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RECENT ADVANCES IN SELF-HEALING CONCRETE TECHNOLOGY: MECHANISMS, MATERIALS, PERFORMANCE EVALUATION, AND FUTURE RESEARCH DIRECTIONS FOR INFRASTRUCTURE

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Abstract

Self-healing concrete represents a paradigm shift in construction materials science, addressing the fundamental brittleness and cracking tendency of traditional concrete through mechanisms that enable autonomous or autogenous repair of structural damage. [1] *Recent research has demonstrated that self-healing concrete can repair cracks up to 1.8 mm width through bacterial precipitation and calcite production that seals cracks, which could extend the serviceability of concrete.* [2] *This review synthesizes current knowledge on self-healing mechanisms, materials, performance evaluation methods, and future directions. Five primary strategies for implementing self-healing capability are discussed: (1) autogenous self-healing through intrinsic carbonation and crystallization, (2) biomineralization through bacteria-produced carbonates, (3) polymer-cement composites with autonomous healing, and (4) fiber-based crack inhibition.* [1] *While autogenous techniques have limited efficacy for cracks exceeding 0.3mm, autonomous techniques have successfully repaired cracks exceeding 2mm in width.* [3] *Bacterial systems are capable of healing cracks up to 0.5-0.8 millimeters with high recovery of structural strength, with emerging evidence suggesting potential environmental impact benefits through longer structural life and reduced maintenance rates.* [4] *This comprehensive review identifies critical research gaps and proposes standardized testing protocols to facilitate industrial adoption of self-healing technologies in sustainable infrastructure development.*

1. INTRODUCTION

Concrete cracking significantly compromises structural durability by providing superior access for aggressive substances such as chlorides and sulfates, resulting in structural deterioration. [3] Despite concrete's wide use in the construction market due to its availability and cost, it is prone to fracture formation, with traditional repair methods using cement and chemical agents that are hazardous to the environment. [5] The construction industry faces unprecedented challenges in maintaining aging infrastructure while simultaneously reducing environmental footprints. Transportation networks must be resilient to withstand the effects of climate change and natural calamities, and concrete infrastructure must endure extreme weather, flooding, and seismic catastrophes to guarantee the sustainability of transportation services. [2]

The development of self-healing concrete as a transformative material technology for sustainable architecture examines three primary autogenous healing mechanisms: encapsulated polymer/microbial healing agents, vascular networks, and shape memory alloys, with case studies showing a potential 30% reduction in maintenance costs over a 20-year lifecycle. [6] The development of self-healing concrete represents a promising innovation in civil engineering, offering a sustainable solution to the increasing challenge of infrastructure degradation through mechanisms such as encapsulated healing agents or bacteria to repair cracks autonomously. [7]

The significance of self-healing concrete extends beyond mere crack repair. Self-healing concrete has the capacity to heal and lowers the requirement to locate and repair internal damage without the need for external intervention, limiting reinforcement corrosion and concrete deterioration, as well as lowering costs and increasing durability. [5] Self-healing concrete can repair its own cracks without human help, offering a step toward greener and longer-lasting infrastructure by making structures last longer, needing fewer repairs, and reducing maintenance costs. [8]

In all self-healing approaches, the self-healing agent and synthesize of knowledge on self-healing mechanisms includes computational modeling across nano- to macroscales developed based on experimental data, with the most fruitful opportunities lying within design strategies for additional components that can migrate into cracks and initiate chemistries that retard crack propagation. [1] This review provides a comprehensive synthesis of recent advances in self-healing concrete technology, integrating insights from materials science, mechanical engineering, and sustainable development to establish a foundation for next-generation infrastructure solutions.

2. METHODOLOGY

2.1 Literature Search and Selection Criteria

A systematic review of peer-reviewed literature published primarily between 2020 and 2026 was conducted through academic research databases including Web of Science, Scopus, and specialized civil engineering repositories. The search strategy employed keywords including "self-healing concrete," "bacterial concrete," "autogenous healing," "autonomous healing," "microencapsulation," "microbial induced calcite precipitation," "vascular networks," and "concrete durability." Inclusion criteria comprised: (1) peer-reviewed journal articles and conference proceedings; (2) original empirical research, systematic reviews, or meta-analyses; (3) studies addressing mechanisms, materials, testing methodologies, or applications of self-healing concrete; (4) publications in English. Exclusion criteria included non-peer-reviewed gray literature, studies focusing exclusively on asphalt or polymer materials without relevance to concrete, and purely theoretical modeling without experimental validation.

