

# Study of Sustainable Building Materials and Their Application in Architecture

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***Abstract***—The construction industry is among the foremost contributors to global environmental degradation, accounting for approximately 36–40% of total energy consumption worldwide and generating close to 39% of all greenhouse gas emissions annually (Springer Nature, 2023). Cement production alone is responsible for roughly 8% of global CO<sub>2</sub> output, while the extraction of natural aggregates, manufacture of virgin steel, and production of synthetic insulation materials add further layers of ecological burden. In response to this crisis, a substantial body of research has emerged over the past three decades investigating sustainable alternatives to conventional construction materials — materials that reuse industrial by-products, draw on rapidly renewable biological resources, or fundamentally reimagine binding chemistry to reduce carbon intensity.

This comprehensive literature review synthesizes findings from four primary research sources alongside data drawn from recent peer-reviewed publications and industry reports (2020–2025). The materials examined span: supplementary cementitious materials including Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), and Silica Fume (SF); Recycled Aggregate Concrete (RAC); waste-derived additives including ceramic tile waste, plastic waste (PET), and steel slag; bio-based systems including bamboo-geopolymer composites, hempcrete, and cement-stabilized rammed earth (CSRE); industrially innovative alternatives including cold-formed steel (CFS), polymer concrete, ferrock, mycelium composites, and aerogel insulation. For each material category, this paper critically examines structural and mechanical performance data, thermal characteristics, durability behavior, life cycle environmental impact, and demonstrated architectural applications. Persistent barriers to adoption — regulatory, economic, and technical — are analyzed, and a structured set of policy and research recommendations is provided. The sustainable construction materials market, valued at USD 333.31 billion in 2024, is projected to reach USD 1,073.73 billion by 2034 at a compound annual growth rate of 12.41% (GlobeNewswire, 2025), underscoring the urgency and commercial opportunity of this transition.

***Index Terms***—sustainable building materials; supplementary cementitious materials; recycled aggregate concrete; bio-based composites; hempcrete; bamboo; cold-formed steel; life cycle assessment; green construction; circular economy; carbon emissions; eco-friendly architecture

## I. INTRODUCTION

Few sectors of the global economy carry as large or as urgent an environmental footprint as construction. Buildings and the infrastructure that supports them together consume more than one-third of the world's energy and emit nearly 40% of global greenhouse gases. Direct emissions from buildings reached just over 3 Gt CO<sub>2</sub> in 2019 — a 5% increase from 2010 levels — and if current trends persist, the built environment will become the world's single largest energy consumer by 2025, surpassing both transportation and manufacturing (Springer Nature, 2023). The construction sector also absorbs approximately 60% of all raw materials extracted from the Earth's lithosphere, placing severe pressure on finite natural resources including limestone, natural aggregates, and iron ore (Springer Nature, 2023).

At the core of this environmental challenge lies material choice. Ordinary Portland Cement (OPC), the binder in virtually all conventional concrete, requires the high-temperature calcination of limestone — a process that chemically releases large quantities of CO<sub>2</sub> and consumes enormous amounts of thermal energy. Natural aggregate mining reshapes riverbeds, fragments habitats, and generates landscape-scale ecological disruption. Construction and demolition (C&D) waste — the rubble from aging buildings and infrastructure — fills landfills and represents one of the largest solid waste streams in industrialized nations.

Against this backdrop, materials science research has produced a growing portfolio of sustainable alternatives that address these problems at source: industrial by-products that substitute for virgin materials; rapidly renewable biological resources that sequester carbon during growth; binders that cure without releasing CO<sub>2</sub>; and structural systems fabricated from recycled feedstocks. Yet despite decades of experimental evidence demonstrating the technical viability of these alternatives, mainstream adoption remains uneven, constrained by regulatory inertia, economic disincentives, and gaps in professional knowledge.

This paper addresses this gap by presenting a structured, critically original synthesis of sustainable building materials research, drawing on four primary research papers alongside recent peer-reviewed publications and industry reports published between 2020 and 2025. The objectives are: (i) to characterize the mechanical, thermal, and durability properties of all major sustainable material categories; (ii) to situate these materials within a life cycle assessment framework; (iii) to examine their realized and potential architectural applications; and (iv) to identify adoption barriers and formulate evidence-based recommendations for policymakers, architects, engineers, and researchers.

## II. SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS)

Supplementary Cementitious Materials (SCMs) are industrial by-products that partially replace Ordinary Portland Cement in concrete formulations. By substituting a portion of the most carbon-intensive ingredient in concrete, SCMs simultaneously reduce CO<sub>2</sub> emissions, consume waste streams that would otherwise require disposal, and — in most cases — improve long-term concrete durability. The three most extensively researched SCMs are Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), and Silica Fume (SF), each originating from a distinct industrial process and offering a different performance profile (Batikha & Mouna, 2020).

Recent research has further expanded the SCM palette to include Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SBA), Tire-Derived Fuel Ash (TDFA), and metakaolin — materials that extend sustainable cement replacement to agricultural and waste combustion by-products (NIH/PMC, 2021). However, GGBS, FA, and SF remain the materials with the most mature research base, the widest commercial availability, and the strongest regulatory acceptance.

### 2.1 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is produced when molten iron-making slag — the mineral residue of iron smelting — is rapidly quenched with water and ground to a fine powder. Its glassy, amorphous microstructure gives it latent hydraulic reactivity: in the presence of calcium hydroxide liberated during OPC hydration, GGBS undergoes pozzolanic reactions that progressively build additional cementitious compounds, densifying the concrete matrix and reducing porosity. Optimal substitution rates lie between 50% and 65% of OPC mass, within which range long-term compressive strength development typically surpasses that of plain OPC concrete, even though early-age (7-day) strengths may be somewhat lower (Oner & Akyuz, 2007).

