ORIGINAL RESEARCH

The Role of Fiber Systems in Enhancing the Thermal and Mechanical Performance of Ultra-High-Performance Concrete (UHPC): A Systematic Review of Recent Research

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Abstract:

This systematic review innovatively evaluates the fundamental role of fiber reinforcement systems in improving the thermal and mechanical performance of UHPC, recognized for its superior strength, dense microstructure, and durability. Among various fibers—including steel, polymeric, basalt, glass, and hybrid types—our analysis identifies the hybrid fiber system combining 1.65% steel fibers with 0.5% polyvinyl alcohol (PVA) fibers as delivering the most substantial performance gains, enhancing compressive strength by up to 30%, flexural strength by up to 50%, and tensile strength by up to 55% compared to fiber-free UHPC. Additionally, polypropylene fibers significantly reduce thermal-induced spalling, maintaining structural integrity at temperatures up to 800°C. It also integrates sustainable UHPC formulations through partial cement replacement with supplementary cementitious materials—such as slag, fly ash, and recycled glass—that lower CO_2 emissions by up to 40% without compromising strength or durability. These findings strongly support the steel-PVA hybrid fiber system with sustainable binder substitutions as a preferred solution for developing resilient, durable UHPC structures capable of withstanding extreme mechanical and thermal stresses. Addressing deficiencies such as industrial scalability, limited long-term field data, and the need for predictive models and standards, this review offers a comprehensive synthesis of recent advances and applied recommendations to balance performance, sustainability, and feasibility for field-scale UHPC applications. The urgent need to overcome these challenges is emphasized to enable effective translation of UHPC technologies from laboratory settings to engineering applications.

Keywords:
Ultra-High-Performance Concrete (UHPC), Fiber Reinforcement, Thermal Performance, Mechanical Properties, Hybrid Fibers, Supplementary Cementitious Materials (SCMs), Durability.

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1. Introduction

UHPC is a promising Composite characterized by high compressive and flexural strength, low porosity, and high durability, making UHPC a potential candidate for use in civil engineering structures that require special safety measures [1,2]. Recent studies have demonstrated that the type and dosage of fibers, including steel, polypropylene, polyethylene, and basalt, have a significant impact on the mechanical properties, impact resistance, and durability of UHPC under various stress conditions. Incorporating various fibers into UHPC significantly boosts its compressive, flexural, and tensile strengths, while also enhancing resistance to high temperatures, cracking, spalling, and thermal degradation [3,4,5]. Recent systematic reviews highlight that incorporating fiber into UHPC is key not only for enhancing shear strength and ductility in deep beams but also for optimizing tensile behavior at low steel fiber contents. These advancements enable the development of fiber-reinforced UHPC systems that meet high-performance design standards and serviceability [6,7]. The significance of investigating the behavior of UHPC at elevated temperatures arises from the fact that critical structures are exposed to events such as fires, making an understanding of the long-term durability, residual behavior, and remaining capacity of concrete increasingly essential and necessary [1,2]. Extensive studies, both experimental and analytical, confirm that the type, amount, and combination of fibers, including hybrid technologies and mineral additives, significantly impact the mechanical behavior, durability, and microstructure of UHPC under various environmental and thermal conditions [4,8,9]. Despite the notable advancements in UHPC technology, a noteworthy issue consistently identified in the literature is the lack of a publicly accessible database focused on creep, shrinkage, rebar-concrete bond, and durability under cyclic loading or harsh environmental conditions. Most existing research is theoretical or based on limited laboratory results, while practical, long-term data at an industrial scale remain scarce [10,11,12]. Recent years have seen numerous studies aimed at understanding how multiple fibers affect the mechanical properties and durability of UHPC, especially under high-temperature conditions. Despite these advances, there remains a need to consolidate and clarify the key findings for practical applications. Therefore, the primary objective of this review is to provide researchers and engineers with a clear and practical understanding of how to develop, design, and optimize UHPC for modern structures that must operate safely in extreme environments, including those exposed to fire.

2. Methodology

This approach involves conducting a systematic literature review combined with a thorough assessment of existing publications on UHPC, with particular emphasis on reinforcing fibers and their high-temperature properties. To achieve the study's goals, we followed the steps outlined below:
Utilizing specialized databases that encompass published scientific articles, research reports, and reputable international sources, a collection of key references related to UHPC was identified. The selection of sources was based on their relevance to parameters such as composition, manufacturing technologies, additives, the type and amount of fibers, as well as the mechanical and thermal behavior of concrete. All selected articles were meticulously reviewed, and critical data about the effects of reinforcing fibers (from various metallic, polymeric, and mineral types), mix proportions, production technologies, experimental assessment methods, and findings on thermal performance were collated. The primary evaluation criteria included compressive and flexural strengths, microstructural characteristics, durability, and performance at elevated temperatures. The obtained data were classified and compared by the type of fiber, mixing method, and thermal performance assessment, to elucidate

the role of each factor in enhancing the properties of UHPC [1,13]. We examined and analyzed the obtained results using empirical and statistical comparisons found in the literature to identify scientific trends and relevant research gaps. During the analysis phase, both quantitative and qualitative comparisons were employed, along with synthesizing the information, to comprehensively elucidate the effectiveness of various fiber-reinforcement strategies and technologies used to enhance the thermal and mechanical performance of UHPC. The selected approach comprised a systematic and critical literature review, which not only ensures repeatability and transparency but also enhances the credibility of the reported findings. This methodology framework enables a comprehensive, organized, and evidence-based compilation of information on state-of-the-art, innovative UHPC technologies and future challenges, particularly in the areas of reinforcing fibers and thermal behavior.

