

Innovative Structural Materials in Construction: Properties, Durability, and Sustainability

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Abstract

The construction sector is under growing pressure to reduce its carbon footprint while meeting increasing performance and durability demands. This article provides a comprehensive review of innovative structural materials that support the transition toward more sustainable civil engineering practice. The discussion covers high- and ultra-high-performance concretes, geopolymer concretes, natural-fibre-based “green” composites, concretes incorporating recycled waste materials, self-healing cementitious systems, and fibre-reinforced polymer (FRP) reinforcement. For each material group, the paper summarizes typical compositions, mechanical properties, and durability performance, with particular emphasis on compressive and tensile strength ranges, resistance to chemical and thermal attack, and long-term degradation mechanisms. Environmental aspects are analysed in terms of embodied CO₂, use of industrial by-products and renewable resources, waste valorisation, and life-cycle impacts related to extended service life and reduced maintenance. The review also identifies key barriers to large-scale implementation, including higher initial costs, lack of design standards, variability of waste-based constituents, and unresolved long-term performance issues. Finally, the paper outlines research and development priorities, such as hybrid material concepts, more robust design guidelines, and demonstration projects, and highlights the importance of coordinated action by researchers, industry, and policymakers to unlock the full potential of innovative materials in sustainable construction.

Keywords: innovative construction materials; ultra-high-performance concrete; geopolymer concrete; fiber-reinforced polymer (FRP) reinforcement

1. Introduction

Civil engineering faces a significant challenge related to sustainable development. The construction sector contributes substantially to carbon dioxide emissions and environmental degradation, primarily due to the widespread use of conventional Portland cement concrete. It is estimated that the production of Portland cement accounts for nearly 8% of global CO₂ emissions [1]. In response to increasing pressure to reduce the carbon footprint of structures, researchers and engineers are searching for new materials that can decrease the environmental impact of construction while improving the operational performance of built facilities.

A material “revolution” can currently be observed in sustainable construction, driven by the emergence of advanced engineering materials that not only enhance structural strength and durability but also deliver meaningful environmental benefits. Key innovations include high-performance concretes (including ultra-high-performance concretes) [2–5], green composites incorporating natural fibers [6–8], and the use of secondary raw materials (e.g., polymer recyclates) [9–13] as fully viable construction materials. For example,

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specialized high-performance concrete mixtures containing modern chemical admixtures and pozzolanic additives (such as fly ash or silica fume) enable the production of elements with increased strength and durability while reducing the consumption of cement and aggregates [5]. Green composites, composed of plant fibers (e.g., flax, hemp) embedded in a bio-resin matrix, exhibit unexpectedly favorable mechanical properties combined with reduced emissions associated with their production [6–8]. Moreover, the use of plastic waste as feedstock for construction materials aligns with circular-economy strategies and helps mitigate the growing problem of persistent plastic waste [9–13].

The implementation of these innovations results in several measurable environmental advantages. Reduced extraction of non-renewable raw materials, lower energy demand during production, and diminished greenhouse gas emissions collectively contribute to a more sustainable development of the construction sector [1, 14–17]. Furthermore, by improving the durability of structures—specifically their resistance to external factors and aging—their service life is extended, and the frequency of repairs and maintenance decreases. This further reduces the total environmental impact of a facility over its full life cycle. The integration of modern materials into engineering practice is therefore consistent with global efforts to minimize the ecological footprint of construction and make the sector more climate-friendly.

This article presents an overview of recent developments in the field of innovative structural materials from the perspective of materials engineering and civil engineering. The following material groups are discussed: high- and ultra-high-performance concretes [2–5], geopolymer binders [14–17], natural-fiber composites [6–8], materials derived from waste recycling [9–13], self-healing concretes [18–20], and composite structural reinforcements [21–23]. For each category, the composition, mechanical properties, and durability aspects are characterized, along with the potential environmental benefits associated with their application. The subsequent section provides a synthetic comparison of key performance parameters and discusses the prospects for large-scale implementation of these solutions. The conclusion summarizes the main findings and identifies directions for future research necessary to overcome existing barriers to the adoption of new materials in construction.

