



REVIEW

## Characteristics and Behavior of Cement-Based Composites with Biomaterials

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**ABSTRACT:** The increasing environmental concerns associated with traditional construction materials have forced the exploration of sustainable alternatives, such as biomaterials in cement-based composites. Despite their potential to significantly reduce carbon footprints and enhance environmental sustainability, comprehensive literature analyzing the integration, characteristics, and behavior of biomaterials within cement matrices remains sparse. This gap underscores a crucial need for a review to consolidate existing knowledge and identify future research trajectories. This study aims to conduct a review of the characteristics and behavior of cement-based composites with biomaterials. It also aims to establish a clear understanding of how biomaterials affect the physical, mechanical, and durability properties of cement-based composites. To maintain a clearly defined objective, this review is guided by three questions: (i) which biomaterial families have been investigated in cement-based composites and how they are integrated at binder, aggregate, fiber, and biologically mediated levels; (ii) what mechanisms most consistently explain reported changes in fresh properties, mechanical performance, and transport-related behavior; and (iii) which testing and monitoring approaches are used to quantify long-term performance, durability, and serviceability implications. The focus extends to evaluating the environmental impact through lifecycle analyses and the potential reduction in carbon emissions. The importance of this research lies in its ability to provide a robust foundation for future innovations in construction material technology. By highlighting current trends and gaps, it serves as a critical resource for researchers and industry practitioners aiming to develop more sustainable building solutions. Moreover, this review is poised to inform policy-making by presenting empirically supported data on the benefits and challenges associated with biomaterials in construction, thereby promoting more informed decisions towards sustainable urban development.

**KEYWORDS:** Cement-based composites; biomaterials; sustainability; mechanical properties; durability; monitoring

### 1 Introduction

Global construction remains heavily dependent on Portland cement and concrete, which consume substantial quantities of materials and fuels and emit significant amounts of carbon dioxide [1–3]. Historical and technical reviews indicate that cement technology has progressed through incremental improvements

in clinker chemistry, process control, and admixture use, despite ongoing environmental pressure [4–6]. Comprehensive reviews of cement-based composites indicate that high-performance mixes, which combine mechanical capacity with extended service life, are still being developed [7–9].

Growing concerns about resource depletion and climate policy have encouraged interest in low-carbon binders, alternative aggregates, and bio-derived constituents that reduce embodied emissions in concrete [2,10,11]. Studies from the fields of cement chemistry and sustainability demonstrate that the introduction of new constituents must preserve the mechanical reliability and durability standards that codes and clients expect [3,6,12]. Reviews on biomaterials in construction describe feedstocks such as agricultural residues, lignocellulosic fibers, biochar, seashells, and microbial products, which shift research attention beyond conventional mineral admixtures [13,14]. Policy-oriented and technological surveys highlight how building sector regulations, climate targets, and bioeconomy strategies support a wider study of bio-based inputs for structural and non-structural elements [11,15,16]. Within this broader shift, biomaterial-modified cement-based composites form a distinct group of materials in which organic, bio-derived, or biologically mediated components interact with hydration products and the pore structure [17–19].

Existing research remains fragmented across material types, scale of testing, and performance indicators, which makes comparison and generalization difficult. Many studies concentrate on specific biomaterials, individual durability mechanisms, or isolated structural functions, while broader patterns across cement-based composites with biomaterials are rarely assembled in a single analysis. Information on the combined effects on fresh properties, mechanical behavior, transport characteristics, and environmental performance, together with mapping of publication trends, remains scattered across the literature. The present study addresses this gap through a review of the characteristics and behavior of cement-based composites with biomaterials. The review is structured around three guiding questions: (i) which biomaterial families have been investigated in cement-based composites and how they are integrated at binder, aggregate, fiber, and biologically mediated levels; (ii) what mechanisms most consistently explain reported changes in fresh properties, mechanical performance, and transport-related durability indicators; and (iii) which testing and monitoring approaches are used to quantify long-term performance in laboratory studies and in service conditions. To maintain a clearly defined objective, the review focuses on cement-based and blended-cement matrices and biomaterials used as additions, partial replacements, aggregates, fibers, or microbial/enzyme-based mineralization agents; other low-carbon binder families are discussed only when they are directly compared against cement-based systems in the cited literature. The primary objective is to establish a comprehensive understanding of how biomaterials impact the physical, mechanical, durability, and environmental performance of cement-based composites, while also identifying research directions that can inform the future development of sustainable construction materials.

## 2 Review Methodology

This study employed a structured literature review methodology to systematically identify, screen, and synthesize research on cement-based composites incorporating biomaterials. Firstly, a comprehensive keyword search was conducted using Scopus and Google Scholar. Search terms combined descriptors related to cement systems (e.g., cement-based, concrete, mortar, blended cement) with biomaterial-related terms (e.g., bio-based materials, agricultural waste, fibers, biochar, ash, and rubber). Reference lists of key publications were also examined to capture additional relevant studies.

Studies were included if they investigated cement-based or blended-cement matrices incorporating biomaterials as binders, aggregates, fibers, or biologically mediated agents, and reported outcomes related to fresh properties, mechanical behavior, transport performance, durability, testing methods, or environmental

aspects. Studies focusing solely on non-cement binders, lacking performance-related data, or unrelated to construction materials were excluded. Only English-language publications were considered.

After removing duplicates, titles and abstracts were screened, followed by assessment. Finally, data were extracted on biomaterial type, integration method, mixture details, curing conditions, testing approaches, and reported effects, and then synthesized by biomaterial category and performance indicators.

### 3 Overview of Biomaterials

Biomaterials within cement-based composites form a wide group of plant-derived, microbially driven, and bio-related industrial constituents that are introduced into cementitious systems for mechanical, durability, hygrothermal, and environmental purposes [1,7,17]. Reviews focusing on biomaterials and construction demonstrate that bio-based inputs are now considered within a structured research area that connects materials science, structural engineering, and environmental assessment [11,18].

Plant and agricultural biomaterials represent one of the most visible families in this context, since they draw directly on renewable biological resources and agricultural residues. Hemp-based concretes and hemp-lime systems demonstrate how plant aggregates can be combined with mineral binders for envelope and wall applications, with a focus on moisture buffering, hysteretic behavior, and hygrothermal response [20–22]. Structural use of hemp fibers within concrete has been presented as an example of bio-based reinforcement for resilient and sustainable applications in building and infrastructure [23–25]. Wood fibers have been considered as additives in mortars, serving as a sustainable reinforcement option and extending the range of lignocellulosic materials used in cement-based composites [19,26,27]. Work on bamboo members and their strengthening technology further illustrates how plant-based materials are examined for structural functions in parallel with more traditional steel or synthetic fiber systems [19,25,27].

Agricultural residues and bio-derived ashes have been studied as cementitious components or supplementary materials that can partially replace conventional binders. Rice husk ash has been developed and assessed as a cement substitute for environmental conservation and green infrastructures, which places it within the broader family of biomass ashes used in construction [8,28,29]. A comprehensive study of building materials and bricks for residential construction reveals that bio-based materials are considered alongside conventional masonry units and binders, reinforcing their relevance in everyday building practice [2,10,12]. Reviews on magnesium phosphate cement and related binders highlight alternative cement systems that can interact with different types of aggregates and additives, including bio-derived components [6,7,30]. Microstructural studies on reinforcement mechanisms and nanoparticles suggest that fine bio-based powders, such as biochar, cellulose, or lignin, are considered in a context where control of pore structure, hydration products, and transport properties is central [31–33]. Reviews on biomaterials-based concrete composites that focus on biochar, cellulose, and lignin summarize this direction and connect it with carbon capture objectives and material performance in a general way [18,34].