3. UHPC Fundamentals

In the references reviewed in this study, each has designed and formulated UHPC materials based on different standards and codes, which mainly include reports and guidelines such as those from FHWA, well-known international and national standards like ASTM, EN, BS, JIS, IS, as well as recommendations and empirical data from research institutions such as Iowa State University for the development of non-proprietary mix designs and mixture optimization. The most predominant ingredients in UHPC are Portland cement, silica fume (also known as microsilica), quartz flour, ultra-fine aggregates such as quartz sand, and water with high-range water-reducing admixtures. There are also often added metallic or polymer fibers to enhance brittleness and to further ductility [14,15]. Recently, the use of substances such as graphene oxide [16] and recycled glass [17] as substitutes or additives to improve the mechanical properties, durability, and reduce the environmental impact of UHPC has been widely encouraged. UHPC generally has compressive strengths exceeding 150 MPa and a very low water-to-binder (w/b) ratio, typically in the range of 0.2 or lower [14,15]. The presence of fibers in the UHPC matrix enhances tensile strength, fracture toughness, and impact energy dissipation. Increased flexural strength and fracture resistance, as well as decreased microcrack accumulation, have been documented in some studies [14,16]. The microstructure of UHPC is essentially characterized by low porosity, which significantly mitigates permeability to water and aggressive ions, making it a crucial pathway to enhance concrete durability and resistance [14,18]. The compactness of the matrix and the incorporation of mineral additives and fibers are responsible for the improvement in the durability of UHPCs against carbonation, chloride penetration, freeze-thaw, and particularly fire [16,18]. Amidst increasing environmental concerns, a growing trend toward the adoption of alternatives and reduced cement consumption has led to the emergence of eco-friendly UHPC. These options retain good mechanical values and a lower CO2 impact [17,19]. The development of UHPC using indigenous materials, along with inexpensive additives that do not require specialized equipment or high-temperature curing, is now a practical option. This progress has significantly contributed to the dissemination and broad use of UHPC in many countries [15,20].

The use of a wide range of fibers, nano-additions, or supplementary cementitious materials not only enhances mechanical properties and durability, but it can also

4. Fiber Reinforcement Systems

enable the design of concretes with autogenous healing, waterproofing, or even distinctive optical properties [20]. With its high strength and durability, UHPC is a new and promising type of construction material that not only features a compact microstructure but also has the potential to achieve high-performance properties through optimized mix design and the use of additives.

Table 1. Properties of fibers used in HPC and UHPC. Source: [14,21].

Matrix & Fibers	Diameter (mm)	Density (g/cm³)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Elongation (%)
Matrix (comparison)	-	2.7	10-45	3.5-8	0.02
Steel	5-500	7.84	200	500-2580	0.5-3.5
Carbon	5	1.9	65-135	2600	1
Glass	9-15	2.6	70-80	2000-4000	2-4.5
Polyvinyl Alcohol	0.038	1.30	25-40	880-1600	6-10
Polypropylene	20-200	0.9	164	500-750	9
Polyethylene	20-200	0.95	14-19.5	200-300	7.5
Asbestos	0.02-0.4	2.6-3.4	196	33000	2-3
Kevlar	10	1.45	5-17	3600	2.1-4
Cellulose	-	1.2	4	300-500	-
Sisal	10-50	1.5	15-20	800	7

Short steel fibers are the most widely used reinforcement in UHPC, playing an essential role in enhancing tensile strength, energy absorption, and controlling crack propagation [14,22,23]. The compressive strength of specimens reinforced with steel fibers is frequently reported above 145 MPa, and ductility has increased by up to 109% compared to fiber-free specimens [22]. The directional distribution of these fibers exerts a positive effect on the dynamic properties and prevents brittle failure of concrete, particularly under impact or flexural loading [24]. Recently developed design models have been proposed to enable more accurate prediction of the shear and tensile performance of steel fiber-reinforced UHPC, thereby facilitating the practical exploitation of these systems' capacity [25]. The most widely used polymeric fibers are polyvinyl alcohol (PVA), polypropylene, and polystyrene. The effect of these fibers is predominantly an enhancement in bending strength and a decrease in microcracking [26,27]. Polypropylene fibers, due to their low melting temperature, increase permeability to water vapor and decrease the tendency for surface spalling in concrete. The optimal thermal performance is, however, achieved by combining steel and polymer fibers [26]. The addition of polystyrene fibers enhances workability and flowability while maintaining mechanical performance, and these fibers are commonly incorporated into modern UHPC formulations [27]. Basalt fibers, plant-derived fibers, or bio-fibers have been explored as environmentally compatible alternatives. Using basalt fibers alongside steel yields improved flexural and tensile resistance in UHPC, while also reducing environmental impacts [28]. Although the mechanical range achieved through natural fibers is less than that of industrial fibers, such blends are recommended for producing green and sustainable concretes. The simultaneous use of fibers differing in origin and dimension (e.g., steel, glass, basalt, or polymer) is referred to as a "hybrid fiber system", which aims to maximize synergy among the diverse properties of concrete [14,26,28]. Research results indicate that a mixing ratio of 1.65% steel fiber and 0.5% PVA is suitable for enhancing the mechanical and thermal properties of UHPC, compensating for the disadvantages of the two different fibers [26,28]. Hybrids, due to their ability to control crack distribution and ductility that varies with load, have great potential to improve the durability of concrete [14,28]. The development and use of various reinforcing fiber systems (steel, polymeric, natural, and hybrid fibers) are the key to the progress of UHPC. The latest studies reveal that the fiber type and content play a crucial role in achieving excellent mechanical and thermal performance of UHPC, as well as enhancing structural stability and broadening its application in structural engineering.