2. Literature Review

2.1. High-Performance and Ultra-High-Performance Concretes

High-performance concrete (HPC) represents an advancement over conventional concrete through the use of improved mix technologies—namely high-range water-reducing admixtures and mineral additives (e.g., silica fume, fly ash)—aimed at enhancing performance parameters. HPC is characterized by reduced porosity and higher strength compared with ordinary concrete (typically 20–40 MPa); compressive strengths above 60–80 MPa are commonly achieved [2–4]. High-performance concretes have been widely applied in bridge and high-rise construction, where significant load-bearing capacity and resistance to external environmental factors are required.

Ultra-high-performance concrete (UHPC) represents the next stage in concrete technology development and was introduced in the 1990s in response to the growing demand for materials exhibiting superior strength and durability. UHPC features a highly dense microstructure and dispersed reinforcement in the form of steel or synthetic fibers, enabling compressive strengths exceeding 150 MPa and tensile strengths of 15–20 MPa [3–5]. Owing to fiber reinforcement and optimized composition, UHPC exhibits pseudo-plastic post-cracking behavior (strain hardening) and high ductility. Key mixture components include a high cement content (often $>600 \text{ kg/m}^3$), a very low water-to-binder ratio (0.15–0.20), and additives such as colloidal silica, silica fume, and high-range superplasticizers. As a result, UHPC demonstrates extremely low permeability and enhanced resistance to environmental exposure—exhibiting improved protection against water ingress, freeze–thaw action, chloride penetration, and other aggressive agents relative to ordinary concrete.

The use of HPC and UHPC enables the design of more slender and lighter structural elements with extended service life. It should be noted, however, that UHPC production is associated with higher costs and increased energy demand (including the need for thermal curing) compared with conventional mixes. Ongoing research focuses on optimizing UHPC compositions through the partial replacement of high-emission cement with more environmentally friendly constituents (e.g., fly ash, slag) and through simplifying production procedures in order to reduce both the cost and carbon footprint of the material [4].

2.2. Geopolymer Concretes

Geopolymer concrete (GPC) is a class of binder-based materials in which conventional Portland cement is replaced with an alkali-activated binder derived from aluminosilicate-rich raw materials such as fly ash or ground granulated blast-furnace slag [14–17]. The process involves geopolymerization—under the action of alkaline hydroxides and silicates, the precursors form a three-dimensional network with an N-A-S-H structure (sodium aluminosilicate hydrate), which functions as the binding phase. Because geopolymer concretes do not require clinker calcination, their production generates significantly lower CO₂ emissions—estimated at 40–80% less than traditional Portland cement concrete [14–16].

In terms of performance characteristics, GPC matches conventional concretes and often surpasses them in chemical and thermal resistance [15–17]. Geopolymers contain negligible amounts of calcium hydroxide in the matrix, making them highly resistant to acids and sulfates—agents that cause severe degradation in ordinary concrete. They also exhibit strong stability at elevated temperatures: studies indicate that geopolymer concretes retain more than 90% of their strength even after exposure to approximately 800°C [14–16]. The mechanical strength of GPC typically reaches 60–80 MPa, and optimized mixtures exceed 80 MPa, enabling their use in structural elements with demanding strength requirements.

Despite their ecological and technical advantages, the widespread adoption of geopolymer technology faces several challenges [14, 16]. The properties of GPC are highly dependent on the quality and uniformity of fly ash or slag; variations in the composition of these industrial by-products result in fluctuations in strength and durability. Furthermore, optimal activation requires strict process control (e.g., alkali concentration, temperature, curing time), which can complicate implementation under construction-site conditions. A shortage of standards and design guidelines also persists—the lack of unified norms limits designers' and contractors' willingness to adopt GPC on a broader scale. Nonetheless, intensive research efforts are currently underway to overcome these limitations [15–17]. Recent literature reviews emphasize that GPC can successfully replace conventional concrete in various applications—from precast elements to cast-in-place structures—while providing measurable environmental benefits due to the use of industrial waste and reduced emissions. The development of execution standards and the wider dissemination of successful demonstration projects using geopolymers are expected to strengthen industry confidence in this technology in the coming years.

