength and ease of manufacturing, while plastic interlocking blocks have gained attention for their lightweight nature and enhanced ductility under seismic loading [2]. Recent advancements have further introduced hybrid and geopolymer-based blocks that integrate industrial by-products or fiber reinforcements to improve mechanical efficiency and sustainability [35]. Notably, emerging bio-engineered blocks incorporating microbial-induced calcite precipitation (MICP) reflect a convergence of biotechnology and construction materials science, offering potential self-healing capabilities and improved microstructural bonding [36]. These diverse material systems exhibit fundamentally different interface mechanics, which directly influence seismic behavior, particularly at critical stress concentration zones such as wall cross-junctions.

The manufacturing of interlocking masonry blocks involves a wide range of conventional, composite, and bio-integrated materials selected based on structural demand and environmental considerations. Cement and concrete remain dominant due to their established mechanical reliability; however, their high carbon emissions have driven research toward alternative binders such as geopolymers and industrial waste-based materials [5]. In parallel, polymer-based systems utilize recycled plastics, aligning with circular economy principles and significantly reducing structural dead load, which is critical in seismic design [37]. Furthermore, bio-cementation techniques using microbial activity introduce a novel material paradigm where calcium carbonate precipitation enhances particle bonding and reduces porosity, directly improving crack resistance and durability under cyclic loading conditions [38]. These material innovations collectively influence interface stiffness, frictional behavior, and energy dissipation mechanisms in interlocking systems.

The mechanical response of interlocking masonry systems is fundamentally governed by contact mechanics rather than traditional mortar-based bonding. Under seismic excitation, these systems exhibit nonlinear behavior characterized by micro-sliding, rocking, and progressive interface separation [6]. As demonstrated in shake-table experimental studies on interlocking plastic block cross-junctions, stiffness degradation and damping variation are strongly dependent on geometric detailing and interface quality. Cross-junctions, in particular, act as critical stress concentration zones where multi-directional loading induces shear, torsional, and opening-closing mechanisms [7]. This leads to localized damage initiation and progressive redistribution of seismic forces. The dynamic response is further characterized by reductions in natural frequency and increased damping ratios due to frictional energy dissipation, making interface stability the governing factor in overall seismic performance.

Interlocking masonry systems offer significant sustainability advantages by reducing material consumption, eliminating mortar requirements, and enabling dry-stack construction methods that are reusable and easily dismantled [4]. Lightweight plastic and geopolymer-based systems reduce transportation energy and embodied carbon emissions, while bio-engineered blocks introduce self-healing capabilities that extend structural lifespan and reduce maintenance demands. From a life-cycle perspective, these systems align strongly with sustainable development goals by minimizing environmental impact while enhancing structural resilience [39]. Additionally, the integration of recycled polymers and industrial by-products contributes to waste valorization, while microbial-based systems introduce a new frontier in environmentally responsive construction materials [40]. Collectively, these innovations position interlocking masonry as a key technology for future earthquake-resistant and environmentally sustainable infrastructure.

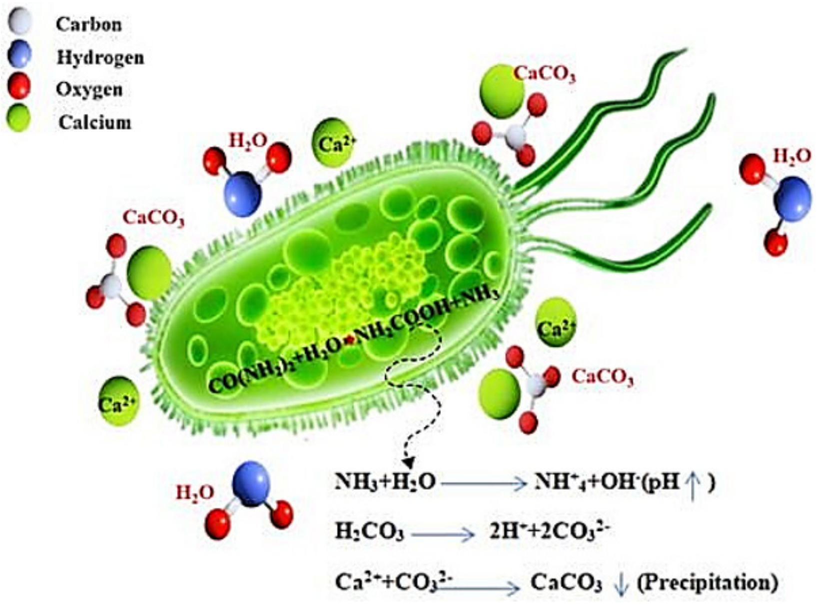

Figure 1: Biochemical pathway illustrating bacterial urease activity, carbonate formation, and calcium carbonate precipitation for crack healing [16].

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Microbial Biotechnology for Self-Healing Systems

Microbial-Induced Calcite Precipitation (MICP)

Microbial-Induced Calcite Precipitation (MICP) is one of the most widely investigated biotechnology-based approaches for developing self-healing construction materials. The process utilizes metabolically active microorganisms to precipitate calcium carbonate ($CaCO_3$) within cracks, pores, and voids of cementitious and masonry materials (Figure 1) [8]. During microbial activity, bacteria hydrolyze urea or metabolize organic compounds, generating carbonate ions that react with available calcium ions to form calcite crystals [41]. These precipitates gradually accumulate within damaged regions and restore structural continuity. Recent studies have demonstrated that MICP can autonomously heal cracks up to 0.8 mm wide while significantly reducing permeability and enhancing durability. The technology is particularly attractive for sustainable construction because it mimics natural biomineralization processes found in geological environments [13]. Research on fiber bioconcrete further indicates that MICP improves compressive strength by up to 42% and tensile strength by approximately 63% through densification of the microstructure and reduction of porosity [42]. In addition to mechanical enhancement, MICP contributes to long-term serviceability by limiting chloride ingress, water penetration, and chemical deterioration [10]. The integration of MICP within masonry blocks and interlocking construction systems therefore offers a promising route toward self-repairing, durable, and environmentally sustainable infrastructure.

Bacterial species

The success of bio-mediated self-healing systems largely depends on the selection of bacterial species capable of surviving harsh construction environments characterized by high alkalinity, limited nutrients, and low moisture availability [43]. Among the most commonly employed microorganisms are species belonging to the genus Bacillus, including Bacillus subtilis, Bacillus pasteurii (Sporosarcina pasteurii), Bacillus sphaericus, Bacillus cereus, and Bacillus safensis [9]. These bacteria are preferred because of their spore-forming capability, which enables long-term survival under dormant conditions until cracks develop and moisture becomes available. Sporosarcina pasteurii is particularly effective due to its high urease activity, which accelerates carbonate production and calcite precipitation [44]. Studies have shown that incorporating these bacterial species into concrete and masonry matrices significantly improves crack-healing efficiency, mechanical strength, and durability performance [12]. The combination of bacterial cultures with fibers further enhances healing effectiveness by providing nucleation sites for calcite growth and controlling crack propagation. Recent investigations indicate that bacterial self-healing systems can substantially reduce maintenance requirements while extending the service life of structures by several decades [45]. Consequently, spore-forming bacteria represent the cornerstone of modern microbial biotechnology applications in self-healing masonry and concrete systems.