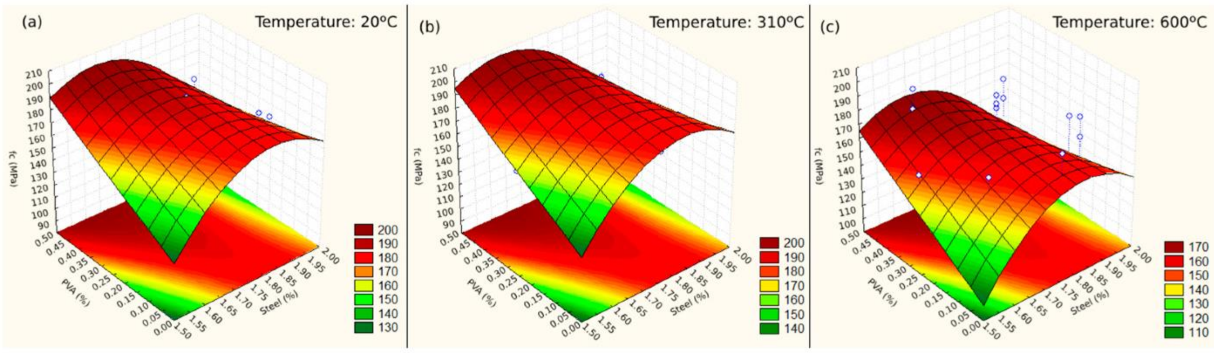

Fig. 1. Response surfaces for: (a) 20°C, (b) 310°C, and (c) 600°C. The blue circles represent the experimental results. Source: [26]

5. High-Temperature Behavior

Today, with structural safety under fire conditions becoming more critical and the number of specialized applications increasing, studying the high-temperature behavior of UHPC has gained greater importance. The dense and microporous structure of UHPC offers benefits such as high strength and excellent durability; however, these same features also make it vulnerable to thermal degradation, particularly surface spalling. The compressive strength, tensile strength, and elastic modulus of UHPC decrease significantly as temperature increases. Studies have shown that temperatures above 300°C cause a marked decline in these properties, and the reduction is more severe when fibers are absent or when only a low fiber content is used [26,29].

Fig. 2. The spalling during heating. Source: [26].

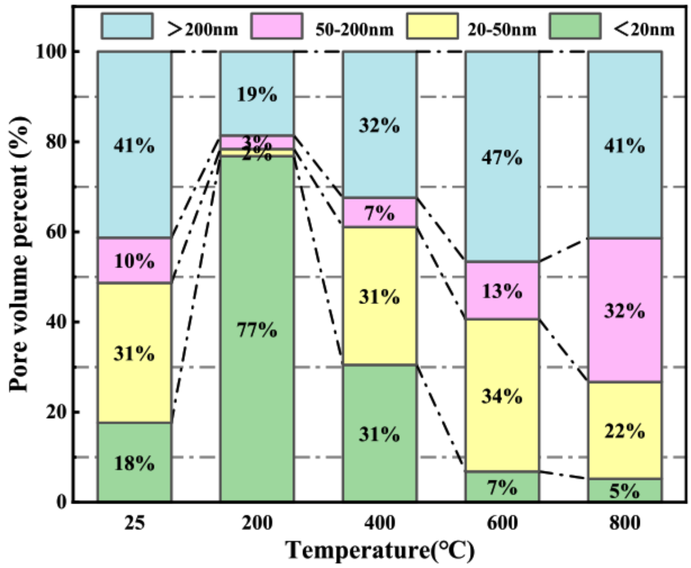

Fig. 3. Distribution of UHPC Pore Percentages Under Various Temperature Effects. Source: [30].

The incorporation of metallic, polymeric, or hybrid fibers into the UHPC structure not only enhances its initial properties but also plays an essential role in mitigating surface spalling and improving structural stability at elevated temperatures. Especially, the presence of polypropylene fibers, due to their melting and the subsequent formation of channels for vapor escape, significantly reduces the risk of thermal-induced spalling. Furthermore, the combination of steel and polypropylene fibers has demonstrated superior performance in numerous experiments. Recent studies have reported an increase in porosity and alterations in the microstructure of UHPC with rising temperature; these changes are accompanied by reduced fiber-matrix adhesion and intensified cracking, ultimately resulting in the deterioration of the concrete's physical and mechanical properties. [26,30].

