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Innovative Materials In Structural Engineering

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Abstract: As infrastructure demands intensify, the construction sector is undergoing a profound transformation. Modern challenges such as rapid urbanization, resource scarcity, climate resilience, and lifecycle cost efficiency are increasingly difficult to address using traditional materials. This has led to the emergence of innovative materials. Ultra-high-performance concrete (UHPC), high-performance fibre-reinforced concrete (HPFRC), fibre-reinforced polymers (FRPs), self-healing materials, and smart adaptive alloys offer superior strength-to-weight ratios. Their adoption can enable structures to be lighter, stronger, and longer-lasting while requiring less maintenance.

Beyond structural benefits, these materials also provide significant sustainability advantages. They are designed to reduce embodied carbon, conserve raw materials, and promote circular construction practices. UHPC components require thinner cross-sections and use less raw material, while self-healing materials can autonomously repair cracks and extend service life. The use of FRP reinforcements reduces the need for frequent repairs. Infrastructure owners and operators can benefit from the long-term durability and cost-effectiveness of these materials.

However, transitioning to innovative materials is not without challenges. High initial costs, limited industrial production capacity, and a lack of standardized design codes have slowed their adoption. Many engineers and contractors also lack training to design and build with these advanced materials. This paper examines the current state of innovative materials in structural engineering and outlines strategies for integrating these materials into mainstream practice.

Index Terms- Innovative materials, structural engineering, UHPC, HPFRC, FRP composites, self-healing concrete, nanomaterials, sustainability

I. Introduction

Structural engineering has traditionally relied on materials such as concrete, steel, and timber. These materials are supported by decades of field experience, well-established design codes, and proven reliability, making them the default choice for most infrastructure projects. However, their inherent limitations are becoming increasingly evident. Maintenance costs for reinforced concrete are high due to its susceptibility to cracking, while steel is vulnerable to fatigue and corrosion. These challenges result in substantial lifecycle costs and raise concerns about the sustainability of conventional construction practices.

At the same time, modern infrastructure faces unprecedented performance demands. The limits of material capability are being tested by high-rise buildings and long-span bridges. Climate change has increased the frequency of extreme weather events, requiring structures to withstand higher loads. The construction industry also contributes significantly to global CO₂ emissions. Advanced materials offer superior mechanical performance, longer service life, and reduced environmental impact.

Innovative materials can help address these challenges. Thinner structural sections and reduced dead loads can be achieved using ultra-high-performance concrete (UHPC) [1]. High-performance fibre-reinforced concrete (HPFRC) and engineered cementitious composites (ECC) provide excellent crack control [3]. The high strength-to-weight ratio of fibre-reinforced polymers (FRPs) makes them ideal for retrofitting aging bridges [7]. Self-healing materials that use encapsulated bacteria or chemical agents to seal microcracks are another recent innovation [5]. These technologies promise a new generation of adaptive and resilient infrastructure. However, there are barriers to adopting innovative materials. High initial costs, lack of standardized testing and design codes, and limited industrial production capacity are major constraints.

Many engineers are unfamiliar with the design methods and construction techniques required for these materials. Approval and certification of new materials for public projects are also slow due to bureaucratic procurement systems. Overcoming these barriers requires coordinated efforts. This paper contributes to that effort by combining current knowledge on innovative materials, evaluating their performance and sustainability benefits, and outlining strategies for their integration into mainstream structural engineering practice.

Cement-based products are responsible for a large share of global greenhouse gas emissions [9]. Innovative materials can help reduce this impact by lowering the amount of material needed per unit of structural capacity, reducing the energy used in production, and extending service life. Reducing the cross-sectional dimensions of beams and slabs by more than half can lead to lighter foundations and lower transportation demands [1]. The use of FRP reinforcements can eliminate the need for protective concrete cover [7]. Such environmental advantages are shaping policy frameworks and support standards for infrastructure projects.

The adoption of innovative materials is being accelerated by digital design and fabrication technologies. Efficient use of high-performance materials can be achieved using techniques such as 3D concrete printing, automated fibre placement, and prefabricated modular construction [10]. Digital construction methods combined with advanced materials are transforming structural engineering practices. As these technologies mature, the synergistic integration of innovative materials and digital fabrication is expected to redefine design paradigms and set new benchmarks for safety, sustainability, and economic efficiency. This paper reviews the most promising materials and strategies for their deployment in future infrastructure systems.