Mechanism of crack healing

The crack-healing mechanism in microbial self-healing systems is based on biological mineralization occurring within damaged regions of the construction material. When cracks form and environmental moisture infiltrates the matrix, dormant bacterial spores become activated and initiate metabolic processes [11]. Through ureolysis or alternative metabolic pathways, bacteria produce carbonate ions that react with calcium ions naturally present within the surrounding material or supplied through nutrient carriers. This reaction leads to the formation of calcium carbonate crystals, predominantly in the form of calcite [46]. The precipitated calcite gradually accumulates within the crack volume, effectively bridging crack surfaces and restoring structural integrity. As crystal growth continues, the permeability of the crack decreases and transport pathways for aggressive agents become blocked. The resulting mineral deposits improve water tightness, reduce chloride diffusion, and enhance resistance against chemical attack [15]. Studies have demonstrated that bacterial healing is capable of restoring mechanical performance while significantly increasing durability and service life [47]. Unlike conventional repair methods, this process is autonomous and occurs repeatedly whenever favorable environmental conditions are available, making it particularly suitable for sustainable and low-maintenance construction systems.

Carrier systems and survival issues

One of the major challenges associated with microbial self-healing technology is maintaining bacterial viability within highly alkaline and mechanically demanding construction environments. Direct incorporation of bacterial cells often leads to rapid loss of activity due to cement hydration products, elevated pH values, and limited nutrient availability [14]. To overcome these challenges, researchers have developed various carrier systems designed to protect microorganisms and ensure long-term survival [48]. Common carrier materials include lightweight aggregates, silica gel, expanded clay particles, hydrogels, polyurethane capsules, biochar, diatomaceous earth, and natural fibers [49]. These carriers provide physical protection while simultaneously serving as reservoirs for nutrients and moisture required for bacterial activation. Hydrogel encapsulation has been particularly successful because it allows controlled release of bacteria and healing agents upon crack formation [16]. Despite these advances, several survival-related issues remain, including nutrient depletion, uneven bacterial distribution, premature activation, and reduced viability during long-term service conditions. Environmental factors such as temperature fluctuations, repeated wetting-drying cycles, and exposure to aggressive chemicals can further influence bacterial performance [50]. Consequently, ongoing research focuses on optimizing carrier design, bacterial encapsulation techniques, and nutrient delivery systems to enhance healing efficiency and ensure reliable long-term performance of bio-mediated self-healing masonry materials.

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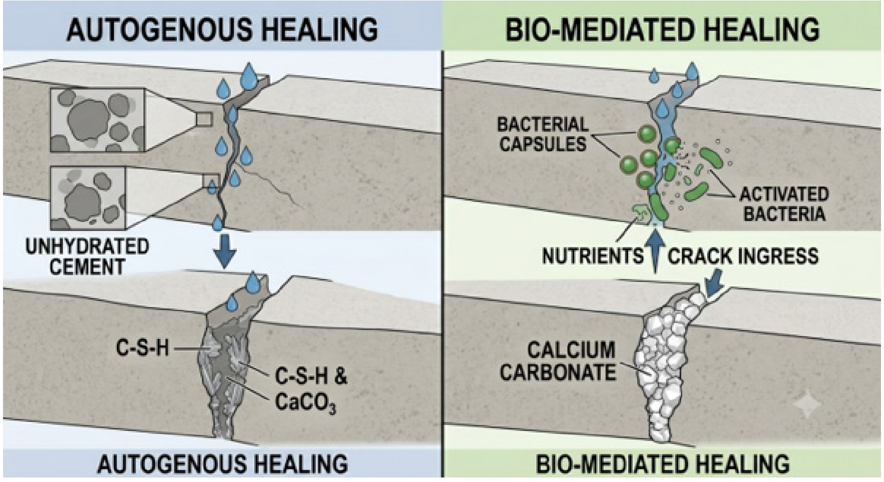

Figure 2: Comparison between Natural Autogenous Healing and Bacterial-Mediated Self-Healing Processes in Masonry Materials.

Self-Healing Mechanisms in Masonry Blocks

Autogenous vs Bio-Mediated Healing

Self-healing in masonry blocks can occur through either autogenous or bio-mediated mechanisms, each differing significantly in healing efficiency and crack repair capacity [7]. Autogenous healing is a naturally occurring phenomenon resulting from continued cement hydration, carbonation reactions, and precipitation of calcium compounds within small cracks [3]. This mechanism is generally limited to crack widths below approximately 0.18 mm and relies heavily on the availability of moisture and unhydrated cement particles [12]. In contrast, bio-mediated healing utilizes microorganisms capable of producing calcium carbonate through biomineralization processes (Figure 2) [18]. The biological approach can repair substantially larger cracks, often reaching widths of 0.8 mm or greater, while providing more reliable and repeatable healing performance [25]. Studies have shown that bacterial self-healing systems significantly outperform conventional autogenous healing in terms of crack closure, permeability reduction, and durability enhancement [9]. Furthermore, bio-mediated healing remains active for extended periods because bacterial spores can remain dormant until environmental conditions become favorable [33]. As a result, microbial biotechnology offers a more advanced and sustainable solution for long-term crack management in masonry blocks and interlocking construction systems [41].

Crack sealing process

The crack sealing process in bio-mediated masonry systems begins immediately after crack formation creates pathways for moisture and oxygen penetration [6]. Water entering the crack activates dormant bacterial spores encapsulated within the masonry matrix or carrier materials [14]. Once activated, the bacteria metabolize available nutrients and generate carbonate ions as metabolic by-products [22]. These ions subsequently combine with calcium ions present in the surrounding environment to form calcium carbonate crystals [28]. The crystals nucleate on crack surfaces and progressively fill the void space through continuous precipitation and crystal growth [31]. As mineral accumulation increases, crack width gradually decreases until complete or near-complete closure is achieved [37]. The deposited calcite acts as a natural cementing material that restores continuity between separated surfaces [44]. This sealing process not only repairs visible cracks but also blocks micro-channels responsible for fluid transport and aggressive ion penetration [19]. Consequently, the crack sealing mechanism improves water tightness, reduces permeability, and enhances the overall durability of masonry structures exposed to harsh environmental conditions [46]. The effectiveness of this process depends on bacterial viability, nutrient availability, environmental conditions, and crack geometry [10].

Strength recovery and durability enhancement

An important advantage of microbial self-healing technology is its ability to recover lost mechanical strength while simultaneously improving durability characteristics [11]. The precipitation of calcium carbonate within cracks creates a denser and more compact microstructure, resulting in enhanced load transfer across damaged regions [16]. Studies have reported substantial increases in compressive strength, tensile strength, and flexural performance following bacterial healing [21]. In fiber bioconcrete systems, compressive strength improvements of approximately 42% and tensile strength enhancements of up to 63% have been documented [27]. The healed microstructure also exhibits reduced porosity and permeability, thereby limiting ingress of water, chlorides, sulfates, and other harmful substances [34]. This reduction in transport properties significantly enhances resistance against corrosion, freeze-thaw cycles, chemical attack, and environmental degradation [40]. Furthermore, the combination of bacterial biomineralization and fiber reinforcement improves crack control and distributes stresses more effectively throughout the material [45]. As a

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result, bio-mediated masonry blocks demonstrate superior structural resilience, longer service life, and reduced maintenance requirements compared with conventional masonry materials [49].