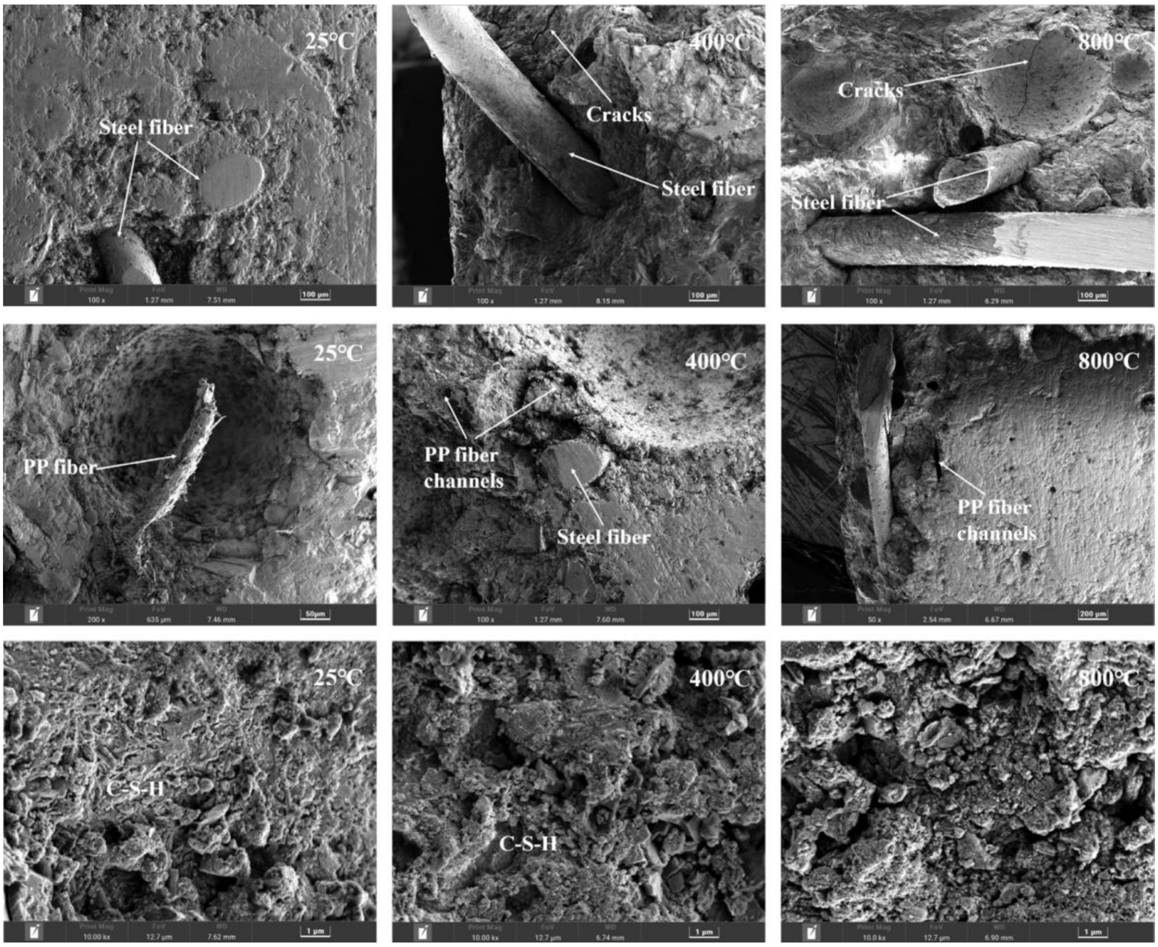

Fig. 4. SEM images of fiber-UHPC interface at different temperatures. Source: [30].

Experimental investigations on fiber-modified UHPC have demonstrated that combining metallic and polymeric fibers can significantly mitigate the occurrence of spalling at temperatures ranging from 600 to 800°C. In contrast, fiber-free specimens experience more severe failure [30]. Exposure to thermal cycles and repeated thermal loading can deteriorate the microstructure, permeability, and autogenous healing capacity of UHPC. The application of mineral admixtures, basalt fibers, and hybrid technologies has been reported as a practical approach to alleviating the adverse impacts of thermal cycling [26,31] models have been developed to estimate the reduction in strength, peak strain, and the stress-strain curve of UHPC at elevated temperatures, and experimental comparisons with laboratory results reveal the satisfactory reliability of these models for future design purposes [29] Studies further indicate that employing advanced materials (such as basalt fibers or nano-admixtures) and optimized mix design ratios can enhance structural stability and minimize the loss of thermal resistance [26,29,30,31]. UHPC containing an appropriate mix of fibers and supplementary materials can also provide adequate resistance to high temperatures. However, mechanical properties degradation, changes in microstructure, and the possibility of surface violent spalling are significant challenges, requiring the use of hybrid technologies and a suitable mix design to minimize them.

6. Mechanical Properties Analysis

Recent research on the mechanical properties of UHPC has shown that it exhibits excellent mechanical characteristics, including a typical dense microstructure, a low water-to-cement (w/c) ratio, and the incorporation of hybrid fibers. Here is a qualitative and quantitative assessment of specific properties.

6.1. Quantitative Findings

Table 2. Compressive, Tensile, and Flexural Strength of UHPC Based on Recent Research

Property/Parameter	Numerical Value / Change	Conditions	Description/Notes	Key Ref
Compressive Strength	110–150 MPa	Standard and specialized mixes	—	[15,32,33]
Compressive Strength (thermal curing)	Up to 144 MPa	Mineral additives, hot water curing	—	[32]
28-day Compressive Strength (RHA vs. FA)	—	—	RHA > FA at 28 days; FA > RHA at 91 days	[33]
Flexural Strength (1:3 & 1:1 ratio, two-layer)	78.8%, 83.3% vs. control	WUHPC-to-NC ratio vs. control	—	[34]
Flexural Strength (1:4 ratio, two-layer)	Up to 89.8% vs. control	WUHPC-to-NC ratio vs. control	Thin WUHPC layer covering NC	[34]
Flexural/Tensile Strength Gain (Steel & Glass)	Up to +50% vs. fiberless	Hybrid fiber UHPC	Steel + glass fibers improve toughness and strength	[14,24]
Flexural Strength (Hybrid, post-crack)	Significant increase	Steel + glass fibers	Energy absorption enhancement	[14]
Flexural Fatigue & Mechanical Similarity	Comparable performance	Conventional vs. high-thixotropy UHPC	—	[14]

1:4 ratio (two-layer): a gradient concrete with a thin WUHPC layer one-quarter the thickness of the normal concrete layer as protective overlay, WUHPC: White Ultra-High-Performance Concrete [34], RHA: Rice Husk Ash, FA: Fly Ash [33]

Table 3. Mechanical Behavior and Load Responses of UHPC Based on Recent Research

Property/Parameter	Numerical Value / Change	Conditions	Description/Notes	Key Ref
Cyclic Loading-Stiffness Loss Delay	Significant improvement	Fiber reinforced	Delayed crack accumulation	[35,36]
Directional Fiber Increase	+0%, +2%, +4%, +6% (upward trend)	—	Peak stress, energy, and ductility increase	[24]
Dynamic Increase Factor (DIF)	Increasing with strain rate, fiber content	Measured by SHPB impact	—	[24]

SHPB: Split Hopkinson Pressure Bar [24]

Table 4. UHPC: Curing, Bond, Durability, Material Replacement, Environmental Effects (Recent Research)