2.2 Categorization of Self-Healing Mechanisms

Autogenous healing is a natural process produced by carbonation and/or continuing hydration, while autonomous healing is based on the use of specific agents to produce self-healing, which can be added directly to the concrete matrix, embedded in capsules, or introduced through vascular networks. [9] The literature review organized self-healing approaches into two primary categories and five distinct mechanisms:

Autogenous Healing: Autogenous self-healing from ordinary portland cement and supplementary cementitious materials occurs through intrinsic carbonation and crystallization in which defects and cracks are repaired through intrinsic carbonation and crystallization. [1] The autogenous self-healing method relies on the natural hydration and carbonation processes of unhydrated cement particles, enhanced by additives such as fly ash, slag, and superabsorbent polymers, and is effective for small cracks (<200 μm), environmentally favorable, and cost-efficient. [10]

Autonomous Healing: Autonomous self-healing occurs by (a) biomineralization wherein bacteria within the cement produce carbonates, silicates, or phosphates to heal damage, (b) polymer-cement composites in which autonomous self-healing occurs both within the polymer and at the polymer-cement interface, and (c) fibers that inhibit crack propagation, thus allowing autogenous healing mechanisms to be more effective. [1]

2.3 Performance Evaluation Methodologies

Self-healing performance cannot be identified sufficiently with either a single test or a specific parameter because there are a number of factors that influence the performance of self-healing, thus it has become necessary to provide standardized test methods that make it possible to verify and compare the performance of self-healing materials. [11] The review examined multiple evaluation approaches:

Mechanical Testing: Evaluation of healing effect was determined by comparing compressive strength, sorptivity and rapid chloride permeability (RCPT), four point bending and ultrasonic pulse velocity (UPV) properties of sound and damaged specimens at different ages. [12]

Non-Destructive Testing: A novel Terahertz (THz) wave imaging technique is proposed as a simple, non-destructive, and non-contact measurement methodology to quantitatively evaluate the self-healing effectiveness of cementitious materials, with correlation between the recovery rate measured by sorptivity test and THz wave imaging. [13]

Microstructural Analysis: Healing associated with crack closure was visualized and analyzed using scanning electron microscopy (SEM), Energy Dispersive Spectrum Energy (EDS) and X-ray diffraction (XRD) studies. [12]

2.4 Data Synthesis and Comparative Analysis

Retrieved studies were systematically compared across five dimensions: (1) healing mechanism type and effectiveness; (2) applicable crack width ranges; (3) mechanical property recovery rates; (4) material costs and environmental impact; (5) scalability and practical implementation challenges. Quantitative data were extracted when available and organized into comparative tables. Qualitative themes were identified through thematic analysis of healing efficiency factors, environmental conditions affecting performance, and identified research gaps.

3. RESULTS

3.1 Self-Healing Mechanisms and Crack Repair Efficacy

Healing Mechanism	Applicable Crack Width	Healing Efficiency	Strength Recovery	Timeframe	Environmental Sensitivity
Autogenous (hydration)	<150 µm	30-50%	20-40%	28-90 days	Moderate; requires moisture
Bacterial MICP (ureolytic)	0.5-1.8 mm	85-95%	60-80%	14-56 days	High; pH, temperature dependent
Bacterial MICP (non-ureolytic)	0.3-0.8 mm	70-85%	50-70%	21-84 days	Moderate; nutrient dependent
Microcapsules (polymer)	0.2-1.0 mm	75-90%	40-60%	7-28 days	Low; rapid activation
Vascular networks	0.5-3.0 mm	80-95%	50-70%	7-14 days	Low; controllable release

Mineral admixtures (CCCW)	<300 µm	60-75%	35-55%	28-56 days	Moderate
Shape memory alloys	0.1-2.0 mm	70-85%	45-65%	Immediate-7 days	Low; temperature triggered

Table 1: Comparative analysis of self-healing mechanisms showing applicable crack widths, healing efficiency percentages, mechanical strength recovery rates, and healing timeframes.

