

Challenges and Opportunities in Scaling Eco-Friendly Ultra-High-Performance Concrete with Hybrid Fibers: A Bibliometric and Technical Review

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Abstract. Ultra-high performance concrete exhibits excellent mechanical properties, such as high compressive strength, good durability, and structural reliability. However, its application is currently hampered by very high cement consumption and a considerable amount of embodied carbon, which is significantly dependent on the energy intensive use of steel fibers. The study conducts a technical and bibliometric review of sustainable UHPC systems that employ hybrid fiber reinforcement and supplementary cementitious materials. A systematic literature review on SCMs and UHPC has been analysed through VOSviewer to identify trends of research, collaboration networks, and thematic clusters of UHPC research. The findings show an increasing trend towards sustainability-oriented mix design in the field of UHPC, characterized by the use of high volume SCMs, optimization of particle packing, and hybrid fiber systems that combine steel fibers with polypropylene, basalt, or glass fibers. Sustainability assessments also indicate that cement production and steel fibers are the largest contributors to embodied carbon in UHPC, and that SCM substitution and hybrid fiber optimization can provide a reduction of up to 40-50 % in global warming potential of UHPC. Although encouraging laboratory scale performances were obtained, large scale implementations are still hindered by material variability, fiber dispersion, cost issues, and lack of standardization.

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1 Introduction

Ultra-High Performance Concrete (UHPC) is a family of highly advanced cement-based composites designed to exhibit compressive strengths generally greater than 120 MPa, high tensile resistance thanks to the use of fibers, and excellent durability as a result of their extremely dense microstructure[1]. The primary attributes that govern the performance characteristics of UHPC are the achievement of optimized particle packing; very low water-to-binder ratios, and the complete omission of coarse aggregate particles to produce a material with virtually zero porosity and therefore improved resistance to the ingress of chlorides and freezing/thawing damage. While UHPC demonstrates superior mechanical and durability properties compared to conventional concrete, it is also characterized by the need for relatively high amounts of binder, typically within the range of 800 to 1000 kg/m³, and the requirement for the inclusion of steel fibers to provide the post-cracking ductility characteristic of fiber reinforced composite systems. UHPC does not demonstrate the same degree of ductility as some other composite systems when not provided with sufficient fiber content to prevent catastrophic failure, and thus fiber systems are essential to the structural application of UHPC.

The environmental benefits of using UHPC are largely outweighed by several key drawbacks. The large amounts of cement required to achieve the desired mechanical properties result in a significant amount of CO₂ being emitted during the manufacturing process[2][3]. The production process for steel fibers used in UHPC requires a considerable amount of energy and, therefore adds to the environmental impact of the composite system[4]. The reliance on traditional silica fume as a micro-filler to improve the performance characteristics of the matrix phase of the composite system can be costly, difficult to obtain, and limited by supply chain logistics. All of these factors have created a barrier to the widespread adoption of UHPC as an alternative to traditional concrete in the construction industry[5].

Research in the field of UHPC is rapidly evolving away from an exclusive focus on improving the mechanical properties of the composite system toward an emphasis on integrating the environmental performance of the composite system. Several researchers are now exploring the use of high volumes of supplementary cementitious materials (SCMs) to reduce the amount of clinker required in the composite system and to maintain the mechanical performance of the composite system. These SCMs include ground granulated blast furnace slag, fly ash, calcined clay, and limestone powder[6]. Researchers are also developing advanced particle packing models that will allow for the use of smaller binder content without reducing the density of the composite system. Ternary and quaternary binder systems are also becoming increasingly common to enhance the chemical reactivity of the binder phases and to refine the microstructure of the composite system. Alkali activated and geopolymer based UHPC systems are also being developed to further reduce the carbon intensity of the composite system. However, researchers have identified several major issues that need to be addressed before these systems can be widely adopted, including: (i) the shrinkage of the matrix phase of the composite system, (ii) the bond between the fibers and the matrix phase of the composite system, and (iii) the long-term durability of the composite system.