Property/Parameter	Numerical Value / Change	Conditions	Description/Notes	Key Ref
Thermal/Hot Water Curing Effect	+35% to +40% increase	Mechanical properties, densification	—	[32,33]
Creep	Up to 5× higher (non-steam cured)	Steam vs. ambient curing	New lab and field data	[38]
Shrinkage	Variable; reduced by water curing and agents	RHA/FA, SRA/EA used for mitigation	Lab and field data	[39]
Durability (Freeze-Thaw, Chemical Attack)	<5% strength loss after 300 cycles or exposure	Specialized durability tests	New field and lab results	[13,40,41]
Bond Strength Influential Parameters	Compressive strength, cover, bond	Nonlinear slip-bond models	More accurate predictive models	[37]
Rebar-Concrete Bond Strength	15–24 MPa	Dependent on fiber fraction, compressive strength, and cover	New nonlinear models	[12]
Durability (Freeze-Thaw, Chemical Attack)	<5% strength loss after 300 cycles or exposure	Specialized durability tests	New field and lab results	[13,40,41]
SCM / Recycled Material Replacement Effect	Up to 40% CO_2 reduction; 5–8% strength gain	Partial replacement: slag, fly ash, recycled glass	—	[13]
Long-Term Field Strength	Retains 80–90% initial strength after 5–10 years	Field data, cyclic loading, and durability studies	—	[10,41,42]

RHA: Rice Husk Ash, FA: Fly Ash, SRA: Shrinkage Reducing Agent, EA: Expansive Agent [39], SCM: Supplementary Cementitious Materials [13]

6.2. Qualitative Findings

- The compact matrix and low w/b ratio of UHPC, complemented by a range of fiber types, demonstrate outstanding mechanical and durability performance. Recent long-term and field studies now provide more substantial evidence of sustained strength, minimized creep, and effective shrinkage control, mainly when optimal curing and admixtures are used [11,12], [42,43,44].
- Incorporating steel, polymeric, glass, basalt, and hybrid fibers not only increases tensile and flexural strengths but also enhances post-cracking toughness, energy absorption, and ductility. The synergistic use of hybrid fibers leads to superior performance in both mechanical reliability and thermal/spalling resistance [28].
- Empirical evidence shows that steam/heat curing dramatically reduces creep (by up to five times compared to ambient curing), and the use of internal curing, shrinkage-reducing admixtures (SRA/EA), and supplementary materials, such as fly ash or rice husk ash, yields noteworthy shrinkage reductions [44].
- Recent research has highlighted that the bond strength between rebar and UHPC is strongly influenced by fiber content, compressive strength, rebar cover, and curing conditions. Nonlinear and advanced slip-bond models offer more accurate simulations, and new field/laboratory data further validate their effectiveness [37].
- UHPC demonstrates robust resistance to freeze-thaw cycles, chloride penetration, and chemical attack, with modern field studies confirming limited strength loss (<5%) after extensive cyclic and chemical exposure. Data from actual projects corroborate these laboratory findings, confirming the long-term performance of UHPC [13].
- Optimized curing (thermal/hot water) continues to yield increases in mechanical performance (up to 40%), and modern mix designs using recycled glass, slag, or SCMs help achieve both high strength and significant environmental benefits [13].

- Under repeated loading and real-world field conditions, UHPC—especially with hybrid fiber systems—shows delayed stiffness loss and crack propagation, confirming durability and mechanical stability over extended service periods [14].
- Substituting up to 40% of binder materials with SCMs or recycled resources reduces CO_2 emissions and production costs, without a significant loss of mechanical properties, thereby aligning UHPC development with current sustainability goals [45]. Field implementation reveals the necessity for updated standards and localized guidelines, given variations between laboratory and industrial outcomes. Real-world projects demonstrate the crucial need for practical optimization in full-scale mixing, curing, and quality assurance [40].

In conclusion, the new experimental and modeling results have significantly enhanced the qualitative understanding, providing a comprehensive picture of the UHPC's mechanical strength, durability, predictive modeling, and sustainability in current research and field practical conditions.

6.3. Quantitative Comparison of Fiber Types and Supplementary Materials

Table 5. Comparative Effects of Fiber Types on UHPC Properties.

Fiber Type	Δ Compressive Strength (%)	Δ Flexural Strength (%)	Δ Tensile Strength (%)	Durability/High Temp Effect	Key Ref
Steel	Up to +25	Up to +50	Up to +50	Significant improvement, crack control, impact/fatigue resistance	[41]
Polymer (PVA, Polypropylene, Polystyrene)	+ (10 to 15)	+ (15 to 20)	+ (15 to 20)	Reduces spalling, improves vapor permeability, and restrains microcracks restraint	[9]
Basalt	+12	+20	+15	increases flexural/tensile; enhances sustainability	[28]
Natural (Sisal, Cellulose)	+ (5 to 8)	+ (8-10)	+ (10 to 12)	Eco-friendly, modest performance	[21]
Glass	+ (10 to 15)	+ (20 to 25)	+ (18 to 22)	Durability and flexural improvement	[14,17]
Hybrid (Steel + Polymer/Basalt/Glass)	Up to +30	Up to +50	Up to +55	Superior synergy in mechanical and thermal properties	[28]

Δ values refer to the percentage increase over fiber-free UHPC.
"Durability/High Temp Effect" is based on resistance to spalling, microcracking, and aggressive environments.

Table 6. Supplementary Materials-Mechanical & Sustainability Performance.