The durability benefits of GGBS concrete are equally significant. Its refined microstructure sharply reduces chloride ion diffusivity, making GGBS concrete the material of choice for marine structures, coastal buildings, and below-grade infrastructure in saline environments. GGBS also suppresses alkali-silica reaction (ASR), mitigates sulfate attack, and reduces heat of hydration — important advantages for mass concrete elements such as foundations, retaining walls, and bridge abutments. Research confirms that when GGBS and SF are combined, they produce the lowest CO<sub>2</sub> intensity profiles across all concrete strength classes studied, with the greatest reductions in low-strength formulations below 30 MPa (Yang et al., 2017).

A ternary blend combining FA (15%), GGBS (10%), and SF (5%) — studied as Mix M3 in recent experimental work — achieved a 28-day compressive strength of 38.6 MPa, a flexural strength of 4.8 MPa, and a water absorption of just 2.81%, outperforming nominal OPC concrete on all three metrics simultaneously (STM Journals, 2026). This finding underscores the value of combined SCM strategies over single-material substitution.

## 2.2 Fly Ash (FA)

Fly Ash is captured from the exhaust flues of coal-fired power stations using electrostatic precipitators. Class F fly ash, derived from bituminous coal combustion, is predominantly pozzolanic — it does not harden independently but reacts with free calcium hydroxide to produce additional C-S-H gel, incrementally strengthening the concrete matrix over months and years. Fly ash is typically used at 25–30% replacement of OPC by mass, a range within which improved workability, reduced water demand, and enhanced long-term strength development are consistently reported (Jalal et al., 2015; NIH/PMC, 2021).

Durability improvements associated with FA substitution include reduced drying shrinkage, lower carbonation rates, and improved resistance to alkali-silica reaction. One important environmental consideration, however, concerns the long-term availability of fly ash: as the global energy sector transitions away from coal-fired power generation in response to climate policy, the reliability of fly ash supply chains may diminish significantly — a risk that warrants attention in long-term concrete specification strategy (NIH/PMC, 2016).

## 2.3 Silica Fume (SF)

Silica Fume is an ultra-fine by-product of silicon and ferrosilicon alloy manufacturing. With particle sizes approximately 100 times finer than OPC, SF possesses an exceptionally large reactive surface area that drives intense and rapid pozzolanic chemistry. Used at dosages of 5–15% of cement mass, SF dramatically densifies the microstructure through micro-void filling and accelerated C-S-H gel production. Adding up to 30% SF to GGBS-based geopolymer concrete has been shown to improve compressive, tensile, and flexural strengths by 30%, 25%, and 20% respectively compared to reference mixes (Nature/Scientific Reports, 2024).

SF is particularly valued in high-performance concrete for bridge decks, offshore structures, and aggressive industrial environments, where its impermeability and chemical resistance are decisive advantages. Its principal limitations are high cost and constrained market availability, both consequences of the relatively small scale of silicon metal manufacturing. For most standard structural applications, SF is neither economically nor logistically accessible at scale, making it a specialist additive rather than a mainstream solution (Wescott et al., 2010).

## 2.4 Environmental Significance of SCM Substitution

Across all SCM types, the environmental benefit of substitution follows a characteristic pattern: CO<sub>2</sub> intensity — measured as kilograms of CO<sub>2</sub> per cubic meter of concrete relative to compressive strength — drops sharply at replacement levels of 15–20%, with diminishing additional returns at higher substitution rates. GGBS-SF blends consistently achieve the lowest CO<sub>2</sub> intensity, followed by GGBS-FA combinations, with pure FA substitution yielding somewhat higher intensities at equivalent substitution rates (Yang et al., 2017). A comprehensive regulatory gap persists in many emerging markets — including UAE, India, and parts of Southeast Asia — where absence of jurisdiction-specific SCM standards prevents adoption even where material supply is available (Batikha & Mouna, 2020).

### III. RECYCLED AGGREGATE CONCRETE (RAC)

The twin pressures of rising natural aggregate demand and escalating construction and demolition (C&D) waste have made Recycled Aggregate Concrete (RAC) one of the most actively researched sustainability interventions in structural concrete engineering. Research output on recycled concrete aggregates indexed in Scopus grew dramatically between 2000 and 2024, reflecting both the urgency of the problem and the maturity of technical solutions (MDPI Buildings, 2024). RAC substitutes aggregates recovered and processed from demolished concrete structures for the virgin quarried stone used in conventional concrete production.

The European construction sector alone consumes approximately 50% of all raw materials available, creating severe resource and waste pressures that RAC is designed to address (NIH/PMC, 2022). In Japan, projections show that natural aggregate demand has been outpacing sustainable extraction capacity since the early 2000s, providing a practical mandate for recycled aggregate use at national scale. In the UAE, Bee'ah Company in Sharjah processes approximately 500,000 tonnes of C&D waste annually, with 70% (roughly 1,000 tonnes per day) being recovered for reuse — a model demonstrating large-scale RAC feedstock production viability (Batikha & Mouna, 2020).

#### 3.1 Properties and Structural Behavior

The structural performance of RAC is governed by the interfacial transition zone (ITZ) — the boundary region between aggregate particles and the surrounding cement paste matrix. Recycled aggregates retain a layer of hardened old mortar attached to their original stone surface, introducing secondary ITZ interfaces into the concrete that create zones of stress concentration and elevated permeability. As a result, RAC typically exhibits lower compressive strength (reductions of 10–30% depending on replacement ratio), reduced tensile capacity, greater water absorption (5–12% higher than natural aggregate concrete), and diminished resistance to chemical ingress compared to conventional concrete at equivalent mix proportions (Xiao, 2018; MDPI Buildings, 2024).

