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# Carbon-Negative and Self-Healing Construction Materials: Advancing Bio-Concrete, Geopolymer Technology, and Circular Economy Models in Sustainable Civil Engineering

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## Abstract

The construction industry accounts for approximately 37% of global greenhouse gas emissions, with ordinary Portland cement production contributing 8-10% of annual CO2 emissions. This review examines the transformative potential of carbon-negative and self-healing construction materials as pathways toward sustainable infrastructure development. The objective is to synthesize current knowledge on bio-concrete incorporating microbial-induced calcite precipitation, geopolymer binders utilizing industrial by-products, and circular economy frameworks that enable material circularity. Key technologies assessed include bacteria-based self-healing systems capable of sealing cracks up to 0.97 mm and achieving compressive strength gains of 32%, alongside geopolymer formulations that reduce carbon footprint by 60-80% compared to conventional concrete. Carbon sequestration mechanisms through mineral carbonation and biochar incorporation are evaluated for their negative emission potential. Circular economy integration is examined through life-cycle assessment methodologies that demonstrate embodied carbon reductions of 14-72% through material substitution and reuse strategies. Major infrastructure application areas include structural concrete elements, transportation infrastructure, and modular building systems. The review concludes that while technical feasibility is established, scalability requires standardization, long-term durability validation, and policy frameworks that internalize environmental costs.

**Keywords:** Bio-concrete, geopolymer binders, microbial self-healing, carbon-negative materials, circular economy, life-cycle assessment

## 1. Introduction

The global construction sector faces an unprecedented challenge in reconciling infrastructure development with climate change mitigation. Cement production alone generates approximately 2.8 billion tonnes of CO2 annually, representing 8-10% of global anthropogenic emissions [1]. When combined with steel reinforcement and other energy-intensive materials, the built environment emerges as the single largest contributor to greenhouse gas emissions, necessitating fundamental innovation in construction materials [2].

Conventional approaches to reducing construction emissions have focused on incremental efficiency improvements and partial clinker substitution. However, these strategies are insufficient to achieve the deep decarbonization required by international climate targets. The Intergovernmental Panel on Climate Change scenarios consistent with 1.5°C pathways require negative emission technologies and systemic material efficiency improvements across all sectors [3]. This imperative has catalyzed research into materials that not only reduce emissions but actively sequester carbon while offering enhanced durability and functionality.

This review addresses three interconnected technological frontiers: bio-concrete with autonomous self-healing capabilities, geopolymer binders derived from industrial by-products, and circular economy models that enable continuous material utilization. The objective is to provide a comprehensive assessment of these technologies' current status, performance characteristics, and implementation pathways within civil engineering practice. The scope encompasses material science foundations, engineering performance, life-cycle environmental assessment, and economic feasibility, with emphasis on applications in structural infrastructure.

## 2. Theoretical and Technological Foundations

### 2.1. Carbon Sequestration Mechanisms in Construction Materials

Carbon-negative construction materials operate through two principal mechanisms: avoidance of process emissions inherent to conventional cement production, and active CO2 sequestration during material service life. Mineral carbonation represents the most direct sequestration pathway, wherein calcium- and magnesium-bearing materials react with CO2 to form thermodynamically stable carbonates [4]. This process occurs naturally in cementitious materials over extended periods but can be accelerated through controlled curing environments and material formulation.

Biochar incorporation has emerged as a complementary carbon sequestration strategy. Produced through pyrolysis of biomass under oxygen-limited conditions, biochar stabilizes carbon that would otherwise decompose and release CO2. When incorporated into cementitious composites at optimal dosages of 1-2% by mass, biochar enhances mechanical performance through pore refinement and internal curing while sequestering approximately 2.5-3.0 tonnes CO2-equivalent per tonne of biochar [5]. Beyond 5-6% replacement levels, however, mechanical properties typically decline, establishing dosage thresholds for practical application [5].