Supplementary Material/Approach	CO_2 Emission (%)	Δ Compressive Strength (%)	Durability Change (%)	Key Ref
Slag/Fly Ash (SCMs, up to 40% replacement)	Up to -40	0 to -10 (neutral/ slight drop)	+(10 to 20) (chloride, chemical)	[1]
Recycled Glass (aggregate/pozzolan)	-(20 to 40)	+(5 to 8)	+(10 to 20)	[17]
Non-proprietary UHPC (local/raw/recycled)	Up to -50 (cost)	Comparable/Variable	Comparable	[15]

Δ values refer to the percentage increase over fiber-free UHPC.
Durability enhancement includes resistance to chloride penetration and freeze–thaw cycles.

6.4. Key Meta-Analytic Insights

- Steel fibers provide the most significant all-around enhance for mechanical and durability properties, especially in flexural/tensile strength and impact/fatigue resistance, with consistent evidence across laboratory, field, and long-term durability studies—including improvements of up to 50% in flexural and tensile strength, enhanced energy absorption, and superior crack control compared to fiber-free UHPCs.
- Polymer fibers, notably polypropylene, play a crucial role in enhancing fire resistance and reducing thermal-induced spalling at high temperatures.
- Hybrid fiber systems yield synergistic post-cracking toughness, spalling control, and high ductility.
- Basalt and glass fibers provide a balanced combination of flexural/durability gains, contributing to the eco-friendly UHPC. Performance is validated via.
- Recycled glass and industrial by-products reduce carbon emissions up to 40%, while maintaining or enhancing strength/durability.
- Natural fibers offer sustainability benefits with moderate gains in strength.

Table 7. Key Mechanical Properties and Performance Enhancements of Non-Proprietary UHPC Under Various Conditions.

Property	Numerical Value (Range)	Condition/Description	Key Ref
Compressive Strength	110-150 MPa	Standard to specialized mixes	[15,32,33]
Flexural Strength	Up to 90 % (improvement vs. normal)	Two-layer structure 1:4	[34]
Hybrid Flexural Strength	+ 50%	A combination of steel and glass fibers	[14]
Dynamic Increase Factor	Increasing trend	Rate and orientation of fibers	[24]
Thermal Curing Effect	+ (35-40) %	Mechanical properties & microstructure	[32,33]

UHPC, with compressive strengths exceeding 110 MPa and excellent fracture toughness, exhibits significantly improved tensile, flexural, dynamic, and bond properties through increased fiber content and diversity. The right choice of composition, curing conditions, and fiber systems is crucial for achieving better mechanical performance and durability in advanced civil engineering applications [14,15,24], [32,33,34].

7. Sustainability Aspects of UHPC

Over the past few years, UHPC has garnered significant academic attention due to its environmental sustainability benefits. Current UHPC is evolving to become increasingly ecological, environmentally friendly, resource-saving, and of higher durability and life-cycle performance. Findings from qualitative and quantitative research in this field are:

- The high level of cement in UHPC would generate a larger amount of CO_2 than regular concrete does. Still, UHPC structures have the advantages of high durability and long service lives, which would compensate for the effect of carbon emissions to some extent compared to standard concrete [46].
- Utilizing waste glass as a partial aggregate replacement will not only benefit the environment but also exhibit improvements in compressive strength (up to 5%) and resistance to chloride ion penetration and chemical attack. In discrete tests, the addition of recycled glass ash to UHPC mixtures resulted in compressive strengths ranging from 147.2 to 155.3 MPa, with increments of up to 20% in durability compared to samples without recycled material [47].
- The development of non-proprietary UHPC, utilizing local materials and eliminating expensive additives, has reduced production costs to less than half those of

proprietary/commercial types. While commercial UHPC may cost up to 10 times more than conventional concrete, new non-proprietary types with comparable performance cost about four times as much, thereby facilitating broader sustainable application [48].

- The use of superplasticizers and mix design optimization, while achieving a water-to-cement ratio as low as 0.20, can increase both mechanical performance and UHPC longevity, thereby reducing the need for structural replacement or repair, a key sustainability aspect [46].
- The use of alternative fibers and locally sourced supplementary materials has also enhanced ecological performance without causing substantial losses in mechanical properties [46,47].

Table 8. Summary of Key Findings on Sustainability, Performance, and Cost Optimization.

Topic	Quantitative/Qualitative Outcome	KeyRef
SCM Replacement	CO_2 emission reduction up to 40%	[46]
Recycled Glass Addition	Compressive strength up to 8% higher; 20% more durable	[47]
Non-proprietary UHPC Cost	4× conventional (vs. 10× for commercial UHPC)	[48]
Water-Cement Ratio	Less than 0.20; improved durability and economy	[46]

Sustainable technologies, such as UHPC, are primarily derived from limiting the consumption of conventional cement and the virgin materials and replacing a certain percentage with waste (industrial/natural) in the mix design. This study has demonstrated that it is feasible to improve sustainability within UHPC without compromising its mechanical/long-term performance by utilizing supplementary cementitious materials (SCMs), waste-based materials, and new technologies. Replacing 30–40% of the cement with recycled glass maintains the structural performance of the mixture while reducing its environmental impact [46,47].

8. Critical Review and Research Gaps

In recent years, the development of UHPC has made significant progress in mixture technology, mechanical performance, and sustainability.

8.1. Types and Properties of Raw Materials

The interaction between the chemical composition of the cement, SCMs, and fiber dosage and their influence on the mechanical properties and durability of UHPC is still pretty much unexplored. The synergistic or interfering effects of specific materials, such as steel-polymer or recycled synthetic fibers, on the microstructural behavior of UHPC have not been precisely identified [14,21]. Most studies have only investigated specific combinations or limited fiber contents, and comprehensive modeling for predicting the performance outcomes of varied mixtures remains incomplete [15,21].

8.2. Weaknesses in Industrial Scalability and Implementation

Most of the success is achieved on a laboratory level, but scaling up these results to an industrial level presents practical difficulties, variations in material quality, and challenges to attain the same properties with large bulk quantities [46,49]. The local material compatibility for UHPC, as well as the high cost and complexity of heat curing and precision curing, are key constraints for its applications [49].