Industrial by-products with a biological link form another important category within biomaterials used in cement-based composites. Oil palm clinker has been treated as a lightweight aggregate in structural concrete, with studies that consider flexural behavior, crack response, compressive strength, tensile strength, and modulus of elasticity in reinforced and plain concretes [25,35,36]. A review of palm oil and its by-products in bio-asphalt and bio-concrete mixtures shows how residues from the palm oil industry can be incorporated in both pavement and concrete materials [13,37,38]. Rubber/crete systems provide another example, as tire-derived rubber from end-of-life tires is studied for its mechanical properties and reuse within concrete [7,39]. Studies that involve biomaterials in conjunction with glass waste, or where cement and sand are partially replaced with biomaterial and glass waste, demonstrate combined recycling approaches that integrate bio-based and non-bio-based residues into a single composite [40,41]. Work on green flowable sand

concrete with seashell-based cementitious material and granite industrial waste further extends this picture of bio-related and industrial by-products within cementitious matrices [8,29,42].

Microbial and bacteria-based biomaterials introduce biological activity more directly into cement-based systems. Reviews on biomaterials synthesized through microbial-induced calcium carbonate precipitation describe a group of techniques where microbial processes are utilized in construction-related applications [14,43,44]. A mini review of enzyme-induced calcite precipitation presents a related technique for eco-friendly biocement production, highlighting enzyme-based pathways for calcium carbonate formation in construction materials [14,45,46]. Studies on biogrouting consider the applicability of microbial processes in sandy ground and foundation conditions, which connect microbially induced cementation with geotechnical practice [43,47,48]. Reviews of advanced bacteria-based biomaterials for environmental applications indicate that similar systems can be applied in water treatment, environmental control, and construction-related contexts [44,49]. Work on factors that affect microbial metabolic processes of biomaterials used for leak repairs offers an example where biological agents are associated with local sealing and maintenance functions within civil engineering systems [2,6,46].

#### **4 Integration of Biomaterials in Cement-Based Composites**

The integration of biomaterials, Table 1, into cement-based composites has evolved within the broader context of sustainable and high-performance concrete, where mixture design, microstructure, and durability are studied in conjunction with environmental pressures on conventional clinker systems [1,7,10]. Reviews on the cement industry and sustainable construction highlight that bio-derived constituents are being considered alongside other alternative materials to reduce emissions while maintaining engineering performance in general [2,17,30].

**Table 1:** Comparative overview of principal biomaterial families used in cement-based composites, including typical roles, performance tendencies, key constraints, and commonly used monitoring indicators.

<b>Biomaterial Family</b>	<b>Typical Form/Integration Route</b>	<b>Main Intended Functions</b>	<b>Commonly Reported Mechanical Tendency</b>	<b>Commonly Reported Durability Tendency</b>	<b>Key Constraints for Implementation</b>	<b>Monitoring/Test Indicators Frequently Used</b>
Plant-based fibers and bio-aggregates (hemp, wood, bamboo, other lignocellulosics)	Fiber reinforcement; porous bio-aggregate substitution	Crack bridging, toughness enhancement, hygrothermal and moisture buffering, density reduction	Post-cracking behavior and deformation capacity often improve; compressive strength may decrease depending on dosage and moisture conditioning	Moisture sensitivity can increase permeability if not controlled; hygrothermal performance may improve envelope behavior	Variability of fibers/aggregates, increased water demand, interfacial bonding challenges, long-term moisture exposure risks	Compressive and flexural strength, elastic modulus, capillary absorption/sorptivity, ultrasonic pulse velocity (UPV), moisture transport and hygrothermal profiling
Bio-derived ashes and powders (rice husk ash, seashell powder, similar materials)	Partial binder replacement or filler/packing modification	Pozzolanic and filler effects, microstructure refinement (material-dependent), clinker reduction	Strength may increase or decrease depending on replacement level, fineness, and ash reactivity	Transport resistance and chemical durability may improve when pore structure is refined; excessive replacement can weaken binding and increase cracking risk	Controlled processing (burning, grinding), consistency of chemical composition, optimization of replacement limits	Strength development curves, porosity and water absorption, chloride transport proxies, carbonation depth (where available), microstructural observation

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Table 1 (continued)

Biomaterial Family	Typical Form/Integration Route	Main Intended Functions	Commonly Reported Mechanical Tendency	Commonly Reported Durability Tendency	Key Constraints for Implementation	Monitoring/Test Indicators Frequently Used
Biochar, cellulose, lignin (fine bio-based modifiers)	Fine powder addition; partial replacement; nano- or micro-scale modifiers	Pore-structure tuning, internal curing, adsorption effects, multifunctional behavior	Reported effects vary widely with dosage and dispersion; some studies indicate improved toughness and transport-related performance	Transport properties may improve when dispersion is controlled and pores are refined; clustering or excessive porosity can negate benefits	Dispersion control, variability in biochar production, interactions with admixtures, increased water demand	Permeability proxies (absorption, sorptivity), electrical or transport indicators (where applied), strength and shrinkage monitoring
Bio-related industrial by-products (oil palm clinker, rubber, combined waste streams)	Aggregate replacement (coarse or fine); hybrid waste incorporation	Density reduction, circular-economy integration, improved impact resistance (rubber)	Compressive strength commonly decreases with increasing rubber content; lightweight aggregates can remain within structural ranges with appropriate mix design	Water absorption and increase with porous replacements unless pore structure is refined; durability depends on interface quality and pore connectivity	Quality control, particle grading, interfacial transition zone behavior, variability in waste processing	UPV, density, water absorption and porosity, compressive and flexural strength, crack pattern development

(Continued)

Table 1 (continued)

Biomaterial Family	Typical Form/Integration Route	Main Intended Functions	Commonly Reported Mechanical Tendency	Commonly Reported Durability Tendency	Key Constraints for Implementation	Monitoring/Test Indicators Frequently Used
Microbial/enzyme-based biomineralization (MICP, EICP, bio-grouting, bacterial concrete)	Biogenic CaCO <sub>3</sub> precipitation within cracks or pores; bio-cementation	Self-healing, crack sealing, permeability reduction, watertightness and repair	Localized strength recovery through crack filling; effectiveness depends on nutrient supply and environmental conditions	Typically targets permeability reduction and crack sealing; long-term field performance depends on moisture, temperature, and biological survivability	Scalability, uniformity of treatment, long-term stability under exposure, verification and standardization of testing protocols	Crack-closure measurements, permeability or flow reduction, strength recovery indices, microscopy of precipitates, durability-related proxy monitoring

Integration at the binder level commonly relies on partial replacement of Portland cement with bio-derived or bio-related powders. The development of rice husk ash as a cement substitute for environmental conservation demonstrates how biomass ash can be blended with cement for green infrastructure applications in a general manner [8,28,29]. Research progress on magnesium phosphate cement presents an alternative binder family that stands beside Portland-based systems in discussions of sustainable cements [6,7,30]. Studies on the microscopic reinforcement and nano-modification of cement-based materials explain how fine particles influence the hydrate structure and pore features, which form the basis for considering biochar, cellulose, and lignin as binder-related additions [31–33]. Reviews focused on biomaterials-based concrete composites summarize how biochar, cellulose, and lignin are introduced into cementitious systems with attention to mechanical and environmental aspects at a general level [18,34].