2.3. Natural Fibers and “Green” Composites

In recent years, construction composites reinforced with natural fibers have experienced a resurgence of interest as a sustainable alternative to traditional materials [6–8]. Plant fibers (e.g., hemp, flax, jute, bamboo) are renewable resources and do not pose health risks—they contain no toxic or irritant substances, in contrast to certain synthetic fibers. Additionally, their use can enhance the thermal insulation and sound-absorption properties of composites due to the intrinsic porosity and acoustic absorption capacity of plant fibers.

Natural fibers may be used as dispersed reinforcement in cementitious matrices (e.g., mortars, concretes) as well as reinforcement in polymer composites, replacing glass or carbon fibers [6–8]. In the former application, they act as micro-reinforcement, limiting the development of individual cracks and shrinkage-induced crack networks in drying or loaded mortars. Although they do not significantly increase compressive strength, they noticeably improve ductility, flexural strength, and the energy required to fracture the composite [6, 7]. For example, cement mortars modified with short hemp fibers—after appropriate surface treatment—exhibited higher tensile and flexural strength compared with unreinforced mortars, along with improved fiber–matrix bond performance [6–8]. This is consistent with the general observation that natural fiber modification enhances crack resistance and impact toughness.

Natural-fiber-reinforced polymer composites (e.g., flax or hemp laminates) also demonstrate promising mechanical properties. Despite the lower strength of individual plant fibers compared with glass fibers, properly oriented and resin-impregnated natural fiber laminates can achieve performance levels comparable to conventional composites, while offering a significantly lower carbon footprint during production [7].

The main limitation hindering the broader application of natural fibers lies in their physicochemical characteristics [8]. Plant fibers are hydrophilic—they absorb moisture, which may lead to swelling and weakened bonding with cementitious matrices. They also contain components such as hemicellulose and lignin that are susceptible to alkaline degradation in the cement environment. In addition, variability in fiber geometry

and composition (presence of pectins, waxes, impurities) complicates the attainment of repeatable composite parameters. To address these issues, various fiber modification methods are applied prior to incorporation into the matrix. Alkaline treatments (immersion in NaOH solutions) are commonly used to remove part of the amorphous components and increase surface roughness, thereby improving adhesion to the binder. Another approach employs coupling agents (e.g., silanes) that form an interfacial bonding layer on the fiber surface [6–8]. Research indicates that appropriate modification significantly improves the interaction between plant fibers and cement matrices, enhancing the strength and stiffness of the resulting composites.

Among natural fibers, hemp fibers are the most extensively studied and used due to their high specific strength, biological resistance, and beneficial impact on mixture rheology [6–8]. The growing interest in hemp-based construction materials (e.g., hempcrete—a composite of lime and hemp shiv) reflects a broader trend toward biomaterials in construction, particularly in buildings with a natural or ecological character. Although these materials do not reach the structural strength of traditional concrete, they find niche applications as wall infill, plasters, or insulation, offering good thermal performance and vapor permeability.

2.4. Recycled Construction Materials

The growing volume of waste and the depletion of natural resources necessitate the development of recycling strategies in the construction sector. One approach involves incorporating plastic waste into cement-based composites [9–13]. Since traditional concrete consists of approximately 70–80% aggregate by volume, a proposed solution is to replace part of the natural aggregate (sand or gravel) with granulated plastic waste or to introduce shredded polymer fibers into the matrix. Studies indicate, however, that direct substitution of sand with fine plastic particles leads to reduced strength and frost resistance—polymer particles do not bond effectively with the rigid cement matrix and can behave as internal inclusions that weaken the structure [11–13].

Promising results have been obtained using more advanced plastic processing methods. Researchers from MIT demonstrated that subjecting waste PET bottles to gamma radiation and subsequently grinding them into powder produces an additive that increases the compressive strength of concrete by up to 15% when incorporated into the cementitious matrix [12]. Concrete modified with this treated plastic exhibited noticeably higher strength compared with control specimens. The improvement mechanism is attributed to enhanced dispersion and surface activation of the polymer particles, which positively influences the microstructure of the interfacial transition zone between cement paste and aggregate. Importantly, this method enables the effective immobilization of PET waste within the concrete and reduces the amount of cement required in the mixture, thereby potentially lowering CO₂ emissions associated with production [9–13].