In addition to advances in binder technology, hybrid fiber reinforcement systems are also emerging as a key strategy to enhance the performance characteristics of the composite system while potentially allowing for the optimization of material usage. Hybrid systems typically consist of macro-scale steel fibers and micro-scale fibers, such as polypropylene, glass, or basalt, which work together to provide multi-scale crack control. Polypropylene fibers, for example, can help to limit early age cracking and reduce thermal spalling of the matrix phase of the composite system, while steel fibers can provide the post-cracking bridging and residual load carrying capacity. By combining these two types of fibers,

researchers hope to develop composite systems with improved toughness and durability, while also reducing the amount of steel fibers used in the composite system[7]. This could ultimately lead to a reduction in the amount of CO₂ emitted during the production of the composite system. Researchers have also identified fiber dispersion and orientation control, and rheological compatibility as key parameters for achieving consistent performance characteristics at larger production scales[8].

A combination of bibliometric mapping and technical assessments of the literature in this area is necessary to determine the current state of the art in the field and to identify potential areas where further research is needed[9]. By using bibliometric mapping techniques, researchers can visualize the different themes that currently exist in the field, such as hybrid fiber mechanics, sustainable binders, durability performance, and environmental assessment, and gain insight into how the research agenda in this area has evolved since 2018. Building on the top of the bibliometric mapping analysis, researchers can synthesize the literature on sustainable mixture design, hybrid reinforcement mechanisms, durability performance, and lifecycle implications of UHPC. The review will also evaluate the major barriers to large-scale implementation of UHPC and outline future research directions that will allow researchers to optimize the mechanical, environmental, and economic performance characteristics of UHPC. The findings of the study support the development of scalable, environmentally efficient UHPC systems that meet the requirements of current decarbonization goals in the construction industry.

2 Methodology

2.1 Literature Selection Protocol

A systematic literature search strategy was implemented to identify relevant publications on materials and structural engineering that have been published in a peer reviewed format using the Scopus database to maximize the breadth of literature searched. The timeframe of the search was limited to 2010-2025 in order to show the transition of UHPC research from performance-based research to current sustainability based research.

A search query that was designed to retrieve relevant research on "Ultra High Performance Concrete" or "UHPC", which are the primary types of fibers of interest; i.e., "Hybrid Fiber," "Steel Fiber," "Polypropylene Fiber," "Basalt Fiber," and those which relate to sustainability; i.e., "Supplementary Cementitious Materials," "Low-Carbon," "Green Concrete," and "Life Cycle Assessment." In addition to being peer reviewed, only research reports and reviews were considered as part of this study. Research was selected if it met one or more of the following criteria:

- Experimental investigation of hybrid fiber reinforced UHPC;
- Sustainable modification of the binders of hybrid fiber reinforced UHPC utilizing supplementary cementitious materials (SCMs), or other activators;
- Environmental assessment or carbon footprint analysis associated with hybrid fiber reinforced UHPC.

Research focused solely on structural models without material characterization, or conventional UHPC without relevance to sustainability were excluded from consideration. Titles and abstracts were screened for thematic relevance, and duplicate studies were removed before the remaining data set was analyzed through both bibliographic mapping and technical synthesis.

2.2 Bibliometric Analysis Using VOSviewer

Bibliometric mapping was conducted using VOSviewer to examine thematic evolution and research concentration within the selected dataset. Four complementary analyses were performed. Keyword co-occurrence analysis was carried out to identify dominant research themes and the relationships among frequently appearing terms in the literature. Overlay visualization was used to detect emerging research directions by analyzing the average publication year associated with keywords, which helps highlight newly developing topics. Country collaboration network analysis was performed to evaluate the global distribution of research activity and the intensity of international partnerships among contributing countries. Source level analysis was also conducted to identify the most influential journals and to understand the concentration of publications across core outlets in the field.