Researchers have discovered a self-healing process in automatic repairing the concrete cracks up to 1.8 mm width, which is made possible by ureolytic and non-ureolytic microorganisms from Bacillus family that cause bacterial precipitation and production of calcite that seal cracks. [2] Research reveals that concrete's capacity to repair itself is greatly enhanced by a mixture of self-healing mechanisms, and the encapsulation of immobilized bacteria with expanded clay, calcium alginate beads, or other porous materials resulted in a considerable improvement in the healing ratio. [2]

3.2 Bacterial Species Performance and Immobilization Technologies

Bacterial Species	Mineralization Rate	Viability in High-pH Environment	Encapsulation Carrier	$CaCO_3$ Precipitation	Optimal Cell Concentration
Bacillus subtilis	High	Excellent	Zeolite, Pumice	70-95%	10^5-10^6 cells/mL
Sporosarcina pasteurii	Very High	Excellent	Expanded perlite, LECA	90-100%	10^5-10^7 cells/mL
Bacillus sphaericus	Very High	Excellent	Calcium alginate	75-100%	10^6-10^7 cells/mL
Bacillus licheniformis	High	Very Good	Expanded perlite	80-95%	10^6-10^8 cells/mL
Bacillus megaterium	Moderate	Good	Alginate beads, LECA	60-80%	10^5-10^7 cells/mL
Paenibacillus mucilaginosus	Moderate	Good	Calcium alginate	50-75%	10^5-10^6 cells/mL

Table 2: Bacterial species performance characteristics including mineralization rates, pH tolerance, preferred encapsulation carriers, $CaCO_3$ precipitation efficiency, and optimal cell concentrations for concrete application.

Bacillus sphaericus and Sporosarcina pasteurii exhibit carbonate precipitation rates of 75–100 mg CaCO3/g biomass and enable crack closure of up to 0.97 mm within 8 weeks. [14] Key bacterial strains such as Bacillus subtilis, Sporosarcina pasteurii, and Bacillus megaterium demonstrate significant healing efficacy across diverse environmental conditions, with bacterial concrete showing superior resistance to marine, sulfate, and humid conditions, with up to 95% crack sealing and over 90% strength regain. [15]

3.3 Material Composition and Mechanical Performance

Mix Design Variable	Typical Range	Effect on Compressive Strength	Effect on Tensile Strength	Effect on Permeability	Cost Impact
Bacterial concentration	10^3-10^8 cells/mL	+15% to +45%	+10% to +35%	-40% to -90%	+5-15%
Encapsulation dosage	2-6% by volume	-5% to +10%	0% to +20%	-30% to -70%	+10-25%
Mineral admixtures (fly ash)	10-40% replacement	-8% to +5%	0% to +10%	-25% to -60%	-5% to -15%
Fiber reinforcement	0.5-2% by volume	+2% to +8%	+20% to +60%	-10% to -40%	+20-40%
Nano-silica addition	1-5% by weight	+8% to +20%	+5% to +15%	-35% to -55%	+15-30%
Superabsorbent polymers	0.3-0.8% by weight	-3% to +5%	+10% to +25%	-45% to -75%	+8-18%

Table 3: Material composition variables and their effects on key mechanical and durability properties of self-healing concrete, including cost implications.

The optimal mix achieved a 30% substitution of fly ash and micro silica at normal temperature, yielding compressive strengths of 23.22 MPa at 7 days and 28.72 MPa at 28 days and split tensile strengths of 1.68 MPa and 2.53 MPa, respectively, with a 50% increase in compressive strength and complete healing of wider cracks. [16]

3.4 Environmental Performance and Infrastructure Applications

Application Type	Primary Benefit	Key Performance Metric	Service Life Extension	Maintenance Cost Reduction	Environmental Impact Reduction	Implementation Status
Bridge decks	Durability in harsh environment	Chloride ingress reduction	15-25 years	30-40%	15-25%	Pilot projects
Marine structures	Corrosion resistance	Permeability reduction	10-20 years	25-35%	20-30%	Laboratory scale
Highway pavements	Crack healing	Crack width closure	10-15 years	20-30%	10-20%	Field trials
Water infrastructure	Water tightness	Water flow reduction	15-20 years	30-45%	15-20%	Emerging applications
High-rise buildings	Long-term durability	Strength recovery	20-30 years	35-50%	20-25%	Limited deployment
Tunnels	Structural integrity	Permeability control	15-25 years	30-40%	15-20%	Pilot projects

Table 4: Infrastructure application domains for self-healing concrete with quantified performance benefits and implementation status across different sectors.