Another direction involves recycling concrete rubble from demolition as aggregate for new concretes. Such recycled concrete aggregate (RCA) is commonly used in less demanding structural applications and especially in road base layers [9, 10]. In structural concrete, replacing a substantial proportion of natural aggregate with RCA typically reduces strength and durability due to the presence of adhered mortar and increased porosity of the recycled particles. However, appropriate processing techniques—such as fractionation, removal of adhered mortar, or surface impregnation—can yield higher-quality RCA. In some studies, concrete made with 100% RCA achieved compressive strengths comparable to natural-aggregate concrete (approximately 50 MPa) [9–10]. In practice, moderate RCA contents (e.g., up to 30%) are recommended for structural concrete or for use in less critical elements [9, 10]. The key benefits include reduced extraction of sand and gravel and decreased quantities of demolition waste sent to landfills.

Other recycled materials are also explored: ground glass used as micro-aggregate (subject to appropriate treatment to prevent alkali–silica reaction), fibers from recycled tires to improve concrete ductility [13], and wood waste incorporated into composite materials [9–13]. Each of these solutions, however, requires careful evaluation in terms of its influence on the final material properties and the economic viability of the recycling process.

2.5. Self-Healing Concretes

The concept of self-healing concrete refers to the material's ability to autonomously seal developing microcracks before they propagate into larger fractures that compromise structural integrity [18]. Conventional concrete exhibits a limited capacity for autogenous crack closure—primarily through continued hydration of unreacted cement or precipitation of calcium carbonate from water permeating the crack—but this effect is

insufficient for larger cracks. For this reason, intensive research is underway to develop technologies that actively enhance the healing process [18–20].

One approach involves the use of microcapsules filled with a healing agent—such as a resin or monomer that polymerizes upon exposure to air. These capsules are incorporated into the concrete mixture; when a crack forms in the element, the capsules rupture and release the reagents, which fill the crack and harden, restoring structural continuity [18]. Another method employs mineral-precipitating bacteria. Selected bacterial strains (e.g., from the genus *Bacillus*) are added to the mixture together with nutrients and a calcium source (e.g., calcium lactate). When moisture enters a crack, the bacteria become active and, upon metabolizing the nutrients, produce calcium carbonate that precipitates and seals the fissure [19, 20]. This biological “filler” blocks the crack from within, limiting further water ingress.

Research confirms the effectiveness of both approaches at laboratory scale [18–20]. Bacteria immobilized in porous granules (which protect them from the highly alkaline cement environment) can fully heal cracks up to 0.5 mm wide within four weeks, provided the concrete is periodically moistened. A significant reduction in reinforcement corrosion has also been observed—the deposited calcium carbonate seals the cracks and prevents water and oxygen from reaching the steel. In one experiment, adding bacteria to concrete made with recycled aggregate not only enabled crack self-healing but also unexpectedly increased compressive strength by approximately 30% and significantly reduced water absorption compared with control mixes without bacteria [19, 20]. These findings indicate that biotechnology may also enhance other performance parameters of concrete.

Self-healing technologies are already entering practical implementation. The Dutch start-up Basilisk has developed commercial bacterial self-healing products used in several pilot infrastructure projects. For example, in 2015 a sewer segment was constructed using bacterial concrete, and in 2020 a cracked bus lane at Schiphol Airport was rehabilitated using a liquid bacterial repair agent. In the latter case, water penetration through cracks was reduced by approximately 93%, and the predicted service life of the pavement was extended by at least 15 years. Life-cycle analysis showed a 33% reduction in overall maintenance costs and a 90% reduction in CO₂ emissions associated with pavement upkeep compared with traditional repair methods. Economic feasibility remains a challenge—microcapsules with healing agents and specialized bacterial cultures significantly increase mixture cost. Ongoing research therefore focuses on optimizing these solutions, for example by seeking cheaper nutrient sources or methods for long-term bacterial activation. Another crucial requirement is the development of standardized testing methods to evaluate self-healing performance, as current design codes do not incorporate provisions for autonomous crack repair. Nonetheless, the development of “intelligent” concretes capable of self-maintenance aligns with the broader concept of smart materials and Construction 4.0 [18–20].