Performance evaluation methods

The performance of self-healing masonry systems is evaluated through a combination of mechanical, durability, microstructural, and non-destructive testing techniques [2]. Crack closure measurements obtained through optical microscopy, image analysis, and digital monitoring are commonly used to quantify healing efficiency [8]. Mechanical performance is assessed through compressive strength, flexural strength, tensile strength, and bond strength tests conducted before and after healing [13]. Durability evaluation typically includes water absorption, sorptivity, permeability, chloride penetration, sulfate resistance, and freeze-thaw testing to determine improvements in long-term performance [17]. Advanced characterization methods such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR) are employed to confirm calcite formation and investigate microstructural changes resulting from biomineralization [23]. More recently, vibration-based monitoring, ultrasonic pulse velocity measurements, acoustic emission analysis, and tomography techniques have been utilized to evaluate internal crack healing and structural integrity without damaging specimens [30]. These comprehensive evaluation approaches provide valuable insights into healing mechanisms, effectiveness of bacterial activity, durability enhancement, and overall structural performance of self-healing masonry blocks designed for sustainable construction applications [50].

Artificial Intelligence in Construction Materials

Machine learning models

Artificial Intelligence has become a transformative technology in construction materials research by enabling rapid prediction, classification, optimization, and decision-making using large experimental datasets (Table 2). Traditional empirical methods often struggle to capture the highly nonlinear relationships among material composition, curing conditions, environmental exposure, and structural performance. Machine learning (ML) models including Artificial Neural Networks (ANN), Random Forest (RF), Extreme Gradient Boosting (XGBoost), Support Vector Machines (SVM), Decision Trees (DT), and Deep Learning (DL) have demonstrated remarkable capability in addressing these complexities [51]. ANN models mimic biological neural networks and are particularly effective in predicting compressive strength, tensile strength, and elastic modulus [52]. RF algorithms provide robust predictions while identifying the relative importance of individual variables affecting material behavior [53]. XGBoost has gained significant attention because of its high accuracy, computational efficiency, and ability to process large multidimensional datasets [54]. Recent studies indicate that these algorithms frequently outperform conventional regression-based approaches in predicting construction material properties [55]. The growing availability of experimental databases and sensor-generated information has further accelerated AI adoption in sustainable construction research.

Table 2: Common Machine Learning Models Used in Construction Material Research [51-55].

AI Model	Principle	Major Applications	Advantages
ANN	Learns nonlinear relationships through interconnected neurons	Strength prediction, durability assessment	High predictive accuracy
Random Forest	Ensemble of decision trees	Material classification, durability prediction	Handles large datasets effectively
XGBoost	Gradient boosting algorithm	Multi-variable performance prediction	High accuracy and efficiency
SVM	Hyperplane-based classification and regression	Crack detection, material characterization	Effective with limited datasets
CNN	Deep learning image analysis	Crack recognition and microstructure analysis	Automated image processing
Genetic Algorithm	Evolutionary optimization	Mix design optimization	Multi-objective optimization capability

Prediction of strength and durability

The prediction of mechanical and durability properties represents one of the most successful applications of AI in construction materials engineering. Conventional laboratory testing procedures for compressive strength, flexural strength, permeability, chloride resistance, sulfate attack resistance, and freeze-thaw durability are often costly and time-consuming. AI models significantly reduce these limitations by establishing predictive relationships between input variables and performance outcomes [56]. Researchers have successfully utilized ANN, RF, and XGBoost models to estimate strength development based on cement content, aggregate properties, water-to-binder ratio, curing conditions, and supplementary cementitious materials [57]. Similar approaches are increasingly being applied to sustainable materials, recycled aggregates, bio-based composites, and self-healing systems (Table 3) [58]. Machine learning algorithms can also predict durability indicators such as crack propagation, carbonation depth, water absorption, and chloride penetration [59]. In bio-mediated materials, AI facilitates the prediction of bacterial healing efficiency, calcite precipitation rates, and long-term performance [60]. These predictive capabilities enable rapid screening of material formulations before experimental validation.

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Mix design optimization

Mix design optimization has traditionally relied on trial-and-error experimentation requiring substantial material consumption and laboratory effort. Artificial Intelligence has transformed this process by enabling rapid identification of optimal material compositions capable of satisfying multiple performance objectives simultaneously.

Machine learning algorithms evaluate the influence of material constituents and environmental conditions on strength, durability, sustainability, and economic feasibility [61]. Multi-objective optimization frameworks can maximize mechanical performance while minimizing cement consumption, carbon emissions, and production costs [62]. In microbial self-healing materials, AI can optimize bacterial concentration, nutrient dosage, carrier systems, and curing parameters to maximize calcite precipitation and crack-healing efficiency [63]. Genetic Algorithms, ANN-based optimization models, and hybrid AI techniques have demonstrated exceptional effectiveness in identifying optimal formulations [64]. Such approaches support circular economy principles by facilitating the utilization of recycled materials, industrial by-products, and bio-based additives.

Table 3: Representative Case Studies on AI-Assisted Self-Healing Construction Materials [56-60].

Study Focus	Material System	AI Technique	Main Outcome
Strength prediction of bio-concrete	Microbial concrete	ANN	Accurate prediction of compressive strength
Durability assessment	Self-healing mortar	Random Forest	Prediction of permeability reduction
Healing efficiency estimation	MICP-treated concrete	XGBoost	Identification of key healing parameters
Crack monitoring	Bio-mediated composites	CNN	Automated crack detection and healing assessment
Lifecycle prediction	Smart bio-construction systems	Digital Twin + AI	Real-time performance forecasting

AI in material characterization

Material characterization is essential for understanding the relationships between microstructure and engineering performance. Artificial Intelligence has significantly enhanced characterization processes by enabling automated analysis of images, sensor data, and laboratory measurements. Computer vision systems integrated with Convolutional Neural Networks (CNNs) can identify cracks, pores, defects, and microstructural features with high precision [51]. Deep learning algorithms are increasingly employed to analyze scanning electron microscopy (SEM), X-ray diffraction (XRD), computed tomography (CT), and vibration monitoring datasets [52]. In self-healing materials, AI-assisted image analysis facilitates quantification of crack closure, calcite deposition, and healing progression [53]. Moreover, AI models can establish correlations between microscopic characteristics and macroscopic mechanical properties, providing valuable insights into material behavior [54]. For masonry and interlocking block systems, AI-based characterization supports automated damage assessment, stiffness degradation analysis, and dynamic response evaluation.