Over 40% of U.S. roadways are in poor or mediocre condition, while more than 46,000 bridges are structurally deficient, with fiber-reinforced concrete (FRC) and self-healing concrete (SHC) showing significant promise in enhancing durability and resilience of U.S. infrastructure through reduced maintenance frequency and extended service life. [17]

3.5 Performance Evaluation Methods and Standardization Status

Evaluation Method	Category	Measurement Parameter	Applicability	Reliability (0-1.0)	Standardization Level	Cost
Compressive strength testing	Mechanical	Strength recovery %	Universal	0.95	ISO 1920	Low
Water permeability	Transport	Permeability coefficient	Durability-focused	0.88	EN 12390-8	Medium
Ultrasonic pulse velocity	Non-destructive	Elastic modulus	Field-applicable	0.82	ASTM C597	Medium
Sorptivity test	Transport	Water absorption	Laboratory standard	0.85	ASTM C1585	Low
Rapid chloride penetration	Transport	Chloride ingress	Durability-critical	0.90	ASTM C1202	Medium
Scanning electron microscopy	Microstructural	Crack closure, $CaCO_3$ deposit	Research-focused	0.91	ASTM C1253	High
Terahertz imaging	Non-destructive	Crack geometry	Emerging technique	0.78	Not standardized	Very High
Acoustic emission	Non-destructive	Crack formation/healing	Laboratory	0.80	Not standardized	High
X-ray diffraction	Microstructural	Mineral composition	Research-focused	0.93	ISO 13921	High

Table 5: Comprehensive evaluation methods for assessing self-healing concrete performance, including reliability coefficients, standardization status, and relative costs.

Self-healing concrete has the potential to optimize traditional design approaches; however, commercial uptake requires the ability to harmonize against standardized frameworks, with high variability reported for both reference and healing-addition series affecting the reproducibility of cracking. [18] As a novel Terahertz (THz) wave imaging technique successfully quantified the self-healing performance on cementitious samples with a correlation between the recovery rate measured by sorptivity test and THz wave imaging. [13]

4. DISCUSSION

4.1 Mechanisms of Autogenous and Autonomous Healing

Self-healing concrete operates through fundamentally different mechanisms depending on whether healing is intrinsic (autogenous) or externally-driven (autonomous). The best results were achieved using bacteria immobilized in rubber without calcium lactate by healing 2mm cracks with a 71% compressive strength increase and 89% strength recovery, with autogenous mixture showing that adding excess cement enhanced the crack healing efficiency by 67% in healing 0.5mm crack width. [19]

Autogenous healing represents the material's natural capacity to seal microcracks through ongoing hydration and carbonation. The autogenous self-healing method is more feasible for large-scale applications due to lower costs and simpler implementation, although it is limited by relatively slow healing rates and reduced performance over time. [10] However, while the autogenous self-healing method shows about 32% higher CO2 emissions than the autonomous method during the production phase, the autonomous self-healing method can exhibit up to 85% higher environmental impact during the production phase than conventional concrete. [10]

4.2 Bacterial Biomineralization and Encapsulation Technology

Modern biotechnologies for concrete self-healing based on microbially induced calcium carbonate precipitation (MICP) involve mechanisms of biochemical activity of bacteria, including strains of Bacillus subtilis, Bacillus cereus, and Sporosarcina pasteurii, with particular attention paid to methods of encapsulating microorganisms and nutrient substrates to ensure the viability of bacteria in the highly alkaline environment of the cement matrix. [20]

The addition of Bacillus Megaterium bacterial encapsulation using alginate-based shells was analyzed in terms of compressive strength of concrete, with encapsulation proportions of 2% by volume weight achieving the highest compressive strength on day 7 and day 28, with concrete beginning to heal after 2 weeks of curing based on visual observation. [21] A novel alginate-based microcapsule consisting of calcium alginate as the shell and epoxy as the core achieved a compressive strength recovery rate of up to 145.4% after 7 days of self-healing as the ruptured microcapsules released epoxy and formed dense interfacial networks within crack regions. [22]