2.6. Composite Reinforcement for Structures (FRP)

Another breakthrough innovation in materials engineering is fiber-reinforced polymer (FRP) reinforcement, consisting of continuous fibers embedded in a polymer matrix. Traditional steel reinforcing bars are susceptible to corrosion, which is a primary cause of durability loss and costly repairs in reinforced-concrete structures. FRP bars, by contrast, are inherently corrosion-resistant—they do not rust even under highly aggressive conditions, making them ideal for structures exposed to marine salts or de-icing chemicals [21–23]. They are most commonly produced using glass fibers (GFRP) or carbon fibers (CFRP), and less frequently basalt or aramid fibers, bound with polymer resins (e.g., vinyl ester).

FRP bars exhibit exceptionally high specific strength. Glass-fiber reinforcement typically reaches tensile strengths of 600–1000 MPa, while carbon-fiber bars achieve 2000–2500 MPa, with a density approximately four times lower than that of steel [21, 22]. This means that a GFRP bar of the same diameter as a steel bar can provide 2–4 times higher tensile strength while weighing roughly 75% less. Such a high strength-to-weight ratio facilitates transportation and installation—long composite bars can be handled manually without heavy machinery, improving construction efficiency and reducing labor costs [21].

A further advantage is the non-magnetic and electrically insulating nature of FRP reinforcement, important in facilities containing equipment sensitive to electromagnetic interference (e.g., hospitals, MRI laboratories). In such applications, composite reinforcement eliminates disturbances that would otherwise be caused by steel [21–23].

From a sustainability perspective, the primary benefit of FRP reinforcement is the extended service life of structures. Since GFRP/CFRP bars do not corrode, concrete elements reinforced with them do not require thick protective cover (reducing concrete consumption) and are not vulnerable to corrosion-induced cracking and spalling. It is estimated that FRP-reinforced elements may retain their full load-bearing capacity for up to 100 years, whereas conventional steel-reinforced structures often require costly repairs or strengthening after 40–50 years due to corrosion [21–23]. Life-cycle cost analyses indicate that although FRP bars are more expensive initially (20–30% higher material cost than steel), the savings on maintenance and the extended service life often make them more economical in the long term.

Challenges associated with FRP implementation include the lower elastic modulus of GFRP (~50 GPa, about one-fifth that of steel), which can result in larger deflections—requiring compensation through design adjustments such as increased reinforcement ratios or larger cross-sections [21]. CFRP offers a higher modulus (~150–200 GPa) but is significantly more expensive than steel; thus it is used primarily where maximum strength and stiffness are required (e.g., prestressed elements, specialized bridge components). Another concern is the behavior of FRP in fire conditions—the polymer matrix softens and degrades at approximately 200–300°C, reducing bar strength. Consequently, FRP-reinforced elements require additional fire protection or the use of high-temperature-resistant resins and matrices [22]. Despite these limitations, the FRP reinforcement market is expanding rapidly—global value is projected to double between 2022 and 2030 (to approximately USD 2 billion) due to increasing demand for durable, maintenance-free materials in infrastructure [21]. More than one thousand bridge structures worldwide have been built using GFRP or CFRP reinforcement, and in some countries (e.g., Canada, Japan) such reinforcement has become standard practice for bridges exposed to severe chloride-induced corrosion [21–23].

3. Mechanical Properties and Durability of Materials

3.1. Strength

The use of innovative materials enables the attainment of significantly higher strength characteristics than those achievable in conventional construction. The highest values are observed in ultra-high-performance concretes, whose compressive strength exceeds 150 MPa (for comparison, a typical structural concrete C30/37 has $f_{cm} \approx 38$ MPa) [2–5]. With fiber reinforcement, the flexural strength of UHPC reaches several tens of megapascals. Traditional HPC also exhibits compressive strengths in the range of 60–100 MPa [2–4], enabling its application in heavily loaded elements such as high-rise buildings and large-span bridges. Despite the absence of Portland cement, geopolymers likewise achieve high compressive strengths of approximately 60–100 MPa and display enhanced chemical resistance (e.g., insensitivity to acids and sulfates) [14–17].