### 2.2. Microbial Self-Healing Mechanisms in Bio-Concrete

Microbial-induced calcite precipitation (MICP) constitutes the fundamental mechanism underlying bio-concrete self-healing. Specific bacterial strains, primarily from genera *Bacillus*, *Sporosarcina*, and *Pseudomonas*, metabolize calcium-containing nutrients to precipitate calcium carbonate crystals that fill cracks and restore material integrity [6,7]. The biochemical pathway involves urea hydrolysis by urease enzymes, generating carbonate ions that combine with calcium ions to form calcite in the presence of bacterial cell walls that serve as nucleation sites [8].

Critical to this mechanism is bacterial survival within the alkaline concrete environment (pH 12-13). Spore-forming bacteria can remain dormant for decades, activating only when cracks expose them to moisture and atmospheric carbon dioxide [7]. Environmental parameters including pH, temperature, oxygen availability, and moisture content critically affect repair efficacy, with optimal performance typically observed under aerobic conditions with relative humidity exceeding 60% [6].

### 2.3. Geopolymer Chemistry and Alkali-Activated Systems

Geopolymers are inorganic polymers formed through alkaline activation of aluminosilicate precursors, producing three-dimensional amorphous networks with cementitious properties [9]. Unlike Portland cement hydration which relies on calcium silicate hydrate formation, geopolymerization involves dissolution of silicon and aluminum from source materials followed by polycondensation into aluminosilicate gels [10].

Common precursors include fly ash, ground granulated blast-furnace slag (GGBFS), metakaolin, and natural pozzolans. Alkaline activators typically comprise sodium hydroxide, sodium silicate, or combinations thereof, with molarity and silicate modulus significantly influencing reaction kinetics and final properties [11]. One-part geopolymer formulations using solid alkaline activators have recently gained attention for their improved handling characteristics suitable for construction site application [12].

The environmental advantage of geopolymers derives from utilizing industrial by-products and eliminating calcination emissions. While alkaline activators carry embodied carbon, comprehensive life-cycle assessments demonstrate 60-80% greenhouse gas reductions compared to ordinary Portland cement [13].

## 3. Carbon-Negative and Self-Healing Material Systems

### 3.1. Bio-Concrete Technologies

Contemporary bio-concrete systems employ bacterial cultures at concentrations of $10^4$-$10^7$ colony-forming units per milliliter of concrete mix. At optimal dosages, bacterial inclusion increases compressive strength by up to 32%, with flexural and tensile strength improvements of 14-29% attributed to pore refinement and enhanced interfacial transition zones [14]. Crack healing capabilities extend to widths of 0.97 mm, with complete sealing achieved within 28 days under favorable moisture conditions [14].

Encapsulation techniques are essential for maintaining bacterial viability during concrete mixing and curing. Approaches include immobilization in porous expanded clay, hydrogel encapsulation, and microcapsule incorporation that releases bacteria upon crack-induced rupture [7]. Advanced encapsulation reduces permeability by up to 50% and decreases chloride ion ingress by 45-55%, significantly enhancing durability in marine and de-icing salt environments [14].

Fungal applications represent an emerging frontier, with certain species offering advantages in extreme pH tolerance and filamentous growth that bridges cracks more effectively than bacterial calcite [6]. However, fungal systems remain at lower technology readiness levels than bacterial approaches.

### 3.2. Geopolymer and Alternative Binder Systems

Geopolymer concrete formulated with fly ash and GGBFS achieves compressive strengths of 20-60 MPa depending on activator concentration and curing regime [11]. Setting times range from 30 minutes to several hours, controllable through activator composition and calcium content. Standard consistency requirements for geopolymer mixes are 39-55%, higher than conventional concrete, indicating greater alkaline solution demand for workability [11].

One-part geopolymer binders utilizing solid calcium hydroxide or calcium oxide combined with sodium or potassium silicate powders offer practical advantages for field application [12]. These formulations produce heterogeneous microstructures with coexisting geopolymer gel and hydrated aluminosilicate phases, achieving mechanical properties suitable for structural applications [12,15].