Integration of AI and Microbial Biotechnology

AI-assisted bacterial selection

The performance of microbial self-healing systems depends strongly on selecting bacterial species capable of surviving harsh construction environments while maintaining high biomineralization efficiency. Artificial Intelligence provides a data-driven approach for identifying suitable bacterial strains by analyzing microbial characteristics such as urease activity, sporulation capability, environmental tolerance, metabolic pathways, and calcium carbonate precipitation potential [55]. Species belonging to the genera Bacillus, Sporosarcina, Lysinibacillus, and Paenibacillus are widely investigated because of their ability to withstand highly alkaline cementitious environments [56]. Machine learning models can compare biological performance under varying environmental conditions and identify optimal candidates for specific construction applications [57]. AI-assisted screening significantly reduces experimental effort while accelerating microbial selection processes [58]. Furthermore, integration of genomic and proteomic databases with machine learning enables discovery of previously unexplored bacterial strains with promising biomineralization potential.

Optimization of nutrient and carrier systems

The effectiveness of microbial self-healing systems depends not only on bacterial species but also on nutrient availability and carrier protection mechanisms. AI-based optimization techniques facilitate identification of optimal nutrient formulations and carrier materials capable of maximizing bacterial survival and calcite precipitation efficiency [59]. Common carrier systems include biochar, expanded clay, hydrogels, silica gel, lightweight aggregates, polyurethane microcapsules, and diatomaceous earth [60]. Machine learning models analyze interactions among bacterial concentration, nutrient release characteristics, carrier porosity, moisture availability, and environmental exposure conditions [61]. Multi-objective optimization algorithms can simultaneously maximize healing efficiency and mechanical performance while minimizing cost and environmental impact [62]. Recent studies have demonstrated that AI-driven carrier optimization significantly improves bacterial viability and long-term self-healing performance [63]. Such approaches are particularly relevant for developing durable self-healing interlocking masonry blocks intended for sustainable infrastructure applications.

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Predictive modeling of healing performance

Predicting healing performance is one of the most promising applications of AI within microbial biotechnology. Healing efficiency depends on numerous interacting factors including bacterial activity, nutrient availability, crack geometry, environmental conditions, and material composition. Machine learning algorithms can analyze large datasets and predict crack closure rates, calcite precipitation, permeability reduction, and strength recovery with high reliability [64]. ANN, RF, and XGBoost models have demonstrated strong predictive capabilities in evaluating self-healing performance under varying exposure conditions [65]. These predictive models reduce dependence on lengthy experimental investigations while supporting rapid assessment of alternative material formulations. AI can further identify the most influential parameters controlling healing efficiency and reveal complex nonlinear interactions that are difficult to capture using traditional analytical approaches.

Smart monitoring of self-healing behavior

Artificial Intelligence enables continuous monitoring of self-healing materials through integration with advanced sensors and structural health monitoring systems. Embedded sensors can collect real-time information related to strain, vibration, moisture, temperature, acoustic emissions, and crack propagation. AI algorithms process these datasets to identify damage initiation, monitor healing progression, and evaluate structural performance throughout the service life of infrastructure systems [17]. Deep learning-based image analysis further enables automatic quantification of crack closure and calcite deposition [52]. Such intelligent monitoring systems facilitate early detection of deterioration and support proactive maintenance strategies [25]. Moreover, continuous monitoring provides valuable datasets for improving predictive models and enhancing understanding of long-term microbial behavior.

Digital twins in bio-construction

Digital Twin technology represents the highest level of integration between Artificial Intelligence, microbial biotechnology, and smart infrastructure systems (Table 4). A digital twin is a dynamic virtual representation of a physical structure continuously updated using real-time sensor data. In bio-construction applications, digital twins can simulate crack development, microbial activity, calcite precipitation, healing efficiency, and long-term structural performance [19]. AI algorithms process incoming data and update virtual models to predict future behavior under changing environmental and loading conditions [55]. This capability allows engineers to optimize maintenance schedules, evaluate durability, and assess structural resilience before significant deterioration occurs [23]. Digital twins also support scenario-based simulations for examining the long-term sustainability of self-healing masonry and concrete systems.

Table 4: Research Gaps and Future Opportunities in AI-Assisted Bio-Based Interlocking Masonry [18,23,55,38,42].

Research Area	Current Status	Major Limitation	Future Opportunity
MICP in interlocking blocks	Very limited studies	Focus on concrete systems	Self-healing masonry units
AI-based bacterial selection	Emerging	Small biological datasets	Large microbial databases
Healing performance prediction	Limited applications	Lack of standardized models	Universal prediction frameworks
Smart monitoring	Early-stage research	High sensor cost	IoT-enabled monitoring
Digital twins	Conceptual stage	Limited validation studies	Real-time infrastructure management
Sustainable carrier systems	Growing interest	Bacterial survival challenges	Biochar and waste-derived carriers

Sustainability and Environmental Impact

Carbon reduction potential

The construction industry is responsible for a substantial proportion of global greenhouse gas emissions, with cement production alone contributing approximately 7–8% of global CO_2 emissions. The development of microbial self-healing interlocking masonry blocks presents a promising strategy for reducing the carbon footprint of construction materials through multiple pathways. Firstly, mortar-free interlocking systems eliminate or significantly reduce the need for cement-based mortar, thereby lowering embodied carbon associated with masonry construction [12]. Secondly, microbial-induced calcite precipitation (MICP) enables autonomous crack repair, extending service life and reducing the frequency of maintenance, rehabilitation, and reconstruction activities [18]. The calcium carbonate precipitated by bacteria acts as a natural mineral filler that restores structural integrity without requiring additional cementitious repair materials [25]. Furthermore, several studies have demonstrated that bacteria can utilize industrial by-products and waste-derived nutrient sources, reducing dependence on virgin materials [33]. AI-assisted mix optimization further contributes to carbon reduction by identifying material combinations that maximize mechanical performance while minimizing cement content [41]. Through predictive modeling and optimization, machine learning algorithms can determine the lowest-carbon formulations capable of meeting performance requirements [52]. Consequently, the integration of AI and microbial biotechnology in interlocking masonry systems offers a dual sustainability benefit by reducing both material consumption and lifecycle emissions while simultaneously enhancing structural durability and resilience [60].

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of construction materials throughout their entire lifecycle, from raw

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material extraction to end-of-life disposal or recycling. Recent LCA studies indicate that self-healing construction materials exhibit significantly lower environmental burdens compared to conventional materials due to reduced maintenance requirements and extended service life [8]. In bio-mediated masonry systems, environmental benefits arise from decreased repair frequency, lower material replacement rates, and reduced transportation-related emissions associated with maintenance operations [14]. The incorporation of recycled plastic aggregates, industrial by-products, or bio-based carriers into interlocking blocks further improves environmental performance by diverting waste from landfills and reducing raw material extraction [21]. AI technologies enhance LCA effectiveness by enabling rapid simulation of numerous design scenarios and identifying optimal combinations of materials, bacterial concentrations, and healing strategies with minimal environmental impact [36]. Digital twin platforms can additionally support lifecycle management by continuously monitoring structural performance and predicting maintenance needs before significant deterioration occurs [44]. Although comprehensive LCA studies specifically focusing on AI-integrated microbial interlocking blocks remain limited, existing evidence strongly suggests that such systems can achieve substantial reductions in energy consumption, resource depletion, and carbon emissions over their operational lifespan [57].