The addition of natural fibers is not intended to increase compressive strength—since such fibers are inherently weaker than steel—but it can enhance ductility and tensile or flexural strength through crack-bridging mechanisms [6–8]. For example, mortars containing chemically treated hemp fibers have shown double-digit percentage increases in flexural strength compared with unreinforced mortars [6–8]. In polymer composites reinforced with plant fibers (e.g., flax laminates), tensile strengths comparable to glass-fiber laminates (approximately 100–200 MPa) are achieved [7], making them attractive substitutes in lightweight structural elements.

Composite reinforcements (FRP) exhibit strengths far exceeding those of steel: GFRP bars typically reach ~600–800 MPa, with specialized versions exceeding 1000 MPa, while CFRP bars surpass 2000 MPa [21–23]. As a result, FRP-reinforced members can carry high tensile forces with relatively small bar diameters. However, due to the lower elastic modulus of glass fibers (approximately 50 GPa versus 200 GPa for steel), deflections may govern serviceability; for this reason, FRP is often used in combination with steel or in applications where durability rather than stiffness is the dominant design criterion [21–23].

3.2. Durability

Most of the innovative materials discussed exhibit markedly improved durability compared with traditional counterparts. Owing to its ultra-low porosity, UHPC is essentially impermeable to water and aggressive ions (chlorides, sulfates) [2–5]. Tests show zero strength loss after 300 freeze–thaw cycles, whereas ordinary concrete may deteriorate after roughly 100 cycles [2–4]. The presence of fibers also enhances fatigue

and abrasion resistance, contributing to UHPC's use in bridge deck overlays that exhibit significantly reduced cracking relative to conventional concrete.

Geopolymer concretes are notable for excellent chemical durability: they retain more than 90% of their strength after exposure to temperatures of several hundred °C and are insensitive to sulfates and other aggressive environments [14–17]. This makes them well suited for applications such as sewer systems, industrial facilities, and marine structures. Fiber additions (both steel fibers in UHPC and natural fibers) improve crack resistance and delay the development of shrinkage cracks, contributing to longer service life [6–8]. Natural-fiber concretes (e.g., incorporating wood fibers) also display improved thermal insulation and reduced susceptibility to thermal cracking.

Self-healing mechanisms—whether capsule-based or bacterial—directly extend durability by sealing cracks before they evolve into significant damage [18–20], thereby maintaining watertightness and protecting steel reinforcement from corrosion. Studies show that biochemical self-healing methods can close cracks up to 0.5 mm wide, a threshold of particular importance for preventing water and chemical ingress [19, 20].

Replacing steel reinforcement with FRP eliminates corrosion-related deterioration. Reinforced-concrete elements that typically suffer from concrete cover spalling due to rebar corrosion after several decades can retain full load-bearing capacity for significantly longer (50–100 years according to aging studies) when reinforced with composite bars [21–23]. Consequently, the need for carbon-intensive and costly repairs or strengthening during the service life is reduced. However, FRP requires fire protection (due to the low thermal resistance of polymer resins) and careful design consideration given its lower stiffness, as noted above.

4. Environmental Aspects and Sustainability

4.1. Reduction of CO₂ Emissions and Raw Material Consumption

The greatest potential for reducing the carbon footprint lies in replacing high-emission Portland cement with alternative binders. Geopolymer concretes, which utilize industrial by-products (fly ash, slag) and eliminate the clinker calcination process, reduce CO₂ emissions by 40–80% compared with standard concrete [14–17]. This reduction is highly significant in the context of global efforts to limit emissions and promote a circular economy. Conventional concretes can also be made more environmentally friendly by incorporating mineral admixtures. For example, replacing 30% of cement mass with fly ash reduces emissions associated with cement production by a similar proportion [14–17].