Research on optimal RCA replacement ratios indicates that 10–30% substitution of fine RCA maintains mechanical performance closest to natural aggregate concrete, with higher replacement ratios requiring compensating mix design measures (MDPI Resources, 2024). Recycled Concrete Aggregates (RCA) from well-controlled demolition sources consistently outperform Mixed Recycled Aggregates (MRA) from heterogeneous C&D waste streams in terms of quality and homogeneity (NIH/PMC, 2022).

#### 3.2 Strategies to Improve RAC Performance

Multiple effective strategies for closing the RAC performance gap have been established by research. Surface modification of recycled aggregates — including acid washing, polymer coating, pozzolan slurry pre-soaking, and calcium carbonate biodeposition — reduces the porosity and improves the adhesion of the old mortar layer (NIH/PMC, 2025). Introduction of SCMs into RAC mixes is particularly effective: fly ash and GGBS pozzolanic reactions fill micro-voids within the

ITZ and densify the paste-aggregate interface, recovering a substantial portion of strength and durability losses attributable to aggregate recycling (Kou et al., 2011).

Advanced research combining FA, GGBS, and SF in 100% recycled aggregate geopolymer concrete demonstrated that an optimal blend ratio of FA:GGBS:SF = 35:50:15 produced the lowest mass loss and compressive strength degradation when exposed to 5% H<sub>2</sub>SO<sub>4</sub>, 5% Na<sub>2</sub>SO<sub>4</sub>, and 5% MgSO<sub>4</sub> solutions for 180 days — confirming that multi-SCM strategies can deliver both structural and durability performance from fully recycled feedstocks (ScienceDirect, 2023). Recent UAE-based experimental work further confirmed that locally sourced recycled coarse aggregates combined with GGBS and silica fume substitution meet international standard performance criteria for structural concrete over 180-day testing periods (NIH/PMC, 2025).

### 3.3 Barriers to Widespread Adoption

Despite strong technical evidence, RAC adoption in structural applications remains constrained by systemic barriers identified across multiple studies. These include: weak fiscal incentives creating no economic motivation for developers; inconsistent aggregate quality across recycling facilities; client and contractor skepticism shaped by unfamiliarity; absence or inadequacy of structural RAC specifications in national building codes; and geographic distance between C&D waste generation sites and processing facilities (Silva et al., 2017; Patel & Rathore, 2024). Addressing these barriers requires coordinated action across testing standards development, supply chain infrastructure investment, financial incentive design, and professional education programs.

## IV. WASTE-DERIVED MATERIAL ADDITIVES

### 4.1 Ceramic Tile Waste

Global ceramic tile production exceeds 12.3 billion square meters annually, with ceramic waste (CW) estimated at approximately 30% of production volume due to manufacturing defects and transportation damage. Ceramic Waste Powder (CWP) — generated at approximately 19 kg per square meter during the final polishing phase of tile manufacturing — amounts to an estimated 234 million tonnes of fine reactive silica-alumina material produced globally each year with no established mainstream reuse pathway (El-Dieb et al., 2019).

Ceramic materials contain reactive silica and alumina phases capable of pozzolanic participation in concrete chemistry. Replacement of OPC with CWP at 20–30% levels yields concrete with improved durability — reduced water absorption and enhanced chemical attack resistance — without unacceptable compressive strength reduction. Replacement levels beyond 30% begin to reduce strength below acceptable structural thresholds (Batikha & Mouna, 2020).

A landmark study funded by the EXPO 2020 University Innovation Program tested multi-stream recycled concrete incorporating CWP (20% cement replacement), Ceramic Fine Aggregate/CFA (20% sand replacement), and 100% coarse aggregate replacement by Recycled Coarse Aggregate (RCA). The optimal Mix M8 achieved: cylindrical compressive strength of approximately 46 MPa; cost savings of approximately 22% relative to fully conventional concrete; CO<sub>2</sub> emissions

approximately 23% lower than the reference mix; and recycled content of 47% by mass of concrete ingredients. A Beneficial Index — defined as compressive strength divided by the product of cost and emissions — showed Mix M8 delivering 66% superior combined value over the control mix (Batikha & Mouna, 2020). This represents one of the most compelling multi-variable demonstrations of waste-derived concrete optimization published to date.

#### 4.2 Post-Consumer Plastic Waste (PET)

Approximately 515 million tonnes of plastic are produced globally each year, with Polyethylene Terephthalate (PET) — used in beverage and water bottles — constituting a particularly high-volume, low-recovery fraction of this stream. Incorporating processed PET into concrete addresses both plastic waste accumulation and specific concrete performance requirements simultaneously. In fiber form, PET additions improve flexural toughness, post-crack energy absorption, and impact resistance — properties relevant to pavements, flooring, and infrastructure (Kim et al., 2010). As a particulate aggregate replacement, PET's low density (significantly lower than natural sand or gravel) reduces concrete unit weight, which is architecturally advantageous wherever structural self-weight governs design: upper floors of tall buildings, long-span slabs, and lightweight prefabricated elements (Pelisser et al., 2012).

The fundamental technical challenge with PET in structural concrete is the poor bond between the smooth, hydrophobic plastic surface and the surrounding cement paste, which limits compressive strength achievable without compensating measures. Surface treatment of PET particles — mechanical roughening, chemical etching, or plasma treatment — improves interfacial adhesion and has been the subject of ongoing research at institutions including Heriot-Watt University Dubai (Batikha & Mouna, 2020).

#### 4.3 Steel Slag

Steel slag is the mineral by-product separated from molten iron during steelmaking. Global steel production has grown substantially over recent decades, proportionally increasing slag accumulation. Current recycling rates remain below 50% in many countries, representing both an environmental liability and a significant underutilized resource (Song et al., 2021). In its raw state, steel slag contains free lime and magnesia that expand upon hydration and heavy metals including chromium and lead that pose leaching risks — necessitating treatment before construction use.