II. Literature Review

2.1 Ultra-High-Performance Concrete (UHPC)

Ultra-high-performance concrete has very low permeability and high durability. It is produced using fine powders, fibres, and a low water-to-binder ratio [1]. Thin, lightweight structural components such as bridge decks, façade panels, and long-span girders are ideal applications for UHPC. In real-world projects, UHPC has demonstrated strong resistance to mechanical fatigue [10]. Studies show cost savings from reduced cross-section sizes. UHPC also contributes to sustainability goals by lowering dead loads and material use.

Its high strength and flowability allow UHPC to be used in 3D printing, enabling novel architectural forms and advanced construction methods. There are opportunities for modular construction where lightweight UHPC components are manufactured offsite and assembled on site. As design codes and specifications mature, the use of UHPC is expected to grow rapidly.

2.2 High-Performance Fibre-Reinforced Concrete (HPFRC) and Engineered Cementitious Composites (ECC)

High-performance fibre-reinforced concrete and engineered cementitious composites are materials that incorporate steel, glass, or polymer fibres to enable pseudo strain-hardening behaviour. They can sustain tensile strains of 2–5 % [3]. The cracking behaviour and stress-hardening response of HPFRC have been well classified [14]. These materials are ideal for components requiring high ductility and earthquake resistance.

Span slabs made from HPFRC have remained joint-free and crack-free for over a decade [15]. Fly ash is often used in their mix to reduce cement consumption and embodied carbon. However, adoption is limited by higher material costs, complex mix design requirements, and a lack of standardized design provisions. Their ability to enhance structural resilience is a major advantage. The ductility of HPFRC/ECC allows components to redistribute stress effectively. They are ideal for slabs, where post-yield capacity is critical. The need for

major repairs after impact events is reduced because damage is confined to fine cracks rather than large fractures.

2.3 Fibre-Reinforced Polymer (FRP) Composites

The high strength of carbon, glass, aramid, and other fibres used in fibre-reinforced polymers (FRPs) makes them an excellent choice for use in construction. They can be used to retrofit reinforced concrete components whose efficiency has reduced over time [7]. Rapid rehabilitation can be achieved using externally bonded or near-surface mounted FRPs. Durability studies show that FRPs retain their strength when exposed to different environments [8]. Their low self-weight helps reduce dead loads. The emergence of hybrid glass-carbon bars is showing a balance between cost and performance. However, challenges include low fire resistance, limited ductility, and reliance on empirical design codes. Research is ongoing on long-term behaviour models and fire protection strategies.

FRPs also offer significant construction and logistical advantages. Their lightweight nature allows the use of smaller cranes, enabling rapid span replacement and minimizing traffic disruption. Their non-magnetic, non-conductive properties make them ideal for environments sensitive to electromagnetic interference. Bridge construction and resilient infrastructure rehabilitation increasingly rely on fibreglass FRP systems.

2.4 Self-Healing Concrete

Self-healing concrete uses mechanisms such as autogenous hydration and encapsulated chemical agents to repair cracks [5]. When water enters the cracks, calcite is produced, sealing the damage. Self-healing concrete can recover over 90% of its original watertightness [17]. It has been used in retaining walls and duct linings. Net savings are achieved through fewer repairs. Current research focuses on improving the distribution of healing agents and scaling up production methods. Self-healing concrete also supports sustainability goals. High carbon emissions are associated with frequent demolition and repairs. Reducing the number of repair works lowers emissions and urban disruption. They are especially attractive for hard-to-access structures.

2.5 Nanomaterial-Reinforced Cementitious Composites

Nanotechnology enables the tailoring of cementitious materials at the nanoscale. Carbon nanotubes (CNTs) can increase the hydration rate, densify the microstructure, and improve crack-bridging [6]. They also help reduce shrinkage cracks. Real-time stress and crack monitoring can be achieved through the use of CNT-based sensing networks [18]. The use of nanomaterial-modified concrete is key to developing smart and durable infrastructure.