The fresh concrete behavior has encouraged further integration of biomaterials in self-compacting and internally cured mixes. Studies on self-compacting concrete with biomaterial-based cement substituents consider rheology, mechanical response, and microstructure when part of the binder is replaced with bio-derived materials [7,34,50]. Research on fly ash-based concrete prepared with bio-admixtures as internal curing agents examines the combinations of mineral additions and bio-derived admixtures in mixes where internal water supply is crucial [8,51,52]. Partial replacement of cement and sand with biomaterial and glass waste provides another route, in which bio-based and glass recyclates appear together in both paste and fine aggregate fractions [40,41]. Experimental work on self-curing concrete using biomaterials as admixtures places organic agents within the paste, where they influence internal moisture conditions during hydration in a general sense [9,51,53].

Aggregate-level integration covers bio-aggregates and bio-related industrial by-products. Studies on stone and several biomaterials as coarse aggregate discuss concrete where part of the natural aggregate is substituted with bio-related materials, which changes the aggregate skeleton and interface environment [6,10,29]. A work that combines seashells as a cementitious biomaterial with granite industrial waste as fine aggregate presents a mix design for green flowable sand concrete, which integrates bio-derived and industrial residues [8,29,42]. The bond behavior of a bio-aggregate embedded in a cement-based matrix is examined to understand how organic particles interact with the surrounding paste along the interface zone [24,25,31]. Oil palm clinker has been introduced as a lightweight aggregate in reinforced concrete beams and other elements, illustrating the use of an agricultural by-product in structural concrete [35–37].

Further aggregate-related systems involve rubber particles, palm oil by-products, and functional aggregates. Reviews on rubber/concrete describe concrete with tire-derived rubber as a partial aggregate replacement, with attention to its mechanical behavior and the reuse of rubber scrap [7,39]. The work on palm oil and its by-products in bio-asphalt and bio-concrete mixtures discusses the integration of oil-industry residues into bituminous and cementitious matrices [13,37,38]. Studies on phosphorus removal from aqueous solutions using adsorptive concrete aggregates demonstrate that these aggregates provide both load-carrying and environmental functions in water treatment contexts [18,44].

Plant-based aggregates and fibers enter cement-based composites at several scales. Hemp concrete and hemp–lime systems involve hemp shiv combined with mineral binders for wall and envelope applications, with hygrothermal and moisture-related performance analyzed through experiments and modeling tools [20–22]. Hemp-fiber concrete for structural applications places hemp fibers within cementitious matrices as reinforcement in structural work [19,23,25]. Wood fibers used as additives in mortars are presented as a sustainable reinforcement option that broadens the range of lignocellulosic components in cement-based mixes [19,26]. Studies on the strengthening of bamboo flexural members examine the interaction between bamboo members and cementitious materials in structural systems [1,7,27]. Agricultural waste reinforcement in green composites and wider surveys of residential building materials indicate that

such bio-based components are being considered alongside conventional bricks and concretes in residential contexts [12,13].

Microbial and bacteria-based biomaterials are integrated through biogenic mineralization and biocementation processes. Reviews on biomaterials synthesized through microbial-induced calcium carbonate precipitation describe systems where bacteria, nutrients, and calcium sources are arranged to form cemented products for construction-related uses in a general sense [14,43,44]. A mini-review on enzyme-induced calcite precipitation presents enzyme-based methods for eco-friendly biocement production that can be associated with soil or material stabilization [14,45]. Assessment of biogrouting in sandy ground discusses the applicability of these microbial processes for ground improvement tasks [6,43,47]. Studies on the factors that affect microbial metabolic processes of biomaterials used for leak repair show how microbial agents can be incorporated into repair systems for civil infrastructure [2,6,46]. Reviews of advanced bacteria-based biomaterials for environmental applications position these materials for use in various applications, including construction and environmental uses such as water-related treatments [44].

Self-healing and internal curing concretes form another major route for biomaterial integration. Reviews of encapsulation methods for biomaterials in self-healing concrete summarize different carrier systems for storing and releasing healing agents inside cementitious matrices [53–55]. Studies on biomaterial-assisted self-healing for high-performance centrifugal concrete piles focus on integrating biomaterials into structural piles, with a primary aim of reducing cracks [7,56]. A framework for biomaterial-assisted self-healing in lightweight concrete with porous aggregate micro-reservoirs shows how aggregates can act as hosts for healing agents in self-healing systems [24,29]. Work on predicting the optimal biomaterial dosage and curing duration for self-healing concrete utilizes designed experiments and decision tree algorithms to relate mix composition and curing conditions [34,51,57]. Internal curing with biomaterial-based admixtures is also observed in studies on fly ash-based concretes and self-curing concretes, where bio-derived admixtures are mixed into the paste as agents that influence internal moisture behavior [41,52,53].

Functional and environmental roles add further directions for integration. Numerical studies on building envelope performance with dynamic phase change material integration in biomaterial concrete walls describe composite walls in which phase change materials and biomaterial concretes work together to achieve thermal and energy-related objectives [21,22,58]. Life cycle studies of hybrid structures with advanced bio- and conventional materialization in dense urban contexts quantify emissions when bio-based materials form part of structural systems [2,11,15]. Reviews on biomaterials technology and policies in the building sector connect technical integration of biomaterials with policy frameworks and sectoral targets [11,17]. Discussions on natural building materials in architectural pedagogy and innovative façade strategies for the seismic design of tall buildings reveal that material choices, including bio-based composites, are closely linked to teaching, energy performance, and seismic behavior in design practice [1,16,59].

Finally, it is useful to position biomaterial-modified cement-based composites within the wider landscape of decarbonization strategies for cement and concrete. Conventional routes such as supplementary cementitious material replacement, optimized particle packing, and recycled aggregate incorporation often offer more mature standardization pathways, yet they still face durability constraints that depend on transport behavior and exposure class. Biomaterial-based routes can overlap with supplementary cementitious material strategies (e.g., bio-derived ashes) while also introducing distinct challenges such as moisture sensitivity of plant-based phases, biological activation requirements in microbial/enzyme-based systems, and higher variability in feedstock properties. For this reason, durability verification and monitoring become central differentiators: biomaterial systems frequently require stronger coupling between mechanical metrics and transport indicators, and, in some applications, *in-situ* monitoring (moisture and chloride exposure proxies) to demonstrate long-term reliability under real service conditions.

## 5 Physical and Mechanical Properties

Physical and mechanical properties, [Table 2](#), serve as a central reference for evaluating the performance of cement-based composites with biomaterials, as they govern strength, stiffness, deformation capacity, and transport behavior, which in turn control service conditions in most applications [\[1,4,7\]](#). Conventional cement systems and sustainable cementitious materials provide benchmarks for density, hydration products, and phase composition, which are used when bio-based constituents are introduced [\[3,5,10\]](#). Reviews on biomaterials in concrete and sustainable construction indicate that experimental programs usually report compressive and flexural strength, modulus of elasticity, and permeability for bio-modified mixtures [\[11,17\]](#). General work on high-performance composites and microscopic reinforcement concepts establishes a framework in which any biomaterial is discussed in relation to its microstructure, cracking patterns, and fracture response [\[1,8,31\]](#).