Following crushing, magnetic separation, and either controlled aging or accelerated carbonation, steel slag becomes a structurally useful material: hard, abrasion-resistant, and possessing latent hydraulic cementitious reactivity. Its long-term contribution to concrete compressive strength can approach that of OPC mixes, though this gain materializes gradually over months rather than within the standard 28-day window (Wang et al., 2013). Accelerated carbonation treatment — exposing slag to concentrated CO<sub>2</sub> — both stabilizes expansive phases and permanently sequesters atmospheric carbon within the slag matrix, creating a material with a net-negative embodied carbon balance for this phase of processing (Song et al., 2021). Treated steel slag has successfully

been applied in road base layers, pre-cast concrete elements, floor tiles, and artificial coral reef structures in marine restoration projects.

## V. EMERGING AND BIO-BASED SUSTAINABLE MATERIALS

### 5.1 Bamboo and Geopolymer-Bamboo Composites

Bamboo is among the most extraordinary structural materials available to architects and engineers: it reaches harvestable maturity in 3–5 years, its tensile strength along the fiber axis rivals mild steel in high-performance species, and it absorbs approximately three times more CO<sub>2</sub> during growth than most other plant species. The global bamboo construction market was valued at USD 68.5 billion in 2024 and is projected to reach USD 214.3 billion by 2034, driven by its carbon-capturing capabilities and expanding use in polymer composites that enhance durability (GlobeNewswire, 2025). Bamboo's biodegradability, low processing energy, and outstanding strength-to-weight ratio make it one of the most compelling structural material options for sustainable architecture globally.

Geopolymers offer a complementary and equally compelling environmental profile. Synthesized by activating aluminosilicate source materials — typically fly ash, calcined clay, or metallurgical slags — with alkaline solutions, geopolymers function as binders analogous to OPC but with dramatically lower embodied carbon. Comparative life cycle analyses consistently find geopolymer concrete to emit approximately 9% less CO<sub>2</sub> than OPC-based concrete, with some formulations achieving considerably greater reductions (Turner & Collins, 2013). Geopolymers additionally exhibit fire resistance, low shrinkage, and acid resistance that OPC concrete does not match.

Combined geopolymer-bamboo fiber composites have emerged as particularly promising materials. Bamboo fiber reinforcement introduces ductility and tensile resistance into geopolymer matrices that would otherwise be brittle, while the geopolymer binder protects bamboo fibers from alkaline degradation more effectively than OPC paste. Studies report flexural strength improvements of up to 3.5 times compared to unreinforced geopolymer, with simultaneous improvements in toughness and acid exposure resistance. These composites are increasingly fabricated into wall panels, floor tiles, and prefabricated structural elements suited to tropical and subtropical construction contexts (Sa Ribeiro et al., 2016; Kumar & Vasugi, 2020).

### 5.2 Hempcrete

Hempcrete is produced by mixing the woody inner core (shiv or hurd) of the hemp plant with a lime-based binder and water. Its environmental accounting is exceptionally favorable: hemp is a fast-growing annual crop that sequesters substantial CO<sub>2</sub> during growth, and lime binders re-absorb atmospheric CO<sub>2</sub> through recarbonation during their service life. Multiple Life Cycle Assessment studies confirm that hempcrete walls typically achieve negative net embodied carbon — meaning they sequester more CO<sub>2</sub> than is emitted during their production — making hempcrete

one of very few building materials with a verified carbon-negative status (Springer Nature, 2025; MDPI Buildings, 2025).

In September 2022, hemp building materials were incorporated into the US model residential building code, paving the way for legal use across American jurisdictions from 2024 onwards — a landmark regulatory development that signals growing mainstream acceptance (Reasons to be Cheerful, 2023). Hempcrete's principal structural limitation is low compressive strength (1–5 MPa), which restricts it to non-load-bearing infill and insulation roles requiring a separate structural frame. Within this role, it excels: its open-cell microstructure provides thermal insulation ( $\lambda = 0.06\text{--}0.11$  W/mK), effective vapor permeability supporting healthy interior humidity regulation, acoustic damping, and natural resistance to mold and insects. Eindhoven University of Technology and other European institutions are actively researching hempcrete in prefabricated modular panel systems to reduce construction waste and installation time (AZoBuild, 2025).

### 5.3 Cement-Stabilized Rammed Earth (CSRE)

Rammed earth construction has a verified heritage of thousands of years across diverse civilizations, evidenced by surviving sections of the Great Wall of China, Moroccan kasbahs, and vernacular architecture across South Asia and the Mediterranean. Contemporary Cement-Stabilized Rammed Earth (CSRE) introduces a small cement component — typically 5–12% by mass — to stabilize the traditional mixture of compacted coarse sand, gravel, clay, and silt within temporary formwork. The cement addition raises compressive strength and reduces moisture sensitivity while preserving rammed earth's signature thermal and ecological advantages (Zhang & Nowamooz, 2023).

CSRE walls function as thermal mass elements: their density and specific heat capacity allow them to absorb solar energy during the day and radiate it gradually at night, buffering interior temperatures against diurnal fluctuation. In climates with large day-night temperature swings — arid regions of India, the Middle East, and southern Europe — this passive thermal regulation can substantially reduce or eliminate mechanical cooling loads. Construction materials are typically sourced from the site itself, virtually eliminating transportation emissions and embodied carbon from material delivery. Applied research in Sri Lanka demonstrated 200mm CSRE walls meeting structural and thermal performance requirements for single-story residential construction, with the Meditation Centre project providing a documented pilot project reference (Kariyawasam & Jayasinghe, 2016).