Table 5: Sustainability Contributions of AI-Integrated Bio-Self-Healing Interlocking Masonry Systems.

Sustainability Aspect	Conventional Masonry	Bio-Self-Healing Interlocking Masonry	Sustainability Benefit
Mortar Usage	High	Minimal or none	Reduced cement consumption
Repair Frequency	Frequent	Significantly reduced	Lower maintenance emissions
Service Life	Moderate	Extended	Improved lifecycle sustainability
Waste Generation	High during demolition	Reusable modular blocks	Circular economy potential
Carbon Emissions	High embodied carbon	Reduced lifecycle carbon	Climate change mitigation
Material Efficiency	Material-intensive	Optimized through AI	Reduced resource consumption
Durability	Crack-prone	Autonomous healing	Enhanced infrastructure resilience
SDG Alignment	Limited	Strong alignment with SDGs 9, 11, 12, 13, and 15	Sustainable development support

Resource efficiency

Resource efficiency represents a critical pillar of sustainable construction, emphasizing the optimal utilization of materials, energy, and natural resources while minimizing waste generation. Interlocking masonry technology inherently promotes resource efficiency through modular design, mortar elimination, rapid construction, and ease of disassembly for reuse or recycling [6]. The adoption of microbial self-healing mechanisms further enhances efficiency by preserving structural integrity and reducing material losses associated with crack formation and deterioration [17]. MICP-based healing processes utilize naturally occurring microorganisms and relatively small quantities of nutrients to generate substantial durability improvements, making them highly resource-efficient compared to conventional repair techniques [29]. AI-driven optimization models contribute by minimizing trial-and-error experimentation during material development and identifying efficient combinations of aggregates, bacterial carriers, and nutrient formulations [38]. Machine learning algorithms can also predict long-term performance, enabling designers to avoid excessive material usage through performance-based design approaches [50]. Additionally, the utilization of recycled plastics, agricultural residues, fly ash, slag, and biochar within interlocking block production aligns with circular economy principles by converting waste streams into valuable construction resources [62]. Collectively, these advancements facilitate more efficient use of materials and energy while supporting sustainable infrastructure development [54].

Contribution to Sustainable Development Goals (SDGs)

The integration of artificial intelligence, microbial biotechnology, and interlocking masonry technology contributes directly to several United Nations Sustainable Development Goals (SDGs) (Table 5). Most notably, SDG 9 (Industry, Innovation and Infrastructure) is supported through the development of innovative, resilient, and sustainable construction materials capable of autonomous self-repair [11]. SDG 11 (Sustainable Cities and Communities) benefits from enhanced structural durability, improved disaster resilience, and reduced maintenance requirements, which collectively contribute to safer and longer-lasting infrastructure [27]. The reduction of cement consumption and associated greenhouse gas emissions aligns closely with SDG 13 (Climate Action), while the incorporation of recycled materials and resource-efficient production practices supports SDG 12 (Responsible Consumption and Production) [34]. Furthermore, microbial self-healing systems that utilize environmentally benign biological processes contribute to SDG 15 (Life on Land) by reducing environmental degradation associated with intensive raw material extraction [46]. AI-assisted optimization also promotes efficient resource utilization and technological innovation, reinforcing SDG 8 (Decent Work and Economic Growth) through the advancement of high-value sustainable construction technologies [58]. Therefore, AI-enabled bio-interlocking masonry systems represent a multidisciplinary solution capable of simultaneously addressing engineering challenges and global sustainability objectives [63].

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Challenges and Research Gaps

Limited experimental data for AI training

Despite the growing application of machine learning in construction materials research, one of the most significant barriers to effective AI implementation is the limited availability of high-quality experimental datasets. Most published studies on microbial self-healing materials are conducted under laboratory conditions using relatively small sample sizes and varying experimental protocols, resulting in fragmented and non-standardized datasets [7]. Machine learning algorithms require extensive, diverse, and reliable data to establish robust predictive relationships between material composition, bacterial activity, healing efficiency, and long-term durability [19]. However, variations in bacterial species, nutrient formulations, curing conditions, environmental exposure, and testing methodologies often make direct comparison between studies difficult [26]. Furthermore, publicly accessible databases specifically focused on bio-mediated self-healing masonry materials remain scarce [39]. This lack of standardized datasets limits model generalization, reduces prediction reliability, and hinders the development of universal AI frameworks [53]. Future research should prioritize large-scale collaborative data-sharing initiatives, standardized reporting protocols, and open-access databases to facilitate more accurate and transferable machine learning applications within bio-construction research [61].

Bacterial survival limitations

The long-term viability of bacteria within masonry materials remains one of the most critical challenges affecting the performance of microbial self-healing systems. The internal environment of masonry and concrete structures is typically characterized by high alkalinity, limited moisture availability, temperature fluctuations, and restricted nutrient access, all of which can adversely affect bacterial survival [13]. Although spore-forming bacteria such as Bacillus and Sporosarcina species exhibit remarkable resistance to harsh environmental conditions, maintaining their viability over extended periods remains challenging [22]. Premature bacterial death can significantly reduce self-healing efficiency and compromise long-term functionality [30]. Researchers have proposed various carrier materials, including expanded clay, biochar, silica gel, hydrogels, and lightweight aggregates, to protect bacterial cells and provide favorable microenvironments [42]. Nevertheless, achieving reliable bacterial activation years after construction remains an unresolved issue [55]. Further investigations are required to improve encapsulation technologies, optimize nutrient delivery systems, and understand long-term microbial behavior under realistic field conditions [64].

Scaling and commercialization issues

Although laboratory-scale studies have demonstrated promising results for microbial self-healing materials, translating these technologies into commercial construction applications remains challenging. Large-scale production introduces numerous technical and economic considerations, including bacterial cultivation costs, carrier material manufacturing, quality control procedures, storage stability, and compatibility with industrial production processes [16]. Variability in environmental conditions across different geographical regions may also influence bacterial performance and healing effectiveness [28]. In addition, industry adoption is often hindered by limited awareness, uncertainty regarding long-term reliability, and lack of established design guidelines [37]. Regulatory approval processes and certification requirements can further delay commercialization efforts [45]. AI technologies may help address some of these challenges by optimizing production parameters, predicting performance variability, and supporting cost-benefit analyses [59]. However, significant research and industrial collaboration are still required to develop economically viable manufacturing strategies and establish confidence among stakeholders [65].

Lack of standardized testing methods

A major research gap within the field of microbial self-healing construction materials is the absence of universally accepted testing standards for evaluating healing performance. Current studies employ diverse methodologies for crack generation, bacterial incorporation, healing assessment, durability evaluation, and mechanical testing, resulting in substantial variability across reported results [10]. Healing efficiency is often measured using different parameters, including crack closure percentage, permeability reduction, strength recovery, water absorption, ultrasonic pulse velocity, and microscopic observations [20]. Such inconsistencies make comparative analysis difficult and hinder the development of reliable performance benchmarks [31]. Furthermore, standardized protocols specifically designed for interlocking masonry systems are largely unavailable [40]. The establishment of internationally recognized testing standards would facilitate reproducibility, improve data quality, and accelerate technology transfer from research laboratories to practical construction applications [49].