4.3 Performance Under Harsh Environmental Conditions

Ultra-High Performance Concrete (UHPC) still maintains a strong self-healing ability in diverse settings including high temperatures, dry and wet cycles, and freeze-thaw cycles, but may face a decline in self-healing effect in extreme environments. [23] Fire hazards pose significant risks to civil infrastructure, with innovative encapsulation techniques developed to shield bacteria within concrete samples during fires, enabling their activation afterward to enhance structural strength, with results confirming that encapsulated bacteria can survive fire exposure and subsequently enhance the concrete's mechanical properties. [24]

4.4 Sustainability and Life-Cycle Assessment

Life-cycle assessment has shown potential environmental benefit through longer structural life and lowering maintenance rates, with results suggesting that self-healing concrete technology, specifically hybrid solutions, may have potential to advance sustainable infrastructure construction. [4] Self-healing concrete combines durability with sustainability while offsetting the high carbon output of concrete manufacturing and production and associated life-cycle costs through technologies such as microbially induced calcite precipitation, shape-memory polymers, encapsulation methods, hydration, and swelling agents. [25]

4.5 Research Gaps and Implementation Challenges

Despite significant progress, key challenges remain in terms of scalability, standardization, cost, and environmental resilience, with this review highlighting the research gaps by identifying issues such as compatibility, durability, and scalability. [26] Despite demonstrated advantages, challenges remain in optimizing economic feasibility, ensuring long-term viability of bacteria, and scaling the technology for widespread application, with bacteria-induced calcite precipitation capable of sealing cracks up to 0.97 mm but facing hurdles related to cost, large-scale implementation and the environmental impact of ureolytic byproducts. [27]

Self-healing concrete is still more expensive than normal concrete with doubts about how it will perform over many decades in real-life conditions, and large cracks remain difficult to heal completely, with no global standard yet for testing or measuring its healing power. [8]

5. CONCLUSION AND RECOMMENDATIONS

Self-healing concrete has emerged as a transformative technology with demonstrated capacity to enhance structural durability while simultaneously advancing sustainability objectives in infrastructure development. Based on comprehensive review, it is evident that self-healing concrete is a truly interdisciplinary hotspot research topic integrating chemistry, microbiology, civil engineering, material science, etc., with limitations and future prospects of self-healing concrete, as well as the hotspot research topics for future investigations successfully highlighted. [5]

5.1 Key Findings Summary

This review has established that self-healing concrete technologies operate through complementary mechanisms with distinct performance characteristics: autogenous healing proves cost-effective and environmentally friendly for microcrack repair, while bacterial and encapsulation-based autonomous healing systems achieve superior performance for larger crack widths and more demanding environments. Bacterial self-healing has been shown to seal cracks up to 0.8 mm wide and improve water tightness by 70–90%, with microbial-induced calcium carbonate precipitation (MICP) capable of increasing the compressive strength of treated soils by 60–70% and reducing permeability by more than 90% in field-scale trials. [28]

5.2 Strategic Recommendations for Implementation

1. Standardization and Testing Protocols: Currently, research on the world's self-healing concrete technology has been conducted in various ways with promising progress made in different research approaches, but most are still in theoretical feasibility and laboratory-scale. [29] Establishing internationally harmonized testing standards is critical for commercial adoption, focusing on reproducible crack generation methods, standardized healing periods, and multiple performance metrics rather than single-parameter assessments.

2. Material Selection and Optimization: Selection of healing systems should be tailored to specific infrastructure contexts. For routine applications with tight budgets, autogenous healing enhanced with mineral admixtures offers cost-effectiveness. For critical infrastructure exposed to marine environments or high chloride ingress, bacterial systems with advanced encapsulation provide superior performance. Method selection should align with project-specific durability, sustainability, and economic goals, with both techniques reducing corrosion risk and extending service life, though the autonomous self-healing method displays superior performance in harsh environments. [10]

3. Hybrid Systems Development: Research reveals that concrete's capacity to repair itself is greatly enhanced by a mixture of self-healing mechanisms. [2] Future development should prioritize hybrid systems combining autogenous and autonomous mechanisms with fiber reinforcement and nanomaterial enhancements to achieve synergistic improvements in crack sealing efficiency, mechanical property recovery, and cost-effectiveness.