The interfacial transition zone is the weakest area in conventional concrete. Nanomaterials improve this zone, enhancing load transfer efficiency, toughness, and fatigue resistance. Their potential to be combined with other innovative materials opens pathways to create hybrid, multifunctional materials that combine ultra-high strength, self-sensing, and enhanced durability in a single component.

2.6 Smart Materials and Shape-Memory Alloys (SMA)

Shape-memory alloys (SMAs) and other smart materials can change their shape in response to external stimuli. When they return to their pre-deformed shape, SMAs provide self-centering capability [11]. SMA dampers can restore structures to their original positions after deformation. Piezoelectric ceramics and magnetorheological fluids are also considered smart materials [12]. Although currently used mainly in niche components, they have potential applications in adaptive, resilient infrastructure systems.

These materials can help reduce post-disaster losses. Recovery times can be shortened, and downtime costs minimized. As sensor technologies mature, integrating these materials into smart structures could transform conventional passive systems into active, adaptive infrastructure capable of real-time response to changing loads and environmental conditions.

Table 1: Summary of Key Innovative Materials in Structural Engineering

Material Type	Typical Strength	Key Advantages	Common Applications	Key Challenges
UHPC	150–200 MPa compressive	High strength, durability, thin sections, low porosity	Bridge decks, girders, precast façades	High cost, special curing
HPFRC / ECC	50–120 MPa compressive	High ductility, crack control, seismic performance	Bridge decks, link slabs, seismic walls	Complex mix design, cost
FRP Composites	800–2000 MPa tensile	Corrosion resistant, lightweight, easy installation	Structural strengthening, stay-in-place form	Fire resistance, code limitations
Self-Healing Concrete	40–80 MPa compressive	Autonomous crack repair, extended durability	Tunnels, retaining walls, canal linings	Cost, large-scale deployment
Nanomaterial Cement Composites	60–100 MPa compressive	High toughness, low permeability, self-sensing	Smart pavements, SHM-enabled elements	Dispersion issues, cost
Smart Materials (SMA, piezo)	300–600 MPa (SMA tensile)	Self-centering, vibration control, adaptive behavior	Seismic joints, adaptive dampers	High cost, limited field data

III. Material Properties and Performance

3.1 Mechanical Properties

Innovative materials deliver step-change improvements over conventional concrete and steel. UHPC can achieve tensile strengths in the range of 150–200 MPa, thanks to its ultra-dense matrix and optimal particle packing [1]. HPFRC/ECC exhibit pseudo strain-hardening behaviour in tension with multiple microcracks and tensile strains in the range of 2–5%, which contrasts sharply with the brittle post-cracking response of normal concrete [3]. Although they have a relatively low elastic modulus compared with steel, they have very high tensile strength at a fraction of steel's weight and show excellent fatigue performance [7]. Increasing the strength of the cementitious matrix can improve the interfacial transition zone [6]. SMAs contribute unique superelastic and self-centering energy-dissipating behaviour [11].

A practical implication is improved member slenderness and connection detailing. Thinner sections and longer spans can be achieved using UHPC's high strength and fibre bridging capacity. Enhanced serviceability limits are achieved by the narrow crack widths. Near-surface mounted FRP strips can be used for flexural and shear strengthening, but design must consider lower ductility and potential debonding [7]. SMAs provide flag-shaped hysteresis and recentering behaviour to reduce residual drift [11].

3.2 Durability and Service Life

Durability, chloride ingress resistance, freeze–thaw resistance, and crack control are key factors governing lifecycle performance. UHPC can be less porous than conventional concrete because of its low water-to-binder ratio [1]. Under service loads, HPFRC/ECC limit crack widths to micro-levels, reducing the ingress of aggressive agents and improving fatigue life of slabs [3]. Long-term studies confirm robust performance of FRPs when resin and fibre types are selected appropriately for harsh conditions, as they retain their properties in marine and de-icing environments where steel deteriorates rapidly [8].

Self-healing concretes can autonomously seal microcracks and restore watertightness [5]. Nanomaterials can reduce permeability and improve freeze–thaw performance [6]. These mechanisms extend inspection/repair intervals and increase projected service life [10].

3.3 Structural Performance Under Extreme Actions

Different materials offer unique performance benefits. Stress redistribution and protection of plastic hinge regions can be achieved through the multiple cracking behaviour of ECC/HPFRC [3]. The punching and shear capacity of thin deck panels can be increased using UHPC [1]. Proper anchorage design and fire protection are essential to ensure reliable performance during seismic or strength-upgrading applications [7].