Table 2: Summary of studies on the physical and mechanical properties.

Reference	Aim of the Study	Findings	Remarks
Hadjadi et al. [42]	This study aimed to determine how replacing natural sand with granite waste and replacing cement with seashell powder affected the fresh and mechanical properties of flowable sand concrete, including slump flow, V-funnel time, compressive strength, modulus of elasticity and ultrasonic pulse velocity.	This study showed that increasing granite waste content reduced workability parameters such as slump flow while increasing V-funnel time, but that introducing finely ground seashell powder improved particle packing and allowed all mixtures to remain within acceptable flow limits; the mixture with 50% granite waste and 10% seashell powder achieved the highest compressive strength and modulus of elasticity and exhibited higher ultrasonic pulse velocity than the control mix, indicating a denser and stiffer material.	The results indicated that, despite a reduction in workability, the combination of granite waste and seashell powder produced concretes with superior mechanical performance and compact microstructure, showing that waste and bio-derived constituents could be used to tailor strength and stiffness without compromising basic fresh properties.
Jonnala et al. [12]	This review aimed to compare the basic mechanical and thermal properties of conventional clay bricks, concrete and fly ash bricks with more advanced options such as aerated concrete and recycled bricks in the context of residential construction.	This review showed that cellular lightweight concrete bricks reached compressive strengths about 30%–40% higher than traditional clay bricks and displayed excellent lateral load capacity and displacement ductility, while composition modifications using fibers such as coconut and basalt produced an approximate 17.4% increase in thermal insulation with minimal adverse effects on the inherent thermal stability of the bricks.	The results indicated that carefully engineered brick products could deliver markedly improved structural capacity and energy performance compared with traditional masonry, and highlighted the potential of fiber-modified and lightweight units as key physical components in modern residential envelopes.

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Table 2 (continued)

Reference	Aim of the Study	Findings	Remarks
Stefanidou et al. [26]	This study aimed to investigate the effect of adding black pine and beech wood fibers on the physical, thermal and mechanical properties of lime-based and cement-based mortars, including workability, strength and thermal conductivity.	This study showed that wood fibers, especially black pine, increased water demand in lime mortars to achieve comparable workability, while cement-based mortars were less sensitive; fiber-reinforced mortars exhibited small reductions in compressive and flexural strengths and increased capillary absorption, but also showed reduced thermal conductivity and retained sample integrity after fracture due to fiber bridging action.	The results indicated that low-volume wood fiber reinforcement altered physical properties by slightly reducing strength but improving crack-bridging and thermal insulation, which suggested that such fibers could be used where modest strength trade-offs were acceptable in exchange for better toughness and thermal performance.
Suzuki and Shi-mamoto [28]	This study aimed to evaluate the tensile strength and cracking behavior of cementitious greening base materials containing different rice husk ash replacement ratios, using acoustic emission energy indices to interpret fracture processes.	This study showed that increasing rice husk ash replacement reduced particle binding strength and tensile strength and changed fracture behavior, which was captured by characteristic changes in acoustic emission energy during loading, demonstrating that the material became more prone to crack initiation and propagation as ash content increased.	The results indicated that rice husk ash significantly influenced mechanical strength and fracture mechanics of cement-based greening substrates, and that a careful balance between ash content and mechanical requirements was necessary to maintain adequate structural integrity while still benefiting from ash-derived porosity for vegetation.

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Table 2 (continued)

Reference	Aim of the Study	Findings	Remarks
Ferreira et al. [24]	This study aimed to characterize the bond behavior between a cement-based matrix and a novel macaúba bio-aggregate by performing pull-out tests and comparing mechanical response with that of a reference granitic aggregate.	This study showed that both bio-aggregate and granitic aggregate presented similar linear-elastic pull-out behavior up to their peak loads, but that the mineral aggregate reached a higher peak load, suggesting stronger chemical adhesion, while the bio-aggregate exhibited a smoother post-peak softening branch, which microscopy linked to its specific outer structure and surface characteristics.	The results indicated that macaúba bio-aggregate could provide acceptable mechanical interaction with cement paste with slightly lower peak bond strength but improved post-peak ductility, suggesting its potential as a coarse aggregate in concretes where energy-dissipating behavior was desirable.
de Oliveira et al. [43]	This study aimed to evaluate the compressive strength and physical integrity of bio-cemented columns made from copper mine tailings using microbial induced calcium carbonate precipitation and to compare them with similar columns made from beach sand.	This study showed that columns produced from copper mine tailings reached a compressive strength of about 0.54 MPa, which was substantially lower than the 1.85 MPa achieved by beach-sand-based bio-columns, and that the reaction in tailings primarily formed a thin crust around the specimen due to limited penetration in the dense, fine-grained material.	The results indicated that while MICP produced measurable strength in fine tailings, the mechanical properties of the resulting material were significantly constrained by particle size and porosity, which limited its use to relatively thin or surface-cemented products rather than thick load-bearing elements.

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Table 2 (continued)

Reference	Aim of the Study	Findings	Remarks
Malathy et al. [52]	<p>This study aimed to determine whether plant extracts from <i>Spinacea oleracea</i> and <i>Calotropis gigantea</i>, used as internal curing agents, could support the development of mechanical properties in fly ash-based concrete to levels comparable with polyethylene glycol-modified or conventionally water-cured concrete.</p>	<p>This study showed that concretes incorporating the plant-based internal curing agents developed compressive strength and bond strength that were similar to or higher than those of polyethylene glycol-based internal curing mixes and conventionally water-cured concretes, and that microstructural analyses indicated well-developed hydration products in specimens with bio-admixtures.</p>	<p>The results indicated that bio-derived internal curing agents were capable of sustaining adequate hydration and strength development in concrete, providing mechanical performance that did not depend on synthetic admixtures or continuous external curing.</p>
Haque and Chen [30]	<p>This review aimed to summarize the physio-mechanical behavior of magnesium phosphate cement-based materials across multiple applications, including structural repair, fiber-reinforced mortars, particle boards and bioceramics.</p>	<p>This review showed that magnesium phosphate cement systems consistently exhibited rapid strength gain and high early compressive strength, that they could be formulated to achieve a wide range of mechanical properties and that they often provided favorable stiffness and bond behavior suitable for structural repair and specialized applications.</p>	<p>The results indicated that magnesium phosphate cements formed a distinct family of binders with robust mechanical performance and design flexibility, making them attractive for situations where high early strength and specific mechanical characteristics were required.</p>

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Table 2 (continued)

Reference	Aim of the Study	Findings	Remarks
Wei et al. [27]	This review aimed to compile information on the mechanical performance of engineered bamboo members and to summarize strengthening techniques for improving the load-bearing capacity and stiffness of bamboo flexural elements.	This review showed that engineered bamboo members possessed high strength-to-weight ratios and good bending and tensile properties, but that ordinary bamboo beams suffered from low bearing capacity and limited cross-sectional stiffness, while strengthened members that combined bamboo with steel bars, fiber-reinforced polymers, concrete or metals achieved substantially improved stiffness and flexural strength.	The results indicated that, when equipped with appropriate reinforcement, bamboo flexural members could fulfil structural roles similar to conventional beams and slabs, with mechanical properties sufficient for multi-storey buildings and bridges, thereby positioning engineered bamboo as a competitive structural material.
Arunya et al. [55]	This study aimed to evaluate the effect of introducing Enterobacter sp. and nano-silica on the mechanical properties of bacterial concrete, focusing on compressive strength and split tensile strength.	This study showed that bacterial concrete with Enterobacter sp., supported by nano-silica and an organic nutrient, developed higher compressive strength and split tensile strength than control concrete, and that the presence of biomineralized calcite with crystalline morphology within cracks and pores contributed to improved mechanical performance.	The results indicated that microbiologically induced calcite precipitation, when appropriately configured with supporting nano-silica, could be exploited to enhance the mechanical properties of concrete in addition to its potential self-healing functions.