UHPC mixes do contain higher clinker content per cubic meter (and therefore higher initial emissions), but their exceptional strength enables the design of structures that use substantially less material overall (slender members, reduced concrete volumes) [2–5]. This compensates—and often outweighs—the initial “carbon cost.” Life-cycle assessments show that the reduced mass of UHPC structures and their extended maintenance intervals result in lower total emissions compared with structures made from ordinary concrete [1]. Moreover, longer service life reduces the frequency of repairs and the need to manufacture additional materials, which must also be accounted for in environmental evaluations.

Replacing non-renewable raw materials with renewable ones aligns with strategies aimed at reducing resource depletion. Natural plant fibers have a very low production carbon footprint [6–8]—plant cultivation sequesters CO₂, and fiber processing (e.g., mechanical separation, drying) is considerably less energy-intensive than the production of synthetic fibers or steel. Additionally, plant fibers are biodegradable, meaning that—at the end of their service life—they do not generate persistent waste. Their use in composites reduces the demand for conventional chemically derived fibers (glass, carbon), whose production processes are significantly more energy- and resource-intensive. It is estimated that producing 1 kg of glass fiber results in approximately 1.7 kg of CO₂ emissions, whereas 1 kg of hemp fiber generates only about 0.3–0.5 kg of CO₂ (even when emissions from cultivation and transport are included). For this reason, bio-composites offer a clear environmental advantage, providing comparable performance with a substantially lower climate impact.

The use of waste as legitimate raw materials in construction provides a dual benefit—it reduces the burden on landfills and decreases the consumption of natural resources (aggregates, cement). An example is the incorporation of PET plastic into concrete: under conventional waste management pathways, PET bottles would end up in a landfill or incinerator, whereas here they become part of a material structure for decades [11–13]. The MIT-developed technology, in which modified plastic replaces a portion of the cement, further

reduces clinker demand and lowers the carbon intensity of concrete [12]. Although this approach is still in the research phase, it is highly promising—each tonne of cement substituted with an alternative component corresponds to roughly 0.8 tonnes of avoided CO₂ emissions. The use of recycled aggregates also reduces energy consumption by avoiding quarrying, crushing, and transporting new aggregate [9–10]. Naturally, waste processing itself requires energy, which underscores the importance of developing highly efficient methods (e.g., on-site crushing of demolition debris).

Extending the service life of structures is a key principle of sustainable construction. The longer an asset remains operational without requiring repair or reconstruction, the lower the annualized material and energy consumption “assigned” to that structure. Innovative materials significantly contribute to this goal. The use of FRP reinforcement enables the design of bridges or parking structures that may not require replacement of reinforcement bars or repair of cracked covers caused by corrosion-induced expansion—potentially over their entire intended service life (75–100 years). This translates into substantial savings in steel, concrete, and fuel that would otherwise be consumed during maintenance operations. Self-healing concrete can also greatly reduce the need for routine sealing and maintenance—according to some sources, by as much as 30–40%. Reductions in repair frequency mean not only lower raw material usage but also decreased emissions from construction machinery and transportation. The example of Basilisk, where traditional milling and surface replacement were avoided on a road section, demonstrated over a 90% reduction in CO₂ emissions associated with maintaining that infrastructure—biological treatment was used instead of energy-intensive machinery and new concrete, and its carbon footprint was negligible compared with that of conventional repairs.

Energy aspects of material production must also be considered. Although UHPC and carbon fibers are energy-intensive to produce, FRP reinforcement is not necessarily so—the pultrusion process for composite bars consumes roughly 30% less energy than the production of steel reinforcement of equivalent length. Moreover, the absence of high-temperature processes (such as clinker burning in cement plants or iron smelting in blast furnaces) in many emerging technologies results in lower emissions of pollutants (NO_x, SO₂, particulate matter). In summary, innovative construction materials represent a vital component of the building sector’s decarbonization strategy—through both direct emission reductions (lower CO₂ from production) and indirect benefits (extended service life, fewer repairs, reduced consumption of primary raw materials).

5. Conclusions

The information presented above clearly demonstrates the considerable potential of innovative materials to improve the technical performance of structures while reducing their environmental impact. However, an important question remains: if these new technologies are so promising, why have they not yet become dominant in mainstream construction practice? The answer is linked to several limiting factors.