Limestone calcined clay cement (LC3) represents a hybrid approach, replacing up to 50% of Portland cement with calcined clay and limestone. This formulation reduces emissions by approximately 40% while maintaining performance comparable to conventional cement [11].

### 3.3. Industrial Waste Utilization and Mineral Carbonation

The cement and concrete industry's scale enables significant waste valorization through material substitution. Fly ash, GGBFS, silica fume, and recycled concrete fines serve as both precursor materials for geopolymerization and supplementary cementitious materials in blended cements [16]. Steel slag carbonation offers dual benefits: CO2 sequestration and production of carbonated aggregates with improved mechanical properties [4].

Table 1 presents a comparative analysis of carbon-negative and self-healing construction materials, summarizing their performance characteristics and application domains.

**Table 1:** Comparative Performance of Carbon-Negative and Self-Healing Construction Materials

| Material Type | Carbon Reduction Potential | Compressive Strength Range (MPa) | Durability Characteristics | Self-Healing Capability | Infrastructure Application Area |
|---|---|---|---|---|---|
| Bio-concrete (bacterial MICP) | 10-30% (embodied) + service life extension | 30-50 | Reduced permeability (50%), enhanced freeze-thaw resistance | Crack sealing up to 0.97 mm | Bridge decks, water retaining structures, foundations |
| Geopolymer concrete (fly ash/GGBFS) | 60-80% vs. OPC | 25-60 | Superior acid resistance, low chloride permeability | Limited intrinsic | Precast elements, pavements, industrial flooring |
| Alkali-activated slag cement | 70-85% vs. OPC | 40-80 | High sulfate resistance, rapid strength gain | Minimal | Marine structures, sewer pipes, mine backfill |
| Recycled aggregate concrete with carbonation | 15-30% + CO2 sequestration | 25-45 | Variable, improved by carbonation treatment | None | Non-structural concrete, road base, backfill |
| Biochar-enhanced cement composites | Carbon-negative (net sequestration) | 20-50 | Improved internal curing, reduced shrinkage | None (unless combined with bacteria) | Low-carbon building products, insulation, lightweight fill |

## 4. Circular Economy and Life-Cycle Integration

### 4.1. Embodied Carbon Assessment Methodologies

Life-cycle assessment (LCA) provides the analytical framework for quantifying environmental performance of construction materials. System boundary definition critically influences results, with cradle-to-gate assessments capturing material production while cradle-to-grave analyses incorporate use phase and end-of-life [17]. For carbon-negative materials, biogenic carbon accounting and temporary storage characterization require specialized methodologies to avoid double-counting and accurately represent climate benefits [18].

Comparative LCA studies demonstrate that replacing steel reinforcement with recycled bio-based fibers yields global warming potential reductions of 14% at 30% replacement rates [19]. Bamboo and hemp fibers processed from waste streams achieve 312-324 kg CO2-equivalent per reinforced concrete beam compared to 362 kg for conventional steel reinforcement [19]. These benefits extend across multiple impact categories, though mechanical performance equivalence must be verified for structural applications.

### 4.2. Material Circularity Models in Construction

Circular economy principles applied to construction materials emphasize prolonged service life, design for disassembly, and high-value recycling at end-of-life. Material circularity indicators quantify the proportion of recycled content and recyclability, with closed-loop systems achieving maximum resource efficiency [20].

Industrial symbiosis represents a mature circular strategy wherein waste from one industry becomes feedstock for another. Geopolymer concrete exemplifies this approach, utilizing power generation fly ash and iron production slag as primary binders [21]. Regional material flows and supply chain coordination determine feasibility, with transportation distances significantly affecting net environmental benefits.

Carbon mineralization integrates circularity with carbon management by converting CO2 into stable carbonates that can serve as construction materials or aggregates. This approach effectively transforms point-source CO2 emissions into valuable products while permanently sequestering carbon [4].