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Table 2 (continued)

Reference	Aim of the Study	Findings	Remarks
Kamaruddin et al. [35]	This study aimed to examine the flexural behavior and load capacity of lightweight oil palm clinker concrete beams reinforced with deformed bars and to compare the measured capacity with predictions based on code equations.	This study showed that oil palm clinker concrete beams carried ultimate loads greater than those predicted by the relevant British Standard, exhibited reasonable stiffness and deflection behavior and developed acceptable cracking patterns, despite having a lower density than conventional concrete beams.	The results indicated that the mechanical performance of oil palm clinker concrete beams satisfied structural design requirements, confirming that agricultural waste-derived lightweight aggregates could be used in flexural members with predictable strength and stiffness.
Kamaruddin et al. [36]	This study aimed to evaluate the basic mechanical characteristics and density of concrete mixtures using oil palm clinker as both fine and coarse lightweight aggregates.	This study showed that oil palm clinker concrete achieved mean compressive strength of about 30.79 MPa, tensile strength of about 3.34 MPa and modulus of elasticity around 13.024 kN/mm <sup>2</sup> , while achieving significantly lower densities than normal-weight concretes, and that these mechanical values met typical requirements for structural lightweight concrete.	The results indicated that oil palm clinker aggregates produced concretes with satisfactory strength and stiffness for structural applications, while simultaneously lowering self-weight and reusing an otherwise problematic waste stream.

Background studies on nanoparticles, supplementary cementitious materials, and polymers clarify how changes in composition affect the mechanical and physical properties of cement-based materials [9,32,33]. Reviews on early-age properties and viscosity-modifying admixtures describe how fineness, rheology, and segregation resistance relate to cracking risk and dimensional stability in fresh and hardening concrete [33,50,51]. Work on transport in unsaturated materials and performance in aggressive aqueous environments enhances the description of durability-related behavior by incorporating permeability, diffusion, and sorption characteristics [6,23,60]. Modelling studies in cementitious materials and computational materials science support the interpretation of test data through microstructure-based descriptions of stiffness and transport [23,61].

Plant-based biomaterials influence both physical and mechanical properties through porosity, moisture affinity, and reinforcement action. Hemp concrete studies have presented hysteretic moisture buffering, sorption, and desorption cycles, as well as their associated effects on temperature and moisture fields in wall elements [20–22]. Numerical tools for hemp–lime envelopes and biomaterial concrete walls analyse hygrothermal behavior and relate density and moisture capacity to indoor conditions [15,22,58]. Studies on hemp-fiber concrete for structural applications consider mechanical resistance and deformation under loading, placing hemp within discussions on resilient bio-based reinforcement [1,7,23]. Work on wood fibers in mortars and the reinforcement of agricultural waste in green composites reports changes in tensile response and crack patterns when lignocellulosic fibers are added to the matrix [19,26]. Research on bamboo flexural members documents strengthening strategies and bending performance, giving examples of hybrid systems that combine plant-based components and cementitious materials [7,25,27].

Aggregate-related biomaterials alter the unit weight, porosity, and interface properties of hardened composites. Studies that use stone and several biomaterials as coarse aggregate report density, compressive strength, and workability for different replacement levels [10,12,29]. Green flowable sand concrete, incorporating seashell-based cementitious material and granite waste as fine aggregate, is evaluated in terms of compressive strength and durability indicators [8,29,42]. Oil palm clinker used as a lightweight aggregate in reinforced beams and other members is examined through flexural, cracking, and strength tests, which describe the behavior of palm-based lightweight concrete [35–37]. Reviews on palm oil by-products in bio-concrete mixtures link these mechanical observations with mixtures that include oils, ashes, or clinkers from the palm industry [13,37,38].

Recycled biomaterials and bio-related wastes used as aggregates bring questions about deformability, toughness, and long-term response. Rubber/concrete reviews present compressive strength, modulus, and impact-related indicators for mixtures with tire-derived rubber aggregate [7,39]. Studies on concretes incorporating biomaterial and glass waste, along with partial replacement of cement and sand by these additions, have reported compressive and flexural strengths, density, and workability [40,41]. Research on adsorptive concrete aggregates for phosphorus removal examines the sorption capacity and mechanical performance of aggregates that serve both environmental and structural functions [18,44].

Binder-related biomaterials influence mechanical behavior through changes in hardened paste microstructure and hydration products. The development of rice husk ash as a cement substitute for environmental conservation involves assessing the compressive strength and performance of blended binders in green infrastructure [10,28,29]. Research on magnesium phosphate cement summarizes the strength development, stiffness, and setting characteristics of this alternative binder family [6,7,30]. Microscopic reinforcement and nanoparticle reviews describe the relationships between refined hydrates and mechanical response, which provide a context for biochar, cellulose, and lignin-based additions discussed in biomaterial concrete reviews [18,31–33]. Papers on self-compacting systems with biomaterial substituents report compressive strength, stiffness, and microstructural observations when part of the binder is replaced [8,34,52].

Rheological properties and early-age behavior form another part of the physical and mechanical description. Self-compacting concrete with biomaterial-based cement substituents is evaluated through slump flow, viscosity, segregation resistance, and compressive strength [7,34,50]. Fly ash-based concretes with bio-admixtures as internal curing agents are examined in terms of shrinkage, early-age cracking, and strength development as internal water is redistributed [51,52,60]. Self-curing concrete with biomaterials as admixtures and mixes with extracts of biomaterials for internal curing has been examined in terms of time-dependent deformation and residual tensile capacity in conjunction with internal moisture measurements [9,41,53]. These studies sit within broader work that relates fineness, hydration rate, and rheology to cracking risk in cement-based materials [3,33,51].

Across the reviewed studies, reported mechanical and physical outcomes are strongly conditioned by differences in experimental design and reporting quality. Many investigations remain limited to short curing ages, laboratory-scale specimens, and a narrow set of response variables, which restricts comparison across biomaterial families and makes it difficult to infer service-level performance. Divergence in findings is also frequently linked to incomplete disclosure of biomaterial pre-treatment (washing, calcination temperature for ashes, fiber surface modification, particle grading, and moisture conditioning), even though such steps directly control interfacial bonding, internal curing behavior, and pore-structure evolution. A further inconsistency arises because some studies emphasize strength metrics while omitting transport indicators that govern durability, whereas others report permeability-related measures without connecting them to the mechanical reliability requirements expected in design practice. These limitations indicate that stronger standardization of reporting (complete mix design, bio-feedstock provenance, pre-treatment steps, and consistent durability indicators reported alongside strength) is necessary before robust cross-study generalizations can be made for code-oriented adoption.