### 5.4 Cold-Formed Steel (CFS)

Cold-Formed Steel (CFS) is produced by roll-forming thin steel coil stock — typically 0.5mm to 3mm thick — at ambient temperature without the high-temperature processing required for hot-rolled structural sections. Critically, CFS production uses recycled steel scrap — including end-of-life vehicles — as its primary feedstock, at an embodied carbon cost of approximately 200 kg CO<sub>2</sub> per tonne. This compares with approximately 2,000 kg CO<sub>2</sub>/tonne for conventional hot-rolled steel sections and a minimum of 500 kg CO<sub>2</sub>/tonne for cement clinker production — making CFS

from scrap one of the lowest-carbon structural materials available per unit of load-bearing capacity (Latawiec et al., 2018). Building a typical house using CFS framing requires approximately 6 recycled vehicles' worth of steel, whereas an equivalent timber-framed house requires 40–50 trees (Batikha & Mouna, 2020).

Comparative research at Heriot-Watt University Dubai demonstrated that CFS structural framing delivers total construction cost reductions of 34–39% compared to reinforced concrete and hot-rolled steel alternatives for equivalent two-story building scenarios, while completing construction in approximately half the calendar time of reinforced concrete construction (Doctolero & Batikha, 2018; Prasad, 2019). These advantages arise from dimensional precision enabling elimination of wet trades, lightweight allowing smaller plant and reduced crew sizes, and factory prefabrication enabling parallel on-site and off-site work streams. CFS was the structural system of the ORA House — Heriot-Watt University's entry in the Solar Decathlon Middle East 2018 competition — which ranked 4th out of 15 international teams in the construction and engineering innovation category.

### 5.5 Polymer Concrete

Polymer concrete replaces OPC with polymeric binders — typically polyester, epoxy, or methyl methacrylate resins — that cure through chemical crosslinking rather than hydration. The resulting material achieves compressive strengths substantially exceeding OPC concrete (50–120 MPa) alongside dramatically superior chemical resistance, permeability, and durability. Service lives exceeding 20 years in aggressive chemical environments have been documented — a durability advantage that justifies polymer concrete's higher unit cost in applications where conventional concrete would require repeated repair cycles (Kiruthika et al., 2021). Optimal polymer-to-aggregate ratios of 1:7 to 1:12 by mass balance performance and economy.

Polymer concrete is primarily used in specialist infrastructure: sewer rehabilitation linings, bridge deck overlays, chemical plant floors, underground utility structures, and acid-resistant pipe systems. Its low permeability and chemical inertness make it the material of choice wherever OPC concrete faces aggressive chemical exposure that would accelerate deterioration. From a life-cycle perspective, extended service intervals and elimination of repair cycles reduce total environmental impact relative to OPC concrete in these applications, even accounting for the higher embodied energy of resin binders.

### 5.6 Mycelium Composites

Mycelium composites represent one of the most genuinely novel material pathways in sustainable construction research. Fungal spores are inoculated onto agricultural waste substrates — hemp hurds, corn stalks, sawdust — and allowed to grow for several days, during which mycelial hyphae colonize and bind the substrate into a dense, cohesive composite. Growth is arrested by heat treatment, producing rigid, lightweight panels with thermal and acoustic insulation properties comparable to expanded polystyrene (Devi et al., 2023). Emerging commercial products including

MycoWood (COMU Labs) and Mycopanel (Myconom Bio Materials) demonstrate the transition from laboratory research to early commercial production (Revalu, 2025).

The environmental credentials of mycelium composites are exceptional: production requires no fossil fuel inputs beyond minimal heating, raw materials are agricultural residues with negligible intrinsic economic value, and the finished product is fully compostable at end of life. Life cycle CO<sub>2</sub> emissions are among the lowest of any building material category studied. Current applications focus on interior elements — insulation panels, acoustic tiles, wall panels, and furniture — where the material's modest compressive strength is sufficient. Architecture and design studios have incorporated mycelium into exhibition installations and bespoke interior environments, and structural applications are an active research frontier.

### 5.7 Ferrock

Ferrock is an experimental binder material derived from waste steel dust — a metalworking by-product — combined with silica from recycled glass. Unlike OPC, which releases CO<sub>2</sub> as calcium carbonate decomposes during clinker production, ferrock cures through a process that chemically incorporates atmospheric CO<sub>2</sub> as iron carbonate into its crystalline structure. This carbon mineralization mechanism makes ferrock a carbon-sequestering material, achieving a net-negative embodied carbon balance over its service life (Devi et al., 2023; Accoya, 2025). Laboratory testing has demonstrated compressive strengths substantially higher than OPC concrete alongside exceptional resistance to seawater and salt environments.

Ferrock represents a critical proof of concept for zero-carbon structural binder chemistry: demonstrating that industrial waste feedstocks can produce a material that is simultaneously stronger than conventional concrete and carbon-negative in its life cycle. Current barriers include high production cost relative to OPC and limited manufacturing scale. As research investment grows and production processes are refined, ferrock has significant potential for niche structural applications in aggressive marine and coastal environments where its salt resistance is most valuable.

### 5.8 Aerogel Insulation

Aerogels are nanoporous silica-based materials produced through supercritical drying of gel precursors, resulting in structures that are more than 90% air by volume. This extreme internal porosity yields thermal conductivity values of 0.013–0.017 W/mK — approximately two to three times lower than the best conventional insulation materials including mineral wool, expanded polystyrene, and polyisocyanurate foam board. In architectural applications, aerogel-incorporated blankets, renders, and board insulation enable ultra-thin envelope assemblies to achieve near-Passivhaus thermal performance targets that would otherwise require wall thickness increases of 100–200mm using conventional insulation.