SMA devices provide self-centering and stable hysteresis, reducing residual drifts and enabling faster post-event re-occupancy of facilities, especially in bridge bearings and beam-column joints. Embedded self-sensing capability provided by nanomaterials enables early damage detection and targeted interventions [6].

3.4 Sustainability and Life-Cycle Performance

Life-cycle benefits include using less material for a given capacity, fewer repairs, and longer replacement intervals. UHPC requires thinner sections, reducing cement content [1]. Supplementary cementitious materials can be used to lower the clinker content of cement [3]. FRP retrofits extend the life of existing assets, preventing premature demolition [7]. Self-healing concretes reduce traffic disruptions and associated emissions [5]. The lower whole-life carbon outcomes highlighted in sustainability roadmaps for cement-based infrastructure align with these effects [9].

3.5 Comparative Summary (Key Metrics)

The table below presents indicative ranges and characteristics to guide preliminary material selection. Actual design must be based on project-specific test data and relevant codes or design guidelines.

Table 2: Comparative summary

Material	Strength/Behavior (indicative)	Durability Traits	Extreme Actions	Sustainability/Asset Management
UHPC	$f'_c \approx 150\text{--}200$ MPa; fibre-bridged tension [1], [2]	Very low permeability; high fatigue & freeze-thaw resistance [1], [10]	High shear/punching; thin deck panels	Thinner sections, fewer joints; long life [10]
HPFRC / ECC	Tensile strain 2–5 %; multiple microcracks [3], [13], [14]	Tight crack widths ↓ ingress; good fatigue overlay behavior [15]	Large cyclic rotations; redistribution	High SCM content; reduced repairs
FRP (externally bonded/NSM)	Tensile 800–2000 MPa; low ductility [7], [16]	Corrosion-immune; environment-tailored resins [8], [15]	Rapid seismic/strength retrofit	Extends life of assets; light logistics
Self-healing concrete	Base concrete strength dependent	Autonomous crack sealing; restores watertightness [5], [17]	Improves post-event barrier performance	Fewer interventions; less downtime
Nano-modified cementitious	↑ modulus/flexural strength; self-sensing [6], [18]	↓ porosity/shrinkage; better freeze-thaw	Embedded damage sensing	Enables condition-based maintenance
SMA (devices/components)	Superelastic; recentering hysteresis [11], [19]	Device-level durability considerations	Cuts residual drift; energy dissipation	Faster recovery; lower repair needs

Note: NSM = near-surface mounted; SCM = supplementary cementitious materials.

IV. Design and Application Aspects

4.1 Design Considerations and Code Integration

The adoption of innovative materials is limited by the lack of codified design provisions. Older design standards such as those from the American Concrete Institute (ACI), Eurocode, and Bureau of Indian Standards (IS) are intended for reinforced concrete and steel. UHPC design often relies on modified provisions from ACI 318 [1]. Conventional concrete design rules are usually followed with empirical adjustments to stress capacity and crack control limits [3]. Engineers tend to be conservative due to the absence of well-defined load-resistance models and safety factors.

Several organizations have issued interim guidelines to bridge this gap. Design and material specifications for UHPC bridge components have been published [7]. FRP design requires higher serviceability margins and robust anchorage detailing, which differ from those used for steel [8]. Performance-based design models are also needed to capture the behaviour of SMA devices [11]. Incorporating these materials into mainstream design codes is a priority.

4.2 Construction and Fabrication Techniques

Special construction techniques are needed for innovative materials. High-shear mixing, extended mixing times, and precise temperature and curing control are required [1]. Their flowability makes them suitable for 3D-printed components. Fibre dispersion must be controlled to achieve uniform performance [4]. Several additional steps are necessary [7]. Quality assurance involves field trials. New dispersion techniques must be developed to prevent agglomeration in self-healing materials [17]. SMA devices are typically installed with mechanical anchorage systems to accommodate their unique stress–strain behaviour [11].