8.3. Structural Performance and Real Conditions Behavior

Studies have revealed that, due to its dense microstructure and high strength, UHPC generally exhibits lower creep than conventional concrete. Nevertheless, long-term experimental data for a valid estimation of creep under multiple conditions and ages are, for the most part, limited to case studies and laboratory specimens [10,11,38,42,50]. The effect of curing (steam vs. ambient curing) significantly affects creep, and in some cases, creep values of ambient-cured specimens were up to five times higher than those of specimens cured with steam [45]. Recent investigations further emphasize the need for the development of comprehensive and practical databases for creep modeling [10]. While the shrinkage behavior, including plastic, autogenous, and drying shrinkage of UHPC, has been examined in some laboratory studies, the influence of environmental factors (temperature, relative humidity, and curing conditions) and structural-scale performance has been sparsely documented experimentally [39,43,44,51,52,53]. Early-age conditions play a crucial role in shrinkage, and controlling temperature and humidity, particularly through water curing, can significantly reduce shrinkage [43]. Nonetheless, data on shrinkage in actual field conditions and long-term behavior in large-scale projects are still minimal, which is necessary for validating numerical models [44,51]. There is still a lack of comprehensive and integrated models to simulate shear, tensile, and rebar–concrete bond (particularly for essential elements under combined actions and with various fiber types and textures) in UHPC [15,45]. Information on creep, shrinkage, long-term sustained load effects, and progressive collapse under aggressive conditions is also limited [14,46]. Despite the proven mechanical performance and durability of UHPC under laboratory conditions, translating these findings to an industrial scale faces several significant challenges. The major hurdles are:

Scaling up from laboratory to industrial batch sizes directly influences the fresh properties and hardened mechanical performance of UHPC. The type of mixer, size of mixer, sequencing, and rate of addition of the components (in particular, superplasticizers and fibers), as well as the duration of mixing, all play a critical role in delivering the required workability and ultimate evenness. Homogeneous microstructure and fiber distribution are still challenging to achieve, especially at the industrial level [46]. Practically, raw materials are usually found locally, and they exhibit significant differences in grade, fineness, and reactivity. Such discrepancies can result in deviations in the mechanical behavior and durability of UHPC compared to reference formulations. Thus, local adaptation of mix designs and recalibration are needed to control the influence of material quality [47]. Many laboratory achievements are based on specific curing methods, such as steam or heat curing, which are not realistically applicable in large-scale field projects. Suboptimal curing may therefore compromise mechanical strength, promote shrinkage, and increase the risk of cracking [46]. The high price of metallic fibers, superplasticizers, and specialized mixing equipment, as well as issues related to transport (caused by the low workability and high viscosity of UHPC), pose economic barriers to the widespread application of UHPC in specific projects [49] While high durability is reported in laboratory studies, in field applications (under real thermal, moisture, and load cycles), microcracking and issues such as segregation may occur more pronouncedly. Therefore, long-term durability monitoring and assessment are essential in real projects [47] It is advised to adopt a laboratory-to-field scaling and optimization approach in UHPC formulation development, systematically document production and construction data, monitor and analyze the impact of local variables on performance, and develop practical guidelines for large-scale production, transportation, curing, and quality control [46]. The bond behavior between rebar and UHPC is more complex than in conventional concrete, due to the denser matrix and presence of fibers. Laboratory results indicate that increasing compressive strength, enlarging the rebar cover, and incorporating fibers all contribute to enhancing bond strength and result in noticeable improvements in bond performance [12], [54,55,56]. However, there are very few field studies that have evaluated bond behavior at real scales or under combined and long-term loadings. Moreover, most existing models are based on limited laboratory data, and their generalizability to industrial applications requires more extensive empirical evidence [12,54]. Multiple studies have highlighted the high potential of UHPC in resisting chloride penetration, freeze-thaw cycles, and chemical attacks [40,57,58]. However, experimental data on the durability of UHPC under long-term cyclic mechanical loading and highly aggressive environments remain limited. The few available laboratory studies generally report positive results, but real-world validation and detailed assessment of damage mechanisms require field monitoring and long-term durability data from actual structures [57,58].

8.4. Sustainability and Life Cycle Issues

Although some methods have been proposed to reduce cement consumption and replace it with industrial by-products, their real impact on complete life cycle assessment (LCA) and carbon emissions is not yet clear or sufficiently supported by field data [41]. Precise schemes for the recovery, recycling, and waste management of UHPC are needed to realize its sustainability claims in practice [47,59] fully.

8.5. Development of Predictive Models and Artificial Intelligence

The majority of numerical and AI models for UHPC prediction performance are derived from poor datasets and are specific to a particular mixture; thus, their ability to generalize is questionable for varying UHPC projects and new formulations [21]. In recent years, machine learning (ML) models have been widely used to predict the mechanical properties and durability of concrete, including UHPC. These models can simulate the intricate behavior of cementitious composites and predict properties such as compressive strength, flexural capacity, and durability under various environmental and thermal exposures, which are derived from extensive experimental databases. The application of methods such as gene expression programming (GEP), artificial neural networks (ANN), and tree-based algorithms has yielded better predictive accuracy and provided insight into the effect of different mix parameters [27]. Moreover, advances in open-data repositories for concrete research have enabled researchers to share raw experimental data, significantly improving the quality and credibility of machine learning models and their validation. Data repositories, such as the Concrete Compressive Strength Data Set and Mendeley Data, are examples that have been commonly queried to train innovative models for predicting concrete properties. Thus, it is suggested that future work should not only develop prediction models using machine learning but also use the data from these community-based databases for accurate modeling and comparison [60].