Aerogel insulation is increasingly applied in historic building retrofits — particularly where planning authorities restrict the addition of significant wall thickness — and in premium new construction targeting net-zero operational energy standards. Hemp Fibre Insulation (Ekolution

AB) represents a bio-based insulation alternative combining hemp fiber's natural thermal properties with environmental advantages (Revalu, 2025). The primary barrier to aerogel's wider adoption remains manufacturing cost, currently placing aerogel products significantly above conventional insulation alternatives. Ongoing development in precursor materials and manufacturing scale suggests cost improvement trajectories over the coming decade.

## VI. COMPARATIVE ANALYSIS OF MATERIAL PROPERTIES

The tables below present synthesized performance data drawn from experimental literature. Values represent typical reported ranges across multiple studies; actual performance depends on specific formulation, curing conditions, and testing standards applied.

Table 1: Mechanical Properties of Sustainable vs. Conventional Materials

Material	Compressive Str. (MPa)	Tensile Str. (MPa)	Flexural Str. (MPa)	Density (kg/m <sup>3</sup> )
OPC Conventional Concrete	25–50	2–5	3–5	2200–2500
GGBS-Blended (60% sub.)	28–55	2–5	3–6	2100–2400
FA-Blended Concrete (40%)	25–48	2–5	3–5	2100–2350
Ternary SCM Blend (Mix M3)	38–42	3–5	4.8	2100–2300
Recycled Aggregate Concrete	20–45	2–4	2.5–5	2100–2350
Ceramic Waste Concrete (M8)	~46 (cyl.)	2–4	3–5	~2200
Polymer Concrete	50–120	8–20	10–30	2200–2400
Geopolymer Concrete	40–65	4–8	6–12	2100–2300
Bamboo (fiber axis)*	40–80	100–350	100–150	600–900
Cold-Formed Steel (yield)*	280–550	280–550	N/A	7850
CSRE Wall Panels	2–12	0.5–2	0.1–0.5	1800–2200

Material	Compressive Str. (MPa)	Tensile Str. (MPa)	Flexural Str. (MPa)	Density (kg/m <sup>3</sup> )
Hempcrete	1–5	0.5–1	0.2–1.0	200–500
Steel Slag Concrete	35–60	3–6	4–8	2300–2500
Straw Bale (wall system)	0.2–0.5	—	1–2	80–120

\* *Bamboo values along fiber axis. CFS values = yield and tensile strength of steel strip.*  
*Sources: Abera (2024); Batikha & Mouna (2020); Bedi et al. (2013); Sa Ribeiro et al. (2016); STM Journals (2026); Wang et al. (2013); Kariyawasam & Jayasinghe (2016).*

Table 2: Thermal and Environmental Properties

Material	$\lambda$ (W/mK)	CO2 eq (kg/m <sup>3</sup> )	Embodied Energy (MJ/m <sup>3</sup> )	End-of-Life Pathway
OPC Conventional Concrete	1.4–2.0	200–300	1,500–2,000	Limited recycling
GGBS-Blended (65%)	0.9–1.6	80–130	900–1,200	Recyclable aggregate
Recycled Aggregate Concrete	0.7–1.2	150–220	1,100–1,600	Re-recyclable
Ceramic Waste Concrete	0.8–1.4	~155	~1,200	Recyclable aggregate
Cold-Formed Steel (scrap)	50 (steel)	~150	~1,400	100% recyclable
CSRE	0.5–1.1	30–80	100–300	Returns to soil
Bamboo composites	0.04–0.17	~50	~200	Biodegradable
Hempcrete	0.06–0.11	Carbon-negative	~250–350	Fully biodegradable
Steel Slag Concrete	0.8–1.4	120–200	1,000–1,500	Recyclable
Straw Bale	0.05–0.09	Carbon-negative	~50	Compostable
Mycelium composites	0.04–0.08	10–30	50–120	Fully compostable

Material	$\lambda$ (W/mK)	CO2 eq (kg/m <sup>3</sup> )	Embodied Energy (MJ/m <sup>3</sup> )	End-of-Life Pathway
Ferrock	—	Carbon-negative	~600	Stable mineral inert
Aerogel insulation	0.013–0.017	~120–200	~2,000–3,000	Specialty recycling

Sources: Turner & Collins (2013); Yang et al. (2017); Latawiec et al. (2018); Song et al. (2021); Walker & Pavia (2014); Springer Nature (2025); Devi et al. (2023); Kymalanien & Sjoberg (2008).

## VII. LIFE CYCLE ASSESSMENT (LCA) FRAMEWORK

Life Cycle Assessment (LCA) is the methodological backbone of evidence-based environmental decision-making in construction material selection. It tracks resource consumption and emission generation across four phases: (1) raw material extraction and processing; (2) manufacturing and fabrication; (3) service life use, maintenance, and repair; and (4) end-of-life management including reuse, recycling, or disposal. The quantitative output — most commonly expressed as kg CO2 equivalent per functional unit — allows direct, scientifically grounded comparison of materials that may appear equivalent on purely structural grounds (Abera, 2024).

### 7.1 LCA Emission Estimation

The generalized emission estimation equation applied across LCA studies in the construction materials literature is:

$$E = A \times EF \times (1 - ER / 100)$$

Where: E = total emissions (kg CO2 eq); A = activity rate (mass or volume of material produced); EF = emission factor for the material (kg CO2 per unit); ER = overall emission reduction efficiency (%) accounting for recycled content, substitution effects, or process optimization (Abera, 2024). This formulation enables scenario comparison across material types, substitution ratios, and geographic contexts.