4.3 Practical Application Domains

Field deployment of these materials is growing through pilot projects. In bridge infrastructure, thin stay-in-place formwork, deck slabs, and field-cast joints have been used to reduce construction time [1]. ECC/HPFRC are used to enhance fatigue performance under heavy traffic and to eliminate joints in bridge decks [13]. FRPs are standard for retrofitting reinforced concrete beams, slabs, and columns in marine environments [7].

Self-healing concretes have been used in tunnels [5]. The research-to-field transition is ongoing for nanomaterial-reinforced cementitious composites used in smart pavements and bridge decks that enable real-time structural health monitoring. Significant reductions in residual drift and downtime have been observed in pilot applications of SMA dampers and recentering devices [11]. Building stakeholder confidence through successful demonstrations is key to driving broader acceptance.

4.4 Challenges in Implementation

Despite clear performance benefits, practical implementation still faces barriers. Adoption is deterred by high initial costs. There is a shortage of contractors and engineers with experience in using these materials. It is difficult to control the quality of materials on site, and lead times for specialized components are often long. Due to the lack of integrated design–specification–construction workflows, most projects require extensive engineering, testing, and approvals, which increases schedule and cost

risks. Developing construction guidelines, training programs, and supply chain infrastructure is essential to transition these materials from niche solutions to mainstream practice.

V. Sustainability and Economic Aspects

5.1 Environmental Sustainability and Embodied Carbon

Structural engineering can use innovative materials to reduce their environmental impact. Cement-based concrete products contribute about 8% of global CO₂ emissions, while steel adds further embodied carbon. Ultra-high-performance concrete (UHPC) can reduce total cement use at the structural level because of its higher strength and smaller cross-sections [1]. This also reduces raw material consumption, transportation energy, and construction time. High-performance fibre-reinforced concrete (HPFRC) and engineered cementitious composites (ECC) often use high volumes of supplementary cementitious materials to cut emissions while delivering superior mechanical performance [3].

Extending the life of existing structures is another way fibre-reinforced polymers (FRPs) and shape-memory alloy (SMA) systems promote sustainability. The use of fibreglass-reinforced polymers reduces the need for component replacement [7]. Structural damage can be mitigated with SMA dampers [11]. Self-healing concretes can prolong service life by preventing corrosion initiation and reducing the number of major rehabilitation works [5]. Circular economy principles align with these effects by emphasizing maintenance, reuse, and extended service life.

5.2 Life-Cycle Cost (LCC) Analysis

Innovative materials can reduce life-cycle costs. UHPC reduces maintenance, inspection, and replacement intervals [1]. The use of prefabricated UHPC bridge deck panels can also decrease construction time and minimize traffic disruption. Even though material costs are higher, life-cycle expenses can be cut by up to half [13]. FRP retrofits can be installed while structures remain in service, reducing downtime costs and avoiding expensive repairs [7]. SMA-based devices can lower earthquake repair costs [11]. Maintenance costs can be further reduced with self-healing concretes [5]. Over a 50–100 year design life, the net present cost of innovative material solutions is lower than that of traditional approaches.

5.3 Circularity and End-of-Life Considerations

End-of-life aspects are gaining importance as sustainability frameworks evolve. UHPC and ECC components can be fully recycled as aggregates for new concrete after their service life [10]. Although thermoset matrices in FRPs are not easy to recycle, new types are being developed to improve recyclability and reduce end-of-life landfilling [15]. SMA components can be recycled into steelmaking streams [19]. Concrete can also be processed at the end of life without environmental hazards if nanoparticles are properly controlled [18]. Design-for-disassembly principles can enhance the circularity of structural systems. These strategies allow component replacement, which reduces embodied carbon and conserves material resources.

5.4 Policy and Market Drivers

Market drivers include government procurement policies and sustainability rating systems. Innovative materials perform well in terms of long service life, low embodied carbon, and reduced maintenance. Several national highway agencies have issued guidelines on using UHPC and FRP to extend the service life of bridges [7]. Asset owners are increasingly being encouraged to consider long-term costs and emissions. As life-cycle assessment (LCA) and environmental product declaration (EPD) requirements become mandatory in infrastructure procurement, the relative economic value proposition of innovative materials is expected to rise significantly.