## 6 Durability and Performance

The durability and overall performance of cement-based composites, Table 3, with biomaterials are typically discussed in relation to their microstructure, transport properties, and long-term mechanical response under environmental and mechanical actions [1,4,7]. Classic work on sustainable cementitious materials, clinker chemistry, and challenges in the cement industry provides a reference for the behavior of hydration products, pore structures, and exposure resistance in conventional systems [2,3,5,10]. Studies on aggressive aqueous environments, unsaturated transport, and computational materials science describe how permeability, sorption, cracking, and pore connectivity control durability limits, and these same aspects frame the evaluation of bio-modified concretes [6,60–62]. Reviews on nanoparticles and supplementary cementitious materials relate pore refinement and matrix densification to durability indicators, which offer a technical baseline for newer bio-based additions [8,32,33].

Table 3: Summary of studies on the durability and long-term behavior.

Reference	Aim of the Study	Findings	Remarks
Hadjadj et al. [42]	This study aimed to assess the durability-related properties of flowable sand concrete mixtures containing granite waste and seashell powder, focusing on water absorption, porosity, ultrasonic pulse velocity and resistance to acid attack as performance indicators.	This study showed that the mixture with 50% granite waste and 10% seashell powder not only achieved the highest strength but also exhibited the lowest porosity and water absorption and the highest ultrasonic pulse velocity at 90 days, and that this mixture performed best under acid attack, indicating superior durability compared with the control concrete.	The results indicated that using granite waste and seashell powder could improve both strength and durability profiles of concrete, producing a material with lower permeability, denser microstructure and better chemical resistance, which was beneficial for long-term performance in aggressive environments.
Malathy et al. [52]	This study aimed to evaluate whether plant-based internal curing agents could provide durability benefits in fly ash-based concrete comparable to polyethylene glycol and conventional water curing by influencing moisture retention and hydration.	This study showed that concretes prepared with <i>Spinacea oleracea</i> and <i>Calotropis gigantea</i> extracts maintained internal moisture and hydration products in a way that led to comparable or improved compressive strength and bond strength relative to water-cured and polyethylene glycol-modified concretes, and that microstructural observations indicated dense matrices without signs of inadequate curing.	The results indicated that plant-derived internal curing agents could maintain sufficient internal water for continued hydration and thus support durable microstructures without continuous external water supply, which was advantageous in regions with water scarcity or limited curing control.

(Continued)

Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
de Oliveira et al. [43]	This study aimed to evaluate the feasibility and performance limitations of microbial induced calcium carbonate precipitation for producing bio-cemented elements from copper mine tailings in terms of achievable strength and solidification depth.	This study showed that the MICP treatment produced only a thin calcified crust on low-porosity tailings and that resulting compressive strength remained modest, suggesting that long-term load-bearing performance of thick elements would be limited, whereas surface stabilization and dust control remained realistic uses.	The results indicated that while MICP could contribute to performance improvements in specific surface or thin-layer applications, durability and structural performance of thick sections in fine mine tailings were constrained by particle size and permeability, requiring alternative strategies or hybrid solutions.
Kidanemariam et al. [45]	This mini-review aimed to synthesize evidence on durability and performance of soils and cementitious systems treated with enzyme-induced calcite precipitation, including strength gain, stiffness enhancement and permeability reduction.	This review showed that EICP treatments typically increased soil strength and stiffness while reducing permeability, enabling applications such as fugitive dust control, self-healing of cracked concretes and improvement of low-volume road surfaces, and that the small size of urease enzymes facilitated penetration into a wide range of soil gradations including fine and silt sands.	The results indicated that EICP provided a flexible, low-energy approach to improving mechanical performance and durability-related properties, particularly permeability, in geotechnical and cementitious systems, and that enzyme source and calcium salt choice could be tuned for target performance.

(Continued)

Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
Arunya et al. [55]	This study aimed to evaluate the impact of microbiologically induced calcite precipitation on durability-related properties of concrete, focusing on the ability of <i>Enterobacter</i> sp. to fill microcracks, voids and pores and thereby improve resistance to crack propagation and environmental attack.	This study showed that bacterial concrete produced calcite that filled microcracks and pores, reduced pathways for water ingress and led to improved compressive and split tensile strength together with enhanced durability indicators compared with reference concrete, and that the presence of nano-silica further contributed to dense C–S–H formation.	The results indicated that bacterial concrete using suitable strains and nutrient systems could act as a self-healing material that improved both mechanical performance and durability by sealing microdefects and limiting deleterious transport processes.
Moissette et al. [22]	This study aimed to quantify the influence of sorption hysteresis on the transient hygrothermal behavior of hemp concrete under cyclic hydric loadings using a numerical model validated against experimental data.	This study showed that numerical simulations including sorption hysteresis reproduced measured temperature and relative humidity profiles in hemp concrete more accurately than models without hysteresis and that hysteresis strongly influenced transient moisture response, which in turn affected the material's ability to buffer indoor humidity and protect against moisture-related degradation.	The results indicated that sorption hysteresis was a key factor in the long-term hygrothermal performance and durability of hemp concrete envelopes and that models needed to incorporate this phenomenon to correctly predict in-service behavior and risks such as condensation or moisture accumulation.

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Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
Aït Oumeziane et al. [21]	This study aimed to assess how sorption hysteresis and initial moisture content influenced the hygrothermal response and performance of a hemp concrete wall exposed to climatic variations by combining experimental measurements with numerical modelling.	This study showed that numerical models incorporating hysteresis and correct initial moisture conditions reproduced experimental profiles of internal temperature and relative humidity more accurately than simpler models, and that initial moisture content had a pronounced effect on subsequent transient responses under changing climate conditions.	The results indicated that both hysteresis and initial moisture state were critical parameters for predicting long-term performance of hemp concrete walls, influencing moisture buffering, risk of condensation and overall durability in real building conditions.
Aït Oumeziane et al. [20]	This study aimed to characterize the hysteretic sorption behavior of hemp concrete using measured scanning curves and to evaluate how different hysteresis models affected predictions of transient hydric response relevant to durability.	This study showed that Huang's hysteresis model fitted the measured scanning curves more accurately than Carmeliet's model and that using a well-calibrated hysteresis representation in a coupled heat and moisture transfer model significantly altered predicted transient moisture histories compared with simpler approaches.	The results indicated that accurate modelling of sorption hysteresis was essential for evaluating hygrothermal performance and moisture-related durability of hemp-based materials and that improper hysteresis representation could lead to misjudgment of moisture risks over the service life.
Kamaruddin et al. [35]	This study aimed to check whether code-based design predictions for ultimate load were conservative for lightweight oil palm clinker concrete beams and thereby to infer the safety margins for structural performance and durability.	This study showed that all tested beams failed at loads higher than design predictions, confirming that code equations provided conservative estimates, and that beam responses in terms of crack patterns and deflections were acceptable, suggesting reliable service performance.	The results indicated that oil palm clinker concrete beams could be used without compromising structural safety or serviceability and that the conservatism in existing design rules contributed positively to the long-term reliability and performance of such lightweight structural elements.