### 7.2 Key LCA Insights from the Literature

Several consistent conclusions emerge across LCA studies of sustainable building materials. First, environmental benefit from SCM substitution or recycled content addition is non-linear: the reduction in CO2 intensity per percentage point of substitution is greatest at moderate replacement levels (15–30%) and diminishes at very high substitution rates where structural performance penalties require compensating mix design measures. Second, the end-of-life phase is frequently underweighted in single-score assessments, yet for materials with high recycling or biodegradation potential — CFS (100% recyclable), bamboo, hempcrete, mycelium — it represents significant credit that improves comparative environmental standing. Third, transportation energy — the

embodied cost of moving bulk materials from source to site — can substantially erode the environmental advantage of materials produced far from the point of use, giving locally sourced CSRE, SCMs, and site-processed RAC a structural advantage in regional LCA contexts (Abera, 2024).

## VIII. ARCHITECTURAL APPLICATIONS

### 8.1 Structural Framing Systems

Cold-Formed Steel framing has achieved meaningful market penetration in residential and light commercial construction across North America, Australia, and the Middle East, valued for dimensional precision, seismic resilience, and compressed erection timelines. Research demonstrates CFS viability for primary structural frames in buildings up to four stories, foundation systems, and load-bearing wall panels — a versatility demonstrated by the ORA House project (Doctolero & Batikha, 2018). Engineered bamboo products including Laminated Bamboo Lumber (LBL) and Cross-Laminated Bamboo (CLBa) panels are gaining traction in South and Southeast Asia as structural alternatives suited to high-rainfall, seismic, and resource-limited construction contexts.

### 8.2 Building Envelope and Wall Systems

Hempcrete infill walls deliver exceptional thermal insulation ( $\lambda = 0.06\text{--}0.11$  W/mK), natural vapor management, and acoustic attenuation — a combination ideally suited to residential buildings in temperate climates targeting Passivhaus or near-zero energy performance standards. CSRE walls achieve a complementary balance: their elevated thermal mass creates a thermal flywheel effect that is most valuable in climates with pronounced diurnal temperature variation, dampening interior temperature peaks without active mechanical systems. Straw bale walls, when detailed with breathable lime plaster and moisture management layers, achieve some of the lowest thermal conductivity values of any structural wall system, and have been successfully deployed in affordable housing, educational buildings, and community facilities across Europe and North America.

Aerogel-enhanced renders and board insulation are increasingly applied to existing masonry building exteriors — including listed and heritage structures where planning restrictions prohibit significant additional wall thickness — enabling deep retrofit to near-Passivhaus thermal performance with minimal visual impact on historic fabric.

### 8.3 Concrete Structural Elements

For conventional concrete structural elements — slabs, beams, columns, foundations, and pavements — the primary sustainable interventions are SCM substitution (GGBS, FA, SF), RAC incorporation, and integration of waste-derived additives such as ceramic waste powder, PET fiber, and steel slag aggregate. These strategies are not mutually exclusive; multi-stream mix designs combining several sustainable inputs have demonstrated cumulative benefits. The EXPO 2020-

funded Mix M8 — incorporating CWP, CFA, and RCA simultaneously — is the most comprehensively documented example of multi-stream optimization achieving simultaneous structural, economic, and environmental performance improvements (Batikha & Mouna, 2020). Polymer concrete occupies a specialized niche in infrastructure rehabilitation where its impermeability and chemical resistance make it the material of choice for bridge deck overlays, sewer lining, and industrial plant flooring. Geopolymer concrete is increasingly specified for precast structural elements, particularly in corrosive environments where its superior chemical resistance delivers decisive service-life advantages over OPC concrete.

#### 8.4 Interior Elements and Circular Economy

Sustainable material application extends beyond structure and envelope into interior finishing. Recycled glass aggregates, processed into terrazzo flooring, countertops, or wall tiles, divert high volumes of glass from landfill while producing aesthetically distinctive, durable surfaces. Mycelium composite panels, grown into bespoke forms using digital molds, provide architects with customizable, simultaneously insulating, acoustic, and biodegradable interior surfaces that align with circular economy principles. Cork wall and floor coverings — harvested from cork oak bark without felling the tree, and carbon-storing in their cellular structure — offer a renewable interior finish with exceptional acoustic and thermal performance (Accoya, 2025).

The circular economy principle — designing building systems for material recovery and reuse at end of life — is increasingly shaping sustainable material specification. Materials with documented closed-loop pathways (CFS, steel slag concrete, recycled glass, bamboo, hempcrete) reduce the permanent environmental liability associated with construction. Building material passports — digital records embedded in Building Information Models documenting material identity, volume, condition, and recovery potential — are being piloted in European sustainable construction projects as tools for enabling genuinely circular building material flows.

## IX. CHALLENGES, BARRIERS, AND RESEARCH GAPS

### 9.1 Regulatory and Standards Deficit

The single most consistently cited barrier to sustainable material adoption across the reviewed literature is the absence of updated, jurisdiction-specific building codes and material standards recognizing alternative materials as structurally viable options. In many markets — including UAE, India, and large parts of Southeast Asia — materials such as RAC, ceramic waste concrete, and hempcrete are not authorized for structural use despite substantial published evidence of technical adequacy. This regulatory lag forces each project team to bear the burden of individual justification, adding cost, time, and risk that most developers are unwilling to absorb. Industry-university-government partnerships modeled on frameworks that have produced structural RAC codes in some European and East Asian contexts offer the most viable path to closing this gap.

### 9.2 Economic Incentive Misalignment

Construction procurement in most markets operates on lowest-initial-cost logic that systematically disadvantages sustainable materials whose primary economic advantages — reduced maintenance, lower operational energy, longer service life — materialize over the building's operational life rather than at the point of material purchase. Life-cycle cost analyses consistently demonstrate long-term financial superiority of sustainable materials over conventional alternatives, but procurement structures comparing only first cost obscure this advantage. Carbon pricing, material-specific taxes on virgin aggregate and virgin cement extraction, and mandatory green procurement thresholds for public contracts are the most structurally effective policy instruments for correcting these market distortions.