First, economic considerations—many of the materials discussed are still more expensive than their traditional counterparts. For example, UHPC requires the use of large quantities of cement and specialized constituents (fibers, nano-additives) [2–5], which significantly increases the cost per cubic meter. Similarly, despite price reductions in recent years, FRP reinforcement remains several tens of percent more expensive than steel reinforcement. Self-healing concretes, in turn, require costly microcapsules or bacterial cultures [18–20]. Investors and contractors often prioritize minimizing initial costs, leading them to choose cheaper, conventional solutions—even if these prove less economical over the full life cycle.

Second, the lack of standards and practical experience. The construction industry is relatively conservative—new materials must undergo a lengthy transition from laboratory research to construction sites. The development of design standards is essential (e.g., guidelines for FRP reinforcement design [23], formulas for dimensioning UHPC elements, or execution recommendations for geopolymer concretes) [2–5]. In the absence of such standards, engineers are often reluctant to take risks and instead opt for familiar materials backed by established design models. Practical knowledge is also limited—many contractors have never worked with geopolymer concrete or GFRP reinforcement, which creates uncertainty and concern about unfamiliar technologies [14–17]. The use of innovative materials frequently requires specialized supervision, crew training, and in some cases investment in new equipment (e.g., for pultrusion of composite bars or thermal curing of UHPC), which constitutes an additional barrier.

Third, each material category presents its own technical challenges. For geopolymers, a key issue is ensuring stable quality of fly ash or slag—their chemical composition may vary depending on the source, which affects the binding properties [14–17]. For natural-fiber composites, it is essential to protect fibers from biological and alkaline degradation and to ensure adequate fiber–matrix adhesion [6–8]. For self-healing systems, long-term retention of healing capability is critical—microcapsules must remain reactive for years, and bacteria must survive in a dormant state until activated by moisture; additionally, these agents must be uniformly distributed throughout the concrete matrix [18–20]. For FRP, challenges include long-term behavior under sustained loading (creep of polymer matrices), compatibility with other materials (e.g., the bond of FRP to concrete is often lower than that of steel and requires longer development lengths), and related issues. Each of these topics is currently the subject of active research [21–23].

Despite these limitations, the direction of development in the construction industry is clear: toward structures that are more efficient, durable, and environmentally responsible. The advancement of innovative materials aligns directly with these objectives. It is reasonable to expect that many of the current barriers will gradually be overcome. The costs of new technologies typically decrease with increased production scale and improved manufacturing processes (for instance, the price of carbon fiber has dropped several-fold over the past 20 years due to production innovations). Similarly, the development of substitutes for expensive constituents—such as affordable nano-additives replacing costly nanotubes in UHPC, or the use of biopolymers instead of epoxy resins—can reduce overall material costs.

Research is already underway on hybrid solutions that combine the advantages of multiple materials—for example, fiber-reinforced geopolymer concrete (hybrid fiber-reinforced geopolymer) or UHPC enhanced with nanomaterials and exhibiting self-healing capabilities [14–17, 6–8]. Such holistic approaches may yield synergistic effects, leading to materials with unprecedented durability and exceptionally low environmental impact.

Equally crucial will be close cooperation between academia, industry, and policymakers. It is necessary to develop appropriate regulations and legal standards that enable the large-scale use of new materials in commercial projects [14, 21–23]. Governments and international organizations, through pro-environmental policies (e.g., carbon footprint requirements for public investments), can create additional incentives to adopt sustainable materials. At the same time, industry stakeholders must have confidence in the reliability and economic viability of these technologies—hence the need for additional pilot projects that demonstrate their performance and costs under real-world conditions.

The social and educational dimension must also be highlighted: design engineers and technical staff must become familiar with these new materials, learn how to work with them, and develop trust in their long-term performance. Incorporating relevant content into university engineering curricula and offering professional training courses within the construction sector will be essential to ensure that future generations of engineers are equipped to fully benefit from advances in materials engineering.

In summary, the current stage of development of innovative construction materials can be likened to the early years of reinforced concrete at the turn of the 20th century—compelling evidence of their advantages already exists, and the first practical implementations have been completed, but widespread adoption will require time, refinement of methods, and acceptance by the engineering community.

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