**Table 2:** Circular Economy Integration in Sustainable Construction Materials

| Circular Strategy | Material Inputs | Environmental Benefit | Economic Feasibility | Implementation Challenges | Policy and Regulatory Considerations |
|---|---|---|---|---|---|
| Recycling | Construction and demolition waste, concrete rubble | 15-40% embodied carbon reduction, landfill diversion | Moderate; depends on transportation and processing costs | Contamination, quality variability, market acceptance | Quality standards for recycled aggregates, green procurement preferences |
| Industrial symbiosis | Fly ash, GGBFS, silica fume, bauxite residue | 60-80% emission reduction, waste valorization | High where by-products are locally available | Supply chain coordination, material variability, transportation distances | Waste classification, end-of-waste criteria, by-product status |
| Carbon mineralization | Steel slag, cement kiln dust, recycled concrete fines | Permanent CO2 sequestration (50-300 kg CO2/tonne), material improvement | Emerging; carbon pricing improves viability | Reaction kinetics, scale-up, product market development | Carbon accounting methodologies, emissions trading inclusion |
| Waste valorization | Agricultural residues, biochar, industrial sludges | Carbon-negative potential, waste diversion | Variable; high-value applications improve economics | Material heterogeneity, processing requirements, long-term performance | Waste-to-product regulations, bio-based material standards |
| Design for deconstruction | Modular components, reversible connections, standardized elements | Extended service life, material reuse (50-70% emission reduction) | Life-cycle cost positive where deconstruction is planned | Industry practice inertia, design complexity, first costs | Building codes, deconstruction permits, material passports |

### 4.3. Infrastructure Scalability and Performance Validation

Scaling novel construction materials from laboratory to infrastructure scale requires systematic performance validation under realistic service conditions. Demonstration projects in Brussels and Barcelona are constructing full-scale buildings using circular economy principles, incorporating construction and demolition waste and designing for modular disassembly [22]. These initiatives aim to demonstrate greenhouse gas reduction potential of 137 million tonnes CO2 annually if scaled across Europe [22].

Performance monitoring over extended periods remains essential for establishing design parameters and durability certifications. Self-healing concrete validation requires crack monitoring under service loads, while geopolymer performance in diverse climatic conditions necessitates exposure site testing [23].

## 5. Engineering Performance, Economic Feasibility, and Policy Implications

### 5.1. Structural Reliability Considerations

Structural design codes traditionally prescribe material properties based on extensive empirical databases for conventional concrete. Novel materials require equivalent reliability verification through probabilistic assessment of strength distributions, creep behavior, and long-term deformations [24].

Geopolymer concrete exhibits distinct stress-strain behavior compared to Portland cement concrete, with implications for structural design. Higher early strength gain enables accelerated construction schedules, while reduced creep in certain formulations benefits prestressed applications [25]. However, variability in precursor materials necessitates rigorous quality control and performance-based specifications rather than prescriptive composition requirements.

Self-healing materials introduce unique considerations for structural reliability. Crack healing restores stiffness and reduces permeability but may not fully recover original strength. Design approaches that account for healed properties as additional safety margins rather than primary load-carrying capacity are appropriate given current validation status [26].

### 5.2. Cost-Benefit Analysis and Market Economics

Economic feasibility of carbon-negative construction materials depends on multiple factors including raw material costs, processing requirements, performance benefits, and carbon pricing. Bio-concrete incorporating bacterial cultures currently carries cost premiums of 20-50% compared to conventional concrete, though volume production and optimized encapsulation technologies are expected to reduce this differential [6].

Geopolymer concrete achieves cost parity with conventional concrete in regions with locally available fly ash or slag and established alkaline activator supply chains. Transportation costs for both precursors and activators significantly affect economics, favoring distributed production models [27].

Life-cycle cost analysis incorporating extended service life and reduced maintenance requirements improves the economic case for self-healing materials. Crack repair costs avoided through autonomous healing can offset initial premiums over 30-50 year analysis periods, particularly for difficult-to-access infrastructure [28].

### 5.3. Standards and Regulatory Frameworks

The absence of comprehensive standards for carbon-negative and self-healing construction materials constitutes a major adoption barrier. Existing concrete standards (ASTM C150, EN 197) are formulated around Portland cement chemistry and do not accommodate alternative binder systems [29].