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Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
Kamaruddin et al. [36]	This study aimed to evaluate long-term performance-related properties such as creep, shrinkage and modulus of elasticity in concrete mixtures using oil palm clinker as lightweight aggregate.	This study showed that creep and shrinkage values for oil palm clinker concrete remained within acceptable ranges for structural lightweight concrete, and that modulus of elasticity, although lower than that of normal-weight concrete, still provided sufficient stiffness for typical applications.	The results indicated that oil palm clinker concrete did not exhibit abnormal time-dependent deformations and therefore could be expected to deliver stable long-term performance, supporting its use in durable lightweight structures.
Adresi and Khoshoo [54]	This study aimed to compare the performance of sixteen encapsulation techniques used to introduce bio-materials for crack healing in concrete by scoring each method against criteria such as mechanical properties, healing effectiveness, complexity, cost, environmental impact and durability.	This study showed that lightweight aggregate encapsulation reached the highest average score of about 0.48, followed closely by slug and chitosan capsules and calcium sulfoaluminate encapsulation, indicating that these methods provided a favorable combination of mechanical robustness and sustained healing performance, whereas other methods showed weaknesses in one or more criteria.	The results indicated that encapsulation strategy played a decisive role in the durability and performance of self-healing bio-concretes and that prioritizing methods with balanced scores could improve long-term crack control and structural reliability.

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Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
Riccardi [38]	This chapter aimed to review durability and performance aspects of asphalt mixtures that used bio-materials as extenders or binders replacing more than 20% of fossil-based binder.	This chapter showed that many bio-modified mixtures matched or approached the performance of conventional mixtures in terms of stiffness, strength and resistance to typical pavement distresses when formulations were finely tuned, but also highlighted concerns about long-term ageing, process complexity and the need for compatible modifiers to maintain performance over the service life.	The results indicated that bio-based binders could support durable pavement performance if designed carefully, yet emphasized that stability, ageing behavior and susceptibility to environmental factors remained critical research areas for reliable long-term use.
Migoni Alejandre et al. [15]	This study aimed to quantify the life cycle embodied carbon performance of hybrid top-up structural systems using engineered timber, concrete and steel and to relate these results to urban and national carbon budgets.	This study showed that predominantly bio-based structural systems achieved around 60% lower cradle-to-grave embodied carbon than more conventional systems and that high-quality reuse of timber elements could offset 30%–60% of positive emissions, leading to potential savings of several megatonnes of CO <sub>2</sub> -equivalent if widely adopted in Amsterdam by 2050.	The results indicated that from a performance perspective that included climate impact, bio-based structural systems delivered superior long-term carbon performance and contributed directly to sustainability targets, which was an increasingly central dimension of “durability” at the system level.

(Continued)

Table 3 (continued)

Reference	Aim of the Study	Findings	Remarks
Di Sarno et al. [23]	This review aimed to evaluate durability-related performance of hemp fiber-reinforced concrete and mortars, including permeability, setting behavior and structural reliability, in addition to mechanical effects.	This review showed that hemp fiber inclusion increased permeability and slowed setting, and that compressive strength often decreased even as flexural performance improved, leading to concerns regarding durability and structural capacity for heavily loaded elements; at the same time, benefits such as improved thermal and acoustic performance and carbon sequestration were documented.	The results indicated that hemp fiber-reinforced composites offered attractive performance in terms of crack control and environmental benefits but required careful control of mix design and perhaps hybrid reinforcement to mitigate durability-related disadvantages such as higher permeability and reduced compressive strength.

Hygrothermal response and water transport are particularly important in composites that contain plant-based aggregates or porous bio-phases. Hemp concrete studies report hysteretic moisture buffering and transient hygrothermal behavior, which links pore structure and sorption capacity with humidity regulation in building envelopes [20,21,60]. Numerical tools for hemp–lime walls and biomaterial concrete envelopes simulate coupled heat and moisture transfer, and provide data on temperature and humidity profiles through the thickness over time [15,22,58]. Studies on adsorptive concrete aggregates demonstrate that modified aggregates can interact with aqueous contaminants while still meeting structural requirements, thereby linking environmental performance with long-term contact with water [18,44,49]. Reviews on nanoparticles and fine-scale modifiers again stress the relation between refined pores, reduced permeability, and improved resistance against harmful agents [8,32,33].

Durability in plant-based fiber and aggregate systems is often interpreted through bond behavior, moisture sensitivity, and structural performance under service actions. Structural hemp-fiber concrete is discussed as a resilient material where mechanical resistance and deformation capacity are evaluated under load, including considerations for long-term use [1,7,23]. Hemp–lime wall systems and related mixes have been studied in terms of moisture storage, temperature response, and potential effects on cracking or shrinkage during service [20–22]. Research on wood fibers in mortars and green composites with agricultural waste focuses on reinforcement efficiency, crack control, and overall performance under repeated or sustained actions [19,26]. Studies on the bond behavior of bio-aggregates embedded in cement-based matrices analyse interface conditions and stress transfer, which influence durability through crack initiation and propagation [24,31,61]. Research on bamboo flexural members focuses on strengthening techniques and serviceability limits in hybrid systems that combine bamboo and cementitious components [7,25,27].

The durability of composites that utilize bio-related coarse or fine aggregates is evaluated through mechanical tests, absorption measurements, and exposure conditions. Concrete with stone and several biomaterials as coarse aggregate is assessed for strength, density, and water uptake, which indicates the suitability of these aggregates in structural applications [10,12,29]. Green flowable sand concrete, containing seashell-based cementitious material and granite waste as fine aggregate, is studied for its mechanical and durability properties to characterize the performance of such hybrid mixtures [8,29,42]. The use of oil palm clinker in lightweight concrete and reinforced beams is examined in relation to flexural cracking, stiffness, and long-term response, with tests reported for compressive strength, tensile strength, and modulus of elasticity [35–37]. Reviews on palm oil and its by-products in bio-concrete and bio-asphalt mixtures discuss long-term behavior of these constituents in binders and aggregates [13,37,38]. Rubber/crete reviews examine mixtures with tire-derived rubber from the perspective of strength loss, improved deformability, impact response, and fatigue-type behavior over time [7,39].

Binder-level biomaterials and alternative chemistries influence durability through modifications of hydrates, pore systems, and chemical stability. The development of rice husk ash as a cement substitute in green infrastructure involves assessing the strength and durability performance of ash-blended binders, which informs the application ranges [10,28,29]. Research on magnesium phosphate cement summarizes its setting, strength development, and service behavior in different environments, placing this binder in discussions of repair and specialized applications [6,7,30]. Reviews of microscopic reinforcement and nanoparticles show how refined hydrates and dense microstructures can reduce permeability and change resistance to aggressive solutions [31–33]. Reviews on biochar, cellulose, and lignin in concrete composites present these materials as potential cement substituents or modifiers, and refer to their influence on mechanical and durability parameters in a broad sense [18,34].