Future Directions

Smart bio-interlocking blocks

Future research is expected to focus on the development of smart bio-interlocking blocks capable of sensing, diagnosing, and autonomously responding to structural deterioration. These next-generation materials may integrate bacterial self-healing systems with embedded sensors, enabling continuous monitoring of crack formation, moisture ingress, and structural performance [24]. Such intelligent masonry units could automatically activate microbial healing processes when damage is detected, creating truly adaptive construction materials [43]. The combination of biological repair mechanisms and real-time sensing technologies represents a transformative step toward self-maintaining infrastructure capable of significantly reducing maintenance costs and extending service life [62].

AI-driven autonomous construction materials

The emergence of AI-driven autonomous materials offers exciting opportunities for the construction sector. Advanced machine learning algorithms may eventually control material design, bacterial activation strategies, nutrient delivery systems, and healing optimization without human intervention [15]. By

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continuously learning from operational data, AI systems could dynamically adjust healing parameters according to environmental conditions and structural demands [35]. Such adaptive materials would represent a paradigm shift from passive construction components toward intelligent systems capable of self-optimization throughout their lifecycle [47]. Future studies should explore reinforcement learning, generative AI, and autonomous optimization frameworks for developing highly responsive bio-construction materials [60].

Integration with IoT and Digital Twins

The integration of Internet of Things (IoT) technologies and digital twins is anticipated to revolutionize monitoring and management of self-healing masonry structures. Embedded sensors can continuously collect data on temperature, humidity, strain, vibration, crack width, and bacterial activity, transmitting information to cloud-based monitoring platforms [9]. Digital twins can utilize this data to create virtual representations of physical structures, enabling real-time condition assessment and predictive maintenance planning [23]. AI algorithms can analyze incoming sensor data to forecast deterioration trends, evaluate healing effectiveness, and recommend intervention strategies when necessary [48]. This integration will significantly enhance reliability, performance monitoring, and lifecycle management of future bio-interlocking infrastructure systems [56].

Field-scale implementation and validation

Although laboratory investigations have demonstrated considerable promise, large-scale field implementation remains the ultimate test for AI-enabled microbial self-healing interlocking masonry systems. Future research should prioritize pilot projects involving residential buildings, retaining walls, pavements, and disaster-resilient housing structures under real environmental conditions [18]. Long-term monitoring programs are necessary to evaluate bacterial viability, healing efficiency, structural durability, and economic feasibility over extended service periods [33]. Comparative studies between conventional masonry and bio-self-healing systems will also be essential for quantifying practical benefits and supporting industry adoption [52]. Successful field validation will facilitate the development of design guidelines, regulatory frameworks, and commercialization pathways necessary for widespread implementation of sustainable intelligent construction materials [65].

Conclusions

Interlocking masonry systems represent a significant advancement in modern construction technology due to their mortar-free assembly and mechanically interlocking geometry. These systems transfer loads through frictional resistance and geometric confinement rather than relying on cementitious bonding. This fundamental shift improves modularity, ease of construction, and dismantling potential for reuse. Their performance under seismic loading is particularly notable due to controlled sliding and energy dissipation mechanisms. However, their structural behavior is highly dependent on interface quality and block configuration. Material innovations such as geopolymer, polymer, and fiber-reinforced blocks further enhance their mechanical efficiency. Bio-engineered versions introduce additional functionality through self-healing capacity. These developments collectively improve durability and sustainability outcomes. Despite these advantages, optimization of joint behavior remains essential. Overall, interlocking systems provide a strong foundation for sustainable masonry evolution.

Microbial biotechnology, particularly microbial-induced calcite precipitation, has introduced a new dimension to self-healing construction materials. This biological mechanism enables autonomous crack repair through calcium carbonate deposition within damaged regions. Compared to autogenous healing, microbial systems can repair wider cracks and provide more reliable long-term performance. The use of spore-forming bacteria such as Bacillus and Sporosarcina ensures survival under harsh alkaline conditions. Carrier systems play a critical role in protecting bacteria and enabling controlled activation. These systems improve crack sealing efficiency and enhance durability under aggressive environmental exposure. The resulting calcite formation restores structural continuity and reduces permeability. Mechanical strength recovery is also significantly improved through microstructural densification. However, maintaining long-term bacterial viability remains a challenge. Continued improvement in encapsulation and nutrient delivery is necessary for full-scale application.

Artificial intelligence has become a powerful tool in optimizing and accelerating the development of construction materials. Machine learning models such as artificial neural networks, random forest, and gradient boosting techniques can accurately predict mechanical and durability properties. These models reduce reliance on extensive laboratory testing by learning complex nonlinear relationships in material behavior. AI also supports mix design optimization by balancing performance, cost, and environmental impact simultaneously. In microbial systems, AI helps optimize bacterial concentration, nutrient composition, and carrier selection. Advanced image-based models assist in material characterization and damage detection. Integration with sensor data enables real-time monitoring of structural health and healing progression. Digital twin systems further enhance predictive maintenance and lifecycle assessment capabilities. Despite these advancements, model reliability depends heavily on data quality and standardization. Expanding datasets and improving interoperability remain critical for future progress.

From a sustainability perspective, the combination of interlocking masonry, microbial healing, and artificial intelligence offers substantial environmental benefits. Reduction in cement usage directly lowers carbon emissions associated with construction activities. Extended service life through self-healing mechanisms reduces repair frequency and material consumption. Use of recycled plastics, industrial by-products, and bio-based materials supports circular economy principles. Resource efficiency is improved through optimized material design and reduced waste generation. These systems align strongly with multiple Sustainable Development Goals, particularly those related to infrastructure,

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climate action, and responsible consumption. However, challenges such as limited field validation, bacterial survival constraints, and lack of standardized testing still restrict widespread adoption. Large-scale implementation will require coordinated research efforts and industrial collaboration. Development of unified standards and long-term performance studies is essential. With continued advancement, these technologies have strong potential to redefine sustainable construction practices.

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Conflict of Interest

Authors declare that they have no conflict of interest with this publication.