### 9.3 Technical and Performance Data Gaps

Most experimental studies on sustainable materials have been conducted under controlled laboratory conditions; long-term field performance data from real building structures — particularly in tropical, arid, and coastal climates — remains comparatively scarce. For emerging materials including mycelium composites, bamboo-geopolymer panels, ferrock, and aerogel-integrated wall assemblies, even the laboratory evidence base is thin. Standardized testing protocols tailored to the specific failure modes and durability mechanisms of sustainable materials — rather than applying OPC concrete test standards to fundamentally different material types — are needed to produce data structural engineers can use with professional confidence.

### 9.4 Prioritized Future Research Directions

- Long-term (15–25 year) field performance monitoring programs for RAC and SCM-blended concrete across diverse climatic regions
- Development and international harmonization of LCA datasets for emerging materials: ferrock, mycelium, aerogel, and geopolymer-bamboo composites
- Systematic optimization of multi-stream waste concrete mixes (SCMs + ceramic waste + PET fiber + RCA) across all structural strength classes
- Urban-scale economic modeling of sustainable material adoption scenarios incorporating supply chain co-benefits and C&D waste processing infrastructure costs
- Material-specific building code frameworks enabling accelerated regulatory adoption cycles
- Research on compatibility of SCM-blended, geopolymer, and bio-based binder formulations with robotic assembly and 3D concrete printing workflows

## X. POLICY RECOMMENDATIONS

The evidence synthesized in this review supports a clear policy imperative: the construction sector's transition to sustainable building materials will not occur at the necessary pace through voluntary market action alone. The following recommendations are drawn from cross-disciplinary synthesis:

- Mandate revision of national building codes to formally incorporate performance-based standards for RAC, SCM-blended concrete, hempcrete, CFS, and bamboo structural systems within defined five-year timelines.
- Introduce carbon pricing or material-specific levies on virgin aggregate and virgin cement production to correct market price signals and enable sustainable materials to compete on a first-cost basis.
- Establish green public procurement requirements stipulating minimum sustainable material content thresholds (e.g., 30% recycled content, maximum embodied carbon per m<sup>2</sup>) for all publicly funded construction.
- Fund dedicated national research programs on long-term field performance monitoring, sustainable material LCA database development, and digital fabrication compatibility.
- Integrate sustainable construction material design into architecture, civil engineering, and construction management curricula at undergraduate and postgraduate levels.
- Expand LEED, BREEAM, IGBC, and EDGE green building certification programs and link government incentives — expedited permitting, property tax reductions, density bonuses — to certification achievement.
- Support development of building material passport systems integrated with BIM platforms to enable circular economy planning and end-of-life resource recovery.
- Establish international knowledge exchange frameworks enabling developing economies to adapt regulatory models, testing standards, and supply chain approaches from more advanced sustainable construction markets.

## XI. CONCLUSION

This comprehensive literature review has synthesized research spanning four foundational papers and over thirty additional sources published between 2010 and 2025, presenting a structured and critically original assessment of sustainable building materials and their application in architecture. The findings are unambiguous in their technical conclusions: across every material category examined, viable sustainable alternatives to conventional construction materials exist, have been experimentally validated, and in many cases deliver structural, economic, and environmental performance that equals or exceeds their conventional counterparts when properly specified and applied.

Supplementary cementitious materials offer an immediately deployable pathway to reducing concrete's carbon intensity without sacrificing long-term structural performance; combined SCM strategies — particularly GGBS-SF and ternary blends — achieve the most significant environmental improvements. Recycled Aggregate Concrete, supported by surface modification and SCM enhancement strategies, can meet structural performance criteria while diverting vast quantities of demolition waste from landfill. Multi-stream recycled concrete mixes combining ceramic waste, plastic fiber, and recycled aggregate represent a frontier of optimization that simultaneously addresses structural, economic, and environmental objectives. Bio-based materials

— bamboo-geopolymer composites, hempcrete, CSRE — demonstrate that genuinely carbon-negative or carbon-neutral structural and envelope systems are not theoretical concepts but demonstrated, deployable realities. Cold-Formed Steel from recycled scrap provides structural framing performance superior to conventional alternatives at substantially lower cost, build time, and embodied carbon. Emerging materials including mycelium composites, ferrock, and aerogel insulation represent transformative opportunities whose commercialization trajectories warrant sustained research investment.

The sustainable construction materials market is already at USD 333.31 billion and growing at over 12% annually — the commercial transition is underway (GlobeNewswire, 2025). What remains is to close the gap between what research has demonstrated and what mainstream construction practice has adopted. That gap is a governance, economic, and educational challenge — and closing it represents one of the most consequential contributions the architecture and construction professions can make to the challenge of sustainable development in the twenty-first century.

The architecture profession, in particular, occupies a uniquely influential position: material choices made during the design process determine the environmental legacy of buildings that will stand for fifty, one hundred, or more years. Exercising that responsibility — thoughtfully, with the best available evidence, and with commitment to long-term environmental stewardship — is both a professional obligation and a meaningful contribution to a more sustainable world.

#### Declarations

#### Conflict of Interest

The author declares no conflict of interest with respect to the research, authorship, or publication of this article.

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#### Data Availability

All data supporting the findings of this study are drawn from published literature cited in the References section. No primary experimental data was generated in this review.

#### Ethical Statement

This article is a literature review and did not involve human participants, animal subjects, or clinical trials. No ethics approval was required.

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