8.6. Need for Standardization and Practical Guidelines

The absence of specialized standards and comprehensive guidelines for the design, construction, and performance assessment of UHPC has led to variations in outcomes and inconsistent data interpretation across projects [21,15]. There is a pressing need to develop regulations and scientific recommendations grounded in standardized empirical evidence [15].

Table 9. Key Research Gaps and Challenges in UHPC Studies

Research Challenge	Current Status	Future Research Necessity
Diversity of Materials and Synergistic Behavior	Limited comprehensive modeling and prediction	Expansion of combined studies
Industrial Transfer and Implementation	Limited success in large/localized projects	Evaluation of field performance
Long-term Behavior and Durability	Insufficient data on long-term performance	Monitoring of in situ performance
Standards and Guidelines	Lack of unified solutions for design/execution	Preparation of localized guidelines

In addition to these developments, further research is needed to address the existing gaps and challenges in the wider and long-term deployment of UHPC, including the development of a deeper scientific understanding, the design of new mixes, the establishment of standards, in-situ monitoring, and the application of simulation techniques [15, 21, 46].

9. Future Research Directions.

Although significant progress has been made in UHPC development, some recent studies suggest that the research direction for UHPC should shortly be a multi-dimensional "targeted" approach to address remaining issues and explore untapped potential. The main research directions are outlined below:

- A more precise and systematic investigation of the effects of higher percentages of Supplementary Cementitious Materials (SCM) (such as fly ash, silica fume, slag, recycled glass) on the durability, strength, and microstructural behavior of UHPC, particularly focusing on suitable compositions for varying climatic regions and resource limitations. Greater emphasis on the use of natural and recycled fibers, examining their environmental impact, and the long-term behavior of structures containing these fibers.
- Development of data-driven models to predict material properties, structural performance, durability, and mix optimization, ensuring higher generalizability and practical applicability compared to existing models, and linking microstructural behavior with mechanical properties and structural performance, alongside the development of multiphase simulators to predict real-scale behavior.
- Conducting comprehensive life-cycle assessments to realistically evaluate environmental impacts, durability, and reduction in maintenance needs at macro levels. Long-term field studies for real-time monitoring of creep, shrinkage, performance under sustained loading, and exposure to aggressive environmental conditions in executed projects.
- Research on additives with autogenous healing capabilities, fire resistance, nuclear radiation resistance, or other special features to expand UHPC's application range in new industries, and investigation of the effects of nanomaterials such as graphene or carbon nanotubes on microstructure, ion transport, and durability.
- Development of more economical and efficient production methods and equipment to enable economic and uniform implementation of UHPC in large-scale projects and resource-limited regions, as well as creation of databases, localized guidelines, and practical standards to facilitate design, evaluation, and quality control in real-world projects.
- The further development of UHPC should be interdisciplinary, model-precise, sustainable materials development, and the establishment of a firm link between laboratory knowledge and industrial application. The success of green, affordable, and durable concretes depends on such

synergies among materials researchers, structural engineers, environmentalists, and data analysts in these paths.

Therefore, extensive large-scale experimental studies, the development of open-access databases, and pilot projects under real-world conditions play essential roles in advancing UHPC technology and developing stricter design provisions.

10. Conclusion

This systematic review clearly demonstrates that fiber reinforcement is essential for significantly enhancing the mechanical and thermal performance of UHPC. Among the various fiber systems analyzed, the hybrid combination of 1.65% steel fibers with 0.5% polyvinyl alcohol (PVA) fibers consistently demonstrated the most favorable balance of mechanical strength, ductility, thermal resistance, and durability. This specific hybrid system enhanced compressive strength by up to 30%, flexural strength by up to 50%, and tensile strength by up to 55% compared to fiber-free UHPC, while also effectively reducing thermal-induced spalling at elevated temperatures up to 800°C.

Additionally, partial replacement of cement with supplementary cementitious materials such as slag, fly ash, or recycled glass was found to reduce CO_2 emissions by up to 40%, with minimal or positive effects on strength and durability, reinforcing the environmental sustainability of these UHPC formulations.

Key Quantitative Highlights

- Steel and hybrid fibers improve compressive strength by 25–30%, with UHPC mixes regularly achieving strengths between 110 and 150 MPa.
- Hybrid fibers combining steel with polymeric, basalt, or glass fibers deliver the highest improvements in flexural (up to 50%) and tensile strength (up to 55%).
- Polypropylene fibers and hybrid systems significantly mitigate thermal spalling risk and maintain mechanical integrity at temperatures from 600°C to 800°C.
- Sustainable binder substitutions enable significant CO_2 reductions (up to 40%) without compromising mechanical performance or long-term durability.

Qualitative Insights

- The dense matrix structure of UHPC enhanced by optimized fiber systems ensures minimal permeability, sustaining structural integrity and preserving 80–90% of initial mechanical strength over 5–10 years under cyclic and aggressive environmental conditions.
- Steam or thermal curing can reduce creep by up to five times, while additives and internal curing effectively control shrinkage.
- Fiber content directly influences rebar bonding strength; advanced nonlinear models better predict bond behavior, enhancing practical design accuracy.
- Incorporating recycled and locally available materials promotes sustainability goals without sacrificing performance.
- Despite laboratory success, challenges remain in industrial scalability—uniform fiber distribution and curing optimization require further research and practical guidelines to ensure consistent large-scale quality.

Practical Recommendations

For engineers and practitioners seeking a fiber reinforcement strategy that balances performance, cost-effectiveness, environmental sustainability, and availability, the hybrid fiber system of steel (around 1.65%) combined with PVA fibers (0.5%) in UHPC stands out as the optimal choice. This system leverages the complementary mechanical advantages of steel and polymer fibers, ensuring superior strength, toughness, and thermal resistance suitable for demanding structural applications while supporting sustainable construction objectives through partial cement replacement.

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