Durability is also discussed in the context of self-compacting and internally cured biomaterial concretes. Self-compacting concrete produced with biomaterial-based cement substitutes is evaluated in terms of

rheology, microstructure, mechanical behavior, and indicators related to durability, such as porosity and water absorption [7,34,50]. Fly ash-based concretes prepared with bio-admixtures as internal curing agents have been studied for their effects on shrinkage control, cracking, and strength evolution, which directly influence service performance [51,52,60]. Self-curing concrete with biomaterials as admixtures and concretes containing extracts of biomaterials for internal curing are examined in terms of moisture redistribution and time-dependent deformation under drying, which relate to durability through shrinkage and crack formation [9,41,53]. Bioconcrete with nano-silica is studied with an emphasis on its durability properties, connecting nano-scale modification with resistance to various degradation mechanisms [31,33,55].

Self-healing systems with biomaterials treat durability through crack management, sealing, and performance recovery. Reviews on encapsulation methods describe various methods for storing biomaterials within concrete, allowing them to be activated upon cracking, and summarize testing on healed specimens [53–55]. Studies on biomaterial-assisted self-healing for high-performance centrifugal concrete piles examine crack reduction and associated structural response under loading cycles [7,56]. Proposed frameworks for lightweight concrete with porous aggregate micro-reservoirs present aggregates as carriers of healing agents, where the porous phase participates in storing both water and agents [24,29]. Decision tree-based work on predicting the optimal biomaterial content and curing duration relates mix design and curing time to self-healing performance measures, such as strength recovery and crack closure [34,52,57].

Biocementation techniques, based on microbial or enzyme-induced calcium carbonate precipitation, address durability in soils and cemented layers formed through biological processes. Reviews on biomaterials synthesized via microbial-induced calcium carbonate precipitation describe the treated media in terms of stiffness and strength development, which are directly linked to performance under mechanical and hydraulic actions [14,43]. Mini reviews on enzyme-induced calcite precipitation report eco-friendly routes for biocement production and discuss general features of the stabilized material [2,14,45]. Assessment of biogrouting in sandy ground examines its applicability for ground improvement in terms of strength and deformation behavior [6,43,47]. Studies on microbial metabolic processes in biomaterials used for leak repairs have identified environmental and material factors that affect the sealing performance and stability of the repair in contact with water [6,44,46].

## 7 Future Trends and Research Directions

Future research on cement-based composites incorporating biomaterials is expected to remain at the intersection of materials science, environmental objectives, and structural performance, with continued pressure to reduce clinker content and align new systems with established reliability expectations in civil engineering. Previous studies indicate that work on biomaterials in concrete is expanding in volume and thematic diversity, while still requiring stronger connections between materials development, structural behavior, and environmental assessment. Within this context, multifunctional composites that combine structural capacity, moisture control, and environmental functions are emerging as a prominent direction, as shown in studies on hemp concretes, hemp–lime walls, biomaterial concrete walls with phase change materials, adsorptive aggregates, and biochar-based binders, where comfort, energy performance, and structural behavior are considered together.

Plant-based fibers and aggregates are likely to retain a central place, with growing emphasis on performance optimization and durability, as highlighted in work on natural fiber-reinforced composites, agricultural waste reinforcement, wood fibers in mortars, bamboo flexural members, and hemp-fiber concretes. Parallel to this, waste-based aggregates and binders incorporating glass, shells, rubber, and industrial by-products, such as oil palm clinker, align with circular economy goals. Future work is expected to refine mix design ranges, durability performance, and design guidance for these systems. Self-healing, internal curing,

and time-dependent behavior form another strong research strand, with biomaterials playing a visible role in encapsulated systems, biomaterial-assisted self-healing in structural members, porous aggregate micro-reservoir concepts, decision tree-based optimization of dosage and curing, and internal curing mixes that address shrinkage and early-age cracking.

Microbial and enzyme-based biomaterials, particularly those associated with microbial-induced and enzyme-induced calcium carbonate precipitation, are expected to remain crucial for eco-friendly ground improvement and cemented systems, with research needs focusing on scale, uniformity, environmental conditions, and performance monitoring. Advanced modelling, multi-scale analysis, and performance prediction are expected to guide many of these developments, drawing on existing computational frameworks for cementitious materials and extending them to bio-modified mixtures, impact-loaded systems, and self-compacting concretes. At building and urban scales, future work is likely to link biomaterial composites with energy performance, comfort, life cycle assessment, and urban densification strategies, while policy frameworks, standardization, and education will continue to shape adoption through test methods, certification, clearer reporting of performance data, and teaching approaches that familiarize designers and engineers with biomaterials. Overall, future trends suggest the need for integrated efforts in multifunctional performance, circular resource utilization, biological processes, and advanced modeling, combined with closer collaboration between materials science, structural engineering, environmental analysis, architecture, and regulatory bodies.

A recurring implementation barrier across biomaterial categories is that promising laboratory performance does not automatically translate into scalable, code-aligned construction practice. Plant-based phases introduce higher variability in properties and moisture affinity, which can increase transport and durability risks if mixture water demand, interface quality, and curing are not carefully controlled. Bio-derived ashes and fine modifiers can deliver performance gains, but only when processing consistency, fineness, and dispersion are managed, because otherwise results become dosage-sensitive and difficult to reproduce. Microbial and enzyme-based routes face additional barriers related to uniformity of treatment, environmental dependence of activation, and the need for robust verification protocols to confirm crack sealing and permeability reduction under service actions. Across all categories, limited field datasets and inconsistent reporting of durability indicators remain major constraints; therefore, long-term monitoring and harmonized test protocols are critical requirements for practical adoption rather than optional additions.

## 8 Conclusion

This review aimed to discuss how biomaterials are incorporated into cement-based composites and how this incorporation affects their physical, mechanical, durability, and environmental performance. It mapped the main biomaterial categories, synthesized reported behaviors, and outlined implications for sustainable cement-based construction. The findings indicate that biomaterials enter cement-based systems through several principal routes, including bio-derived binders and additions, plant-based fibers and aggregates, microbial and enzyme-based treatments, and waste-derived components such as shells, glass, rubber, and agricultural residues. Across these families, the literature reveals a strong interest in reducing clinker content, reusing waste streams, and assigning additional functions such as internal curing, self-healing, or moisture regulation. Reported physical and mechanical behaviors show that bio-based additions frequently alter density, stiffness, and strength through changes in porosity and transport properties, with documented trade-offs between lower density or enhanced energy absorption and reduced compressive strength in some mixtures, as well as evidence of improved crack control and toughness in fiber- or nano-modified systems. Durability and service performance emerge as central themes, with extensive work on hygrothermal response, moisture buffering, sorption, chemical exposure, cracking, and long-term stiffness, alongside

growing interest in self-healing systems based on encapsulated agents, microbial processes, and internal curing biomaterials. Environmental and life cycle assessments increasingly frame biomaterials in terms of embodied emissions, resource efficiency, and their roles in low-carbon envelopes and hybrid structures, underscoring the importance of linking mix design with whole-building performance. Future work should emphasize long-term field monitoring of biomaterial-based concretes in real structures, harmonized protocols for durability and mechanical testing, tighter integration of multi-scale modelling with life cycle assessment, and targeted case studies that connect material behavior with architectural and structural design decisions, so that biomaterial-modified cement-based composites can progress from experimental concepts to consistent, code-ready solutions in sustainable construction.

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