VI. Challenges and Future Directions

6.1 Technical and Material-Science Challenges

Innovative materials face several technical barriers. Ultra-high-performance concrete (UHPC) requires a very low water-to-binder ratio, specialized curing, and high fibre content to achieve its exceptional strength and durability [1]. If mixing and curing protocols are not strictly followed, the risk of variability in mechanical properties increases. High-performance fibre-reinforced concrete (HPFRC) and engineered cementitious composites (ECC) depend on uniform fibre dispersion and optimal micromechanics for ductility, which are difficult to achieve on large-scale construction sites [3]. Premature debonding can undermine their strength [7].

Although advanced dispersion methods are used to avoid agglomeration and ensure uniform performance, there is still no consistency in large-scale production techniques [6]. The behaviour of shape-memory alloy (SMA) components requires precise design modelling [11]. This technical complexity makes it difficult for contractors and engineers to fully understand and adopt these materials.

6.2 Standardization and Code Development Gaps

There are currently no universally accepted testing standards. Most innovative materials are governed by project-specific approvals [10]. Performance-based testing increases both cost and time requirements. The lack of codified methods often leads to overly conservative designs [14]. The design guidelines included in American Concrete Institute (ACI) 440 are largely empirical and do not fully address durability under long-term fatigue or fire exposure [7]. SMA-based seismic devices also require specialized review and

performance-based design approaches. The development of robust codes and standardized testing methods will be essential to move these materials from niche applications to mainstream structural practice.

6.3 Economic, Market, and Supply Chain Barriers

High initial material costs remain a barrier despite potential life-cycle savings. The cost of UHPC and ECC can be up to five times higher than conventional concrete, and the cost of FRP systems can be up to seven times higher than steel [10]. Infrastructure procurement is often driven by the lowest initial cost. Long lead times and price fluctuations are also common due to limited supply chains. Few contractors have the experience or equipment to work with these materials, raising concerns about construction risks. The lack of market maturity keeps costs high. Scaling up production capacity, training skilled labour, and strengthening supply chains will be essential to lowering costs and enabling large-scale implementation.

6.4 Knowledge, Training, and Institutional Barriers

Widespread use is also limited by gaps in professional education. Civil engineering curricula tend to focus mainly on conventional concrete systems. Most students receive little or no training in design principles, durability models, and construction methods for innovative materials [13]. This knowledge gap contributes to overly conservative specifications. It is also difficult to evaluate long-term economic value within current institutional procurement models. Training programs, demonstration projects, and collaborative research–practice partnerships are needed to overcome these barriers.

6.5 Future Directions and Research Opportunities

Future development should focus on simplified mix designs and production methods. Alternative binders can be used to reduce embodied carbon [9]. Fire resistance and recyclability can be improved [16]. Enhancing self-healing capability can be achieved with engineered networks and more robust delivery techniques [17]. Multifunctional performance can be realized by combining self-sensing and crack-resisting properties [18].

Research on low-cost iron-based SMAs could help reduce cost barriers [19]. Real-time monitoring and self-sensing technologies could help extend service life. Long-term performance data will be essential for code development and regulatory acceptance. The American Concrete Institute (ACI) could collaborate with the International Federation for Structural Concrete (fib) to accelerate the adoption of standards.

VII. Conclusion

Structural engineering is being reinvented through the use of innovative materials that address the limitations of conventional steel and concrete systems. Ultra-high-performance concrete (UHPC), high-performance fibre-reinforced concrete (HPFRC), engineered cementitious composites (ECC), fibre-reinforced polymers (FRPs), self-healing concretes, and shape-memory alloys (SMAs) are some of the key materials. They offer superior mechanical properties, enhanced resistance to aggressive environments, reduced maintenance needs, and extended service life, all of which improve the reliability and efficiency of critical infrastructure. These materials also contribute meaningfully to sustainability by lowering embodied carbon, enabling thinner cross-sections, incorporating supplementary cementitious materials, and extending structural life. Policy trends increasingly emphasize life-cycle economic value, environmental product declarations, and circular economy strategies. Despite higher initial costs, many of these materials achieve lower life-cycle costs by reducing repair frequency and downtime.