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References

1. Dias Oliveira J, Rodrigues H, Asteris PG, Varum H (2022) On the seismic behavior of masonry infilled frame structures. Buildings 12(8): 1146.
2. Feizolahbeigi A, Mendes N (2025) Evaluation of different types of advanced analysis for the study of the seismic behavior of masonry minarets. Structures 78: 109134.
3. Farahani EM, Yekrangnia M, Rezaie M, Bento R (2021) Seismic behavior of masonry walls retrofitted by centercore technique: A numerical study. Construction and Building Materials 267: 120382.
4. Qiao Q, Ding R, Liu W, Cao W (2023) Experimental study on seismic behavior of masonry walls retrofitted with steel-member and high-performance polymer mortar. Journal of Building Engineering 75: 106940.
5. Zhang Y, Lin X, Wang T, Skalomenos K (2021) Seismic behavior of masonry walls strengthened by precast reinforced concrete panels with different connection details. Engineering Structures 242: 112597.
6. Yu QQ, Wu JY, Gu XL, Wang L (2023) Seismic behavior of hinged steel frames with masonry infill walls. Journal of Building Engineering 77: 107536.
7. Deng Z, Chen M, Gong M (2022) Seismic behavior of brick masonry walls strengthened with different types of fiber nets. Structural Engineering International 32(4): 491–500.
8. Sleiman E, Ferrier E, Michel L, Saidi M (2024) Seismic behavior of masonry-infilled reinforced concrete frames strengthened using ultra-high performance concrete diagonal strips. Structures 59: 105790.
9. Ochoa Victoria Elena Meza, Naren Grajales Rios, Marco Antonio Márquez Godoy, Harveth Gil (2026) Life cycle assessment of MICP-treatment specimens from kaolin mining residues: Environmental hotspots on the path to bio-brick production. Bioresource Technology Reports 34: 102848.
10. Luan Ji yuan, Huan xiang Qiu, Jing yi Shen, Shuai kang Su, Cheng hao Li, et al. (2026) Han Dynasty bricks reinforcement and repair by microbial method (MICP): Mechanical and microstructural investigation. SSRN 528: 6024841.
11. Gao Yu, Mingjian Zhu, Chi Li, Shuanhu Li, Meng Wang (2026) Study on the mechanisms of wind erosion resistance and restoration for rammed earthen sites via MICP modified with bio-based additives. Construction and Building Materials 520: 145943.
12. Chen Zhongyuan, Xiaolong Xu, Jianping Wei, Xueyan Guo, Xinyi Ke (2026) Mechanism of the EICP centrifugal cementation method for short-term brick crack rehabilitation. Buildings 16(6): 1251.
13. Qiao Jing, Hongxian Guo, Xichen Xu, Xiaohui Cheng (2026) A review of MICP technology’s status and opportunities in weathering and conservation of geomaterial-based cultural relics. Bulletin of Engineering Geology and the Environment 85(6): 374.
14. Murugesan Yogesh Kumar, V Sivasubramanian, Nithya V Pillai (2026) Life cycle assessment informed process development for sustainable biocement bricks reinforced with plant-based natural fibers and supplemented with biosilica from renewable biomass. In Biomass Processing Technologies for Sustainable Energy and Material Production (CRC Press) pp. 143–157.
15. Lessly Herald, Veerammal Subramanian, Asokan Dandapani (2026) A study on the mechanical and self-healing behavior of bio-concrete blocks based on Spirulina algae. Environmental Science and Pollution Research 2026: 1–6.
16. Guo Zhongqun (2026) Experimental study on the disintegration characteristics of rare earth tailings improved by BF-MICP. Scientific Reports 16(1): 11064.
17. Surnam Khooshal, Mahendra Gooroochurn, Hudaa Neetoo (2026) Development and performance evaluation of microbially-formed bio-bricks incorporating recycled glass and rocksand for sustainable energy-efficient construction 11(3): 173.
18. Al Breiki Safa, Behrooz Raeesi, Pavel Gramin, Abdullah Al Anboori, German Merletti, et al. (2026) Fluid compartmentalization and enhancing saturation-height modelling through conditioning capillary pressure data in microporosity-dominated Barik Formation, Oman Block 61. In SPE EOR Conference at Oil and Gas West Asia (SPE, 2026): D021S034R001.
19. Zhong Z, Jialiu Pan, Jiaxu Shen, Hongpeng Wang, Yongqun Zhang, et al. (2024) Experimental study on seismic performance of damaged masonry walls reinforced with high-polymer cementitious composite material. Journal of Building Engineering 96 (2024): 110629.
20. Parisi MA, Chesi C, Sferrazza Papa G (2026) The role of interventions on roofs in the seismic behavior of masonry churches: Studies and observations. Structural Analysis of Historical Constructions (SAHC 2025) RILEM Bookseries 68 (Springer) pp. 1629-1640.
21. Liu Y, Hua Guo, Wenlong Wei, Shuo Chen, Yan Liu, et al. (2026) Pushover behavior of unreinforced masonry walls based on multiple modeling methods: Damage mechanism and failure mode. Buildings 16(7): 1439.
22. Yücel G (2026) Nonlinear seismic assessment of masonry buildings strengthened with textile-reinforced mortar: Two case studies. DUJE 17(1).
23. Al Ahdal A, Abdelrahman B, Galal K (2025) Compressive, shear, and tensile behaviours of concrete masonry: Experimental and numerical study. Construction and Building Materials 458: 139266.
24. Abdelrahman MZ, Belal Abdel Rahman, Khaled Galal (2026) Comparative study on the in-plane shear and compressive behaviour of concrete masonry with different unit bonding patterns. Engineering Structures 358: 122556.
25. Liu S, Pao Huang, Jiawei Zhang, Kuangmin Zheng, Jinpeng Dai, et al. (2025) Experimental study on shear behavior of brick masonry strengthened with CFRP flexible tendons embedded in mortar joints. Journal of Building Engineering 119: 114980.
26. Hyseni A, Carmelo Caggegi, Nadege Reboul, Francesco Micelli (2025) Diagonal shear behaviour of limestone masonry walls strengthened with jute-TRM composite systems. Construction and Building Materials 470: 140572.

Citation: Zeenat Khan*, Mahin Jamil, Shahrose Ashraf, Daud Khan and Abdullah Ikram. Synergistic Integration of Artificial Intelligence and Microbial Biotechnology for Next-Generation Self-Healing Interlocking Masonry Systems: Towards Sustainable and Intelligent Construction Materials. Sci J Biol & Life Sci. 4(3): 2026. SJBLS.MS.ID.000588. **DOI:** 10.33552/SJBLS.2026.04.000588

27. Zhang W, Mengna Jing, Rusheng Hao, Zhaoyao Wang, Yong Zhang, et al. (2025) Enhancing shear performance of masonry wallettes with high ductile fiber-reinforced concrete. Case Studies in Construction Materials 22: e04891.

28. Pulatsu B, Gonen S (2025) A probabilistic computational framework for predicting the diagonal tensile strength of unreinforced masonry walls. Structures 72: 108272.

29. Riaz M, Nisar Ali Khan, Muhammad Noman, Bruno Briseghella, Angelo Aloisio (2026) Seismic performance of soft-burnt brick masonry with fiber-reinforced mortars: Anisotropic strength and joint behavior. Journal of Building Engineering 123: 115853.

30. Abdoulaye K, Koteng DO, Gathimba N, Mutuku RN (2026) Investigation of interlock geometry sizes effect on the shear capacity of dry-joint interlocking core block masonry. Nigerian Journal of Technological Development 23(1): 100–112.

31. Cavuslu M, Ülger T (2026) Seismic vulnerability mitigation of historical masonry minarets using FRP clamp and dowel connectors: Experimental failure characterization and ambient vibration-calibrated numerical modelling. Engineering Structures 359: 122679.

32. Wang Y, Zhu C, Zhang R, Liu H, Liu C, et al. (2026) Recycled mixed aggregate concrete: quadruple interfacial structure system and its influence mechanisms on mechanical properties. Journal of Building Engineering 115611: 2026.