Performance-based standards that specify required properties rather than composition enable innovation while maintaining safety. RILEM technical committees and national standardization bodies are developing test methods and specification frameworks for geopolymer concrete and bio-concrete [30].

Carbon accounting standards must address the unique characteristics of carbon-negative materials, including biogenic carbon storage duration and avoided emissions from industrial by-product utilization. Methodological alignment across carbon markets and green building certification systems is essential for creating market pull [18].

### 5.4. Industry Adoption Barriers

Construction industry conservatism, fragmented supply chains, and liability concerns impede adoption of novel materials. Contractors and engineers prefer materials with proven track records and established specification frameworks, creating a chicken-and-egg problem for innovation [31].

Professional education and training represent critical enablers for adoption. University curricula and continuing professional development must incorporate sustainable materials science to equip practitioners with the knowledge required for specification and design with novel materials [32].

## 6. Challenges and Future Research Directions

### 6.1. Long-Term Durability Validation

The extended design lives of infrastructure (50-100 years) necessitate durability validation that exceeds typical research funding cycles. Accelerated testing protocols must be calibrated against natural exposure to reliably predict long-term performance [33]. For bio-concrete, bacterial spore viability over decades remains uncertain, requiring improved encapsulation or periodic reactivation strategies.

Geopolymer concrete durability in diverse exposure conditions requires systematic investigation. While acid resistance is generally superior to Portland cement concrete, carbonation rates and reinforcement corrosion mechanisms differ and require specific design provisions [34].

### 6.2. Standardization Gaps and Testing Protocols

Harmonized test methods for self-healing efficiency are needed to enable comparison across studies and materials. Crack healing metrics including sealing ratio, permeability recovery, and mechanical restoration require standardized measurement protocols [35].

Geopolymer specification must address precursor variability through performance-based approaches. Rapid test methods for assessing reactivity and predicting strength development would facilitate quality control and material certification [29].

### 6.3. Scaling Microbial and Geopolymer Systems

Industrial-scale production of bacterial cultures and encapsulation materials requires bioprocess engineering optimization.

Cost reduction through waste-based nutrient sources and simplified cultivation methods is essential for economic viability [6].

Geopolymer production at scale necessitates consistent precursor supply chains and activator logistics. Regional material characterization and mix design databases would enable rapid deployment while managing variability [27].

### 6.4. Digital Monitoring and Smart Material Integration

Embedded sensors and structural health monitoring systems offer opportunities for validating self-healing performance in service. Distributed fiber optic sensing can detect crack formation and monitor healing progression, providing data for performance verification and design optimization [36].

Digital material passports tracking composition, provenance, and performance throughout service life facilitate end-of-life circularity by enabling material identification and deconstruction planning [22].

## 7. Conclusion

Carbon-negative and self-healing construction materials represent a paradigm shift in civil engineering practice, offering pathways to infrastructure development that actively mitigates climate change rather than contributing to it. Bio-concrete incorporating microbial self-healing mechanisms demonstrates crack sealing capabilities up to 0.97 mm with compressive strength improvements of 32%, extending service life while reducing maintenance requirements. Geopolymer binders utilizing industrial by-products achieve 60-80% emission reductions compared to Portland cement while maintaining structural performance suitable for diverse infrastructure applications. Circular economy frameworks integrating material recycling, industrial symbiosis, and carbon mineralization enable systemic resource efficiency and waste valorization.

The convergence of these technologies within life-cycle assessment frameworks confirms their environmental benefits, with embodied carbon reductions of 14-72% documented across multiple studies. Economic feasibility improves when life-cycle costs and carbon pricing are considered, though initial cost premiums persist for certain applications. Standards development, professional education, and demonstration projects are accelerating technology readiness, positioning carbon-negative and self-healing materials for scaled deployment in the coming decade.

Realizing this potential requires sustained research investment, policy support through carbon pricing and green procurement, and industry commitment to innovation. The civil engineering profession has both the opportunity and responsibility to lead this transition, building infrastructure that serves society while restoring planetary health.

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