However, their deployment still faces challenges, including the lack of comprehensive design codes, high initial costs, and limited industrial supply chains. Coordinated efforts across research, manufacturing, and regulatory bodies will be needed to overcome these barriers. Future research should focus on hybridizing these materials for multifunctional performance, integrating digital monitoring and predictive maintenance models, and piloting large-scale projects to build confidence and generate long-term performance data. Structural engineering with innovative materials represents a paradigm shift. Such sustainable infrastructure systems can meet the demands of rapid urbanization, climate change, and resource constraints. With continued advances in material science, these materials are poised to transition from specialized applications to core components of mainstream structural practice.

References

- [1] K. Wille, A. E. Naaman, and G. J. Parra-Montesinos, "Ultra-high performance concrete with compressive strength exceeding 150 MPa: A simpler way," *ACI Materials Journal*, vol. 108, no. 1, pp. 46–54, 2011.
- [2] P. Richard and M. Cheyrezy, "Composition of reactive powder concretes," *Cement and Concrete Research*, vol. 25, no. 7, pp. 1501–1511, 1995.
- [3] V. C. Li, "Tailoring ECC for special attributes: A review," *International Journal of Concrete Structures and Materials*, vol. 6, no. 3, pp. 135–144, 2012.
- [4] A. Bentur and S. Mindess, *Fibre Reinforced Cementitious Composites*, 2nd ed., CRC Press, 2006.
- [5] H. M. Jonkers, "Self-healing concrete: A biological approach," *Heron*, vol. 56, no. 1/2, pp. 1–12, 2011.
- [6] M. S. Konsta-Gdoutos, Z. S. Metaxa, and S. P. Shah, "Multifunctional carbon nanotube reinforced cement-based materials," *Cement and Concrete Research*, vol. 40, no. 7, pp. 1052–1059, 2010.
- [7] L. C. Hollaway, "A review of the present and future utilisation of FRP composites in the civil infrastructure," *Construction and Building Materials*, vol. 24, no. 12, pp. 2419–2445, 2010.
- [8] H. Toutanji and S. Saafi, "Durability of FRP materials for construction," *Construction and Building Materials*, vol. 17, no. 5, pp. 365–373, 2003.
- [9] G. Habert, C. Denarié, A. Šajna, and N. L. Antoni, "Lowering the global warming impact of cement-based materials," *Journal of Cleaner Production*, vol. 161, pp. 993–1001, 2017.
- [10] P. J. M. Monteiro, E. M. Gartner, and C. P. Ostertag, "Concrete materials science: Past, present, and future innovations," *Cement and Concrete Research*, vol. 124, p. 105827, 2019.
- [11] D. C. Lagoudas, *Shape Memory Alloys: Modeling and Engineering Applications*, Springer, 2008.
- [12] F. Pacheco-Torgal, "Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020," *Construction and Building Materials*, vol. 51, pp. 151–162, 2014.
- [13] D. J. Kim, S. Park, G. Fischer, and V. C. Li, "Effect of fibre reinforcement and aggregate size on the tensile behavior of ECC," *Cement and Concrete Composites*, vol. 32, no. 9, pp. 676–685, 2010.
- [14] A. E. Naaman and H. W. Reinhardt, "Proposed classification of HPFRC composites based on their tensile response," *Materials and Structures*, vol. 39, no. 5, pp. 547–555, 2006.
- [15] H. Toutanji, Y. Han, S. G. Gilbert, and T. C. Ravi, "Strength and durability performance of glass fibre reinforced polymer bars embedded in concrete," *ACI Materials Journal*, vol. 94, no. 4, pp. 362–371, 1997.
- [16] S. R. Rizkalla and L. W. Lu, "FRP strengthening of existing concrete structures," *Progress in Structural Engineering and Materials*, vol. 3, no. 2, pp. 196–204, 2001.
- [17] S. W. Alghamri, J. Kanellopoulos, and A. Al-Tabbaa, "Impregnation and encapsulation of lightweight aggregates for self-healing concrete," *Construction and Building Materials*, vol. 124, pp. 910–921, 2016.
- [18] S. P. Shah, M. S. Konsta-Gdoutos, Z. S. Metaxa, and P. Mondal, "Nanoscale modification of cementitious materials: State of the art," *Transportation Research Record*, vol. 2142, no. 1, pp. 97–104, 2010.
- [19] B. Andrawes and S. DesRoches, "Unseating prevention for multiple-frame bridges using shape memory alloys," *Smart Materials and Structures*, vol. 16, no. 2, pp. 279–289, 2007.