33. Özmen A, Sayın E (2026) Typical damage patterns in masonry structures after various major earthquakes. Firat University Journal of Experimental and Computational Engineering 5(1): 94–118.

34. Sun G, Wu B, Li H (2026) Damage evaluation of a multi-story brick masonry building with reinforced concrete framed ground floor under seismic loading: A case study. Case Studies in Construction Materials 24: e05888.

35. Latha L, Ray Chaudhuri S (2026) Augmenting seismic sustainability of unreinforced brick masonry walls through cost-efficient nominal RC band interventions. Soil Dynamics and Earthquake Engineering 204: 110190.

36. Paudel S, Adhikari R, Bhatt L, Karki B, Shrestha AR (2026) Post-earthquake seismic performance assessment of masonry buildings after the 2023 Jajarkot earthquake, Nepal. Bulletin of Earthquake Engineering 24: 4293-4316.

37. He J, Zhu J, Liu W, Li J, Zhou W, et al. (2026) Structure, properties and decay of ancient Chinese blue brick masonry in the Bell Tower of Xi'an. Construction and Building Materials 523: 146203.

38. Wen TH, Yuen TY, Zhou X (2026) Enhancing out-of-plane seismic resistance of masonry walls with fiber-reinforced overlays: tests, modeling, and fragility analysis. Structures 84: 111119.

39. Çelik A (2026) Seismic resilience of masonry buildings with a novel arch-type hollow brick (ArchBrick): Multi-scale numerical assessment from unit to building level. Engineering Structures 353: 122190.

40. Avcil F, Radu D, Işık E, Yuzbasi J, Büyüksaraç A, et al. (2026) Post-2023 Kahramanmaraş earthquake assessment of masonry mosques and minarets in Türkiye: field observations and numerical earthquake analysis. Sustainability 18(6): 2680.

41. Vecchio D, Ilyas B, Mendes N, Lourenço PB (2026) Experimental dynamic out-of-plane response of masonry buildings: mechanism activation, progression, and collapse. SSRN 365: 123198.

42. Unal ME, Wallace JW (2026) Nonlinear modeling of C-shaped reinforced concrete walls tested under wind and seismic loading protocols. Journal of Structural Engineering 152(4): 04026012.

43. Yucel G, Mısir IS, Kuran F, Cansu Beril Eser (2026) Experimental and numerical investigation of the out-of-plane behavior and strengthening of a historic stone masonry wall replica using embedded steel cords. Bulletin of Earthquake Engineering 24: 4259–4291.

44. Baniček M, Shaqfa M, Vaing S, Atalić J (2026) Tracking modal evolution through damage and retrofit scenarios in historic URM buildings: a numerical study of a representative downtown Zagreb typology. Journal of Earthquake Engineering pp. 1–27.

45. Sahal N, Kaloni S, Bhatra S (2026) Fundamental period prediction for irregular hillside RC buildings using numerical simulation and machine learning. Journal of Earthquake Engineering pp. 1–35.

46. Xin R, Dong Y, Qu Z (2026) Experimental investigation of seismic performance of brick veneer connected on RC frame by using shaking table test. Engineering Structures 352: 122128.

47. Tie S, Kang Q, Pan T, Wang X, Ye Y (2026) Seismic performance optimization and constrained stiffness analysis of infilled mortise tenon masonry RC frame structure. Journal of Earthquake Engineering 30(2): 545–575.

48. Burd HJ, Houlsby GT, Chow L, Augarde CE, Liu G (2026) Analysis of settlement damage to masonry structures. Numerical Methods in Geotechnical Engineering CRC Press pp. 203–208.

49. Calò S, Salem AS, Ghiassi B, Cascardi A (2026) Shear strengthening of masonry walls with inorganic-based composites: quantifying fiber exploitation through a numerical approach. Engineering Structures 354: 122390.

50. Xia Q, Zhang Y, Wang Y, Li Y, Xu L, et al. (2026) Shear strength evolution and cross-scale coupling in heritage masonry under soluble-salt attack. Construction and Building Materials 523: 146250.

51. Villar S, Camata G, Di Trapani F (2026) Influence of structural unit-interconnection degree on the seismic response of unreinforced masonry building aggregates. Engineering Structures 358: 122286.

52. Ogwumeh CM, Kuandyk L, Zhang D, Shon CS, et al. (2026) In-plane cyclic responses and seismic assessments of unreinforced masonry walls retrofitted with engineered cementitious composites. Engineering Structures 359: 122678.

53. Calderón S, Fredes J, Sandoval C (2025) Masonry panels with different bed-joint reinforcement ratios under diagonal compression: an experimental and numerical study. Construction and Building Materials 493: 143179.

54. Dong X, Guo X, Wang BAL, Luo R (2025) Suggestions for a collapse-resistant design for frame–masonry hybrid buildings based on the concept of balancing seismic shear forces. Buildings 15(8): 1357.

55. Giresini L, Pantò B, Casapulla C (2026) Interlocking formulation for the assessment of the out-of-plane dynamics of masonry walls interacting with sidewalls. Journal of Building Engineering pp. 115630.

56. Oktiovan YP, Lemos JV, Pulatsu B, Messali F, Rots JG, et al. (2026) Evaluating damping schemes for the discontinuum seismic analysis of masonry cross-vaults. Bulletin of Earthquake Engineering pp. 1–41.

57. Ghezelbash A, Rots JG, Messali F (2025) Review of the influence of the interaction between in-plane and out-of-plane behaviors on the seismic response of non-framed unreinforced masonry walls. Buildings 15(16): 2874.

58. Oz I, Raheem SEA, Turan C (2025) Mitigation measure using tuned mass dampers for torsional irregularity impact on seismic response of L-shaped RC structures with soil–structure interaction. Structures 79: 109449.

59. Keikha H (2026) Pathology of seismic deficiencies in non-structural walls and facades: lessons from as-built practice. Preprint pp. 1-22.

60. Chen K, Ma J, Bai H, Wang G, Liang J (2026) Deterioration analysis and strengthening schemes for plain brick masonry under service environment impact. Structures 87: 111687.

61. Khan Z, Ali M (2025) Innovative Building Insulation Solutions: Combating Global Warming with Advanced and Eco-Friendly Technologies. Construction Technologies and Architecture, 14th International Civil Engineering Conference, Trans Tech Publications Ltd, 2025 17: 81-90.

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62. Khan Z, Ali M (2025) Biomineralization and High Calcite Formation by Bacillus: Implications for Fiber Bio-Concrete Applications. Fusion Journal of Engineering and Sciences 34: 1-6.
63. Khan Z, Khan D (2024) Reviewing microbial calcite precipitation in fiber bioconcrete: advancing durability and sustainability in construction. Advances in Biotechnology & Microbiology 18: 3.
64. Khan Z, Khan D (2024) Enhancing Ancient Concrete Durability through Urease-Mediated Calcite Precipitation by Staphylococcus succinus: Implications for Sustainable Preservation in Archaeological Sites. Archives & Anthropology Open Access 5: 3.
65. Khan Z, Jamil M, Khan D (2026) Cyborg Concrete as an Engineered Convergence of Living Systems and Machine Intelligence. COJ Robotics & Artificial Intelligence 5: 2.

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