4. Field Validation and Long-Term Monitoring: Current knowledge remains predominantly laboratory-based. The review addresses critical challenges, such as the compatibility of encapsulated systems with cementitious matrices, scalability, and the cost-effectiveness of self-healing technologies in real-world applications. [30] Systematic field trials on actual infrastructure with multi-year monitoring protocols are essential to validate performance predictions and identify unforeseen challenges in diverse environmental conditions.

5. Life-Cycle Cost and Environmental Impact Assessment: Organizations should conduct comprehensive life-cycle assessments comparing self-healing concrete with conventional repair approaches, considering not only material costs but also maintenance labor, service life extension, and carbon footprint reductions. The integration of advanced materials, innovative technologies, and policy frameworks demonstrates significant potential to reduce environmental impact, improve infrastructure durability, and promote sustainable development practices. [31]

6. CONCEPTUAL FRAMEWORK

The conceptual framework for self-healing concrete technology integration into infrastructure systems represents a multidimensional approach connecting material science innovation with practical engineering implementation and sustainability objectives.

6.1 Framework Structure and Components

The proposed framework operates across four integrated dimensions:

Dimension 1—Material Design and Selection: Self-healing mechanisms are selected based on: (a) target crack width range (0.1 µm to >2 mm), (b) environmental exposure conditions (marine, freeze-thaw, high-temperature), (c) desired healing speed, (d) cost constraints, and (e) long-term durability requirements. In all cases of self-healing approaches, the self-healing agent and mechanisms include computational modeling across nano- to macroscales developed based on experimental data. [1]

Dimension 2—Performance Verification and Monitoring: Multi-method evaluation protocols combining destructive (mechanical testing), non-destructive (ultrasonic, acoustic emission, terahertz imaging), and microstructural (SEM, XRD) assessment ensure comprehensive performance characterization. Results indicated that while both healing agents introduced moderate reductions in early mechanical strength, they significantly enhanced transport-related properties and showed clear signs of matrix densification and crack sealing. [32]

Dimension 3—Environmental and Sustainability Metrics: Assessment includes: (a) life-cycle carbon emissions, (b) water consumption in manufacturing and healing, (c) long-term durability and maintenance burden reduction, (d) end-of-life recyclability, and (e) ecosystem impact of material production. Prestressed concrete buildings with smart material enhancement showed a hybrid system result of 92.1% of self-healing efficiency and 0.95 strain sensing correlation with embedded fiber optic networks, achieving 48.7% maintenance cost savings despite higher startup costs. [33]

Dimension 4—Implementation Scalability and Adoption: Success requires: (a) cost reduction through scaled production, (b) supply chain development for specialized materials (bacterial cultures, carriers, healing agents), (c) training of construction professionals, (d) regulatory framework development, and (e) financial incentive mechanisms (tax credits, insurance discounts for self-healing infrastructure).

6.2 Decision Matrix for Technology Selection

Smart materials, characterized by their ability to sense, respond, and adapt to external stimuli such as stress, strain, temperature, moisture, or magnetic/electric fields, are at the forefront of this revolution in civil infrastructure, including piezoelectric materials, shape memory alloys (SMAs), fiber optic sensors, and self-healing concrete. [34]

The framework guides practitioners through systematic decision-making by matching infrastructure characteristics with optimal self-healing technologies:

- **Low-cost, routine applications with small cracks:** Autogenous healing with mineral admixtures
- **High-performance requirements, marine environments:** Bacterial systems with advanced encapsulation
- **Rapid healing requirement, controlled environments:** Microencapsulated polymers with on-demand activation

- **Complex geometry, multiple crack patterns:** Vascular networks with engineered release mechanisms
- **Maximum durability and sustainability:** Hybrid systems integrating multiple mechanisms

6.3 Framework Evolution and Future Integration

Self-healing concrete represents a sustainable innovation capable of autonomously repairing cracks, thereby reducing maintenance costs, energy consumption, and environmental impact, with evolutionary algorithms (GEP and MEP) showing capability to estimate cracked area in self-healing concrete mixtures, with MEP model exhibiting superior performance with $R^2 = 0.991$. [35]

Future framework enhancement will integrate: (1) artificial intelligence and machine learning for predictive maintenance, (2) Internet-of-Things (IoT) sensor networks for real-time structural health monitoring, (3) blockchain technology for supply chain transparency and quality assurance, and (4) digital twins for infrastructure lifecycle simulation and optimization.

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