Minimum occurrence thresholds were applied to keywords to improve clarity and reduce noise in the generated clusters. Fractional counting was adopted to normalize link strength and ensure balanced representation of coauthored contributions. The resulting clusters were interpreted based on node size, proximity between nodes, and total link strength, which collectively indicate the importance and connectivity of research topics. This approach enabled the identification of major research domains, including hybrid reinforcement mechanisms, sustainable binder systems, durability performance of advanced materials, and the integration of life cycle assessment within concrete research.

3 Bibliometric Analysis of Eco-UHPC Research

To visually depict research collaborations and thematic developments in the area of eco-friendly UHPC, bibliometric mapping using VOSViewer has been employed. The methodology used for the analysis involved the use of three types of analyses, including: author collaboration networks; country-based collaboration patterns; and keyword co-occurrence networks. Each of these network types provides a different type of information regarding who the major contributors to UHPC research are; how research is distributed globally; and what research themes are evolving. These visualization tools allow identification of the main research clusters that have developed in UHPC research, and assist in identifying new research trends for the development of UHPC, especially those areas dealing with hybrid fiber reinforcement, sustainable binder systems, and performance durability.

3.1 Author Collaboration Network

The author collaboration network illustrates the primary research groups that have contributed to the development of UHPC. In Figure 1, it can be seen that there exists a dense cluster around highly prolific researchers, including but not limited to Wu Cheng Qing, Wang Jing Quan, Zhang Wei, Shao Xu Dong, and Fang Zhi, illustrating a very high level of collaborative effort by top-tiered research institutions on high-strength cementitious materials. Larger nodes represent authors with greater numbers of publications and citations, and lines connecting the nodes illustrate co-authoring relationships. Smaller peripheral clusters indicate smaller research groups and emergent contributors to UHPC. Additionally, the gradient overlay colors also suggest an increased collaboration over time, indicating an increase in inter-disciplinary collaboration over recent years in the areas of hybrid fiber reinforcement, sustainable mixes, and enhanced durability of UHPC.

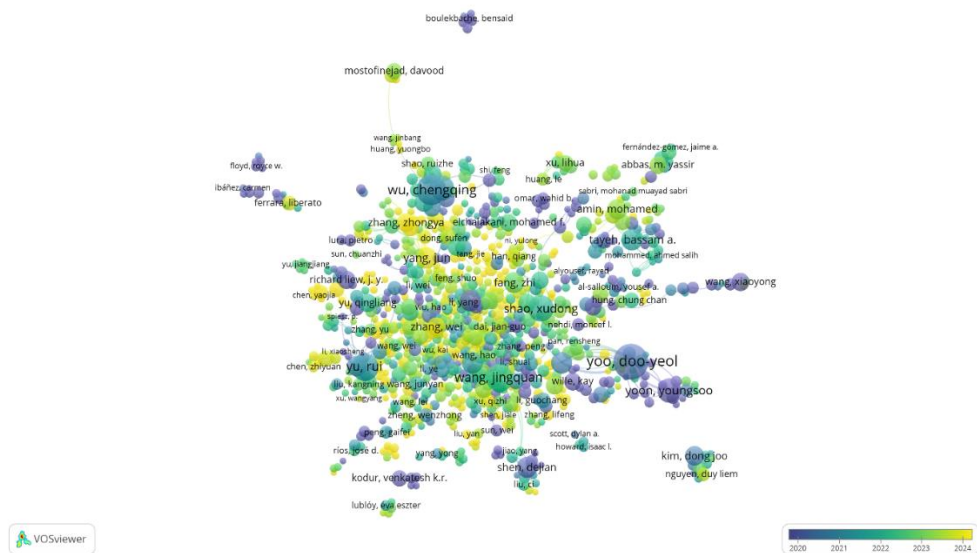


Fig. 1. Author collaboration network in eco-friendly UHPC research visualized

3.2 Country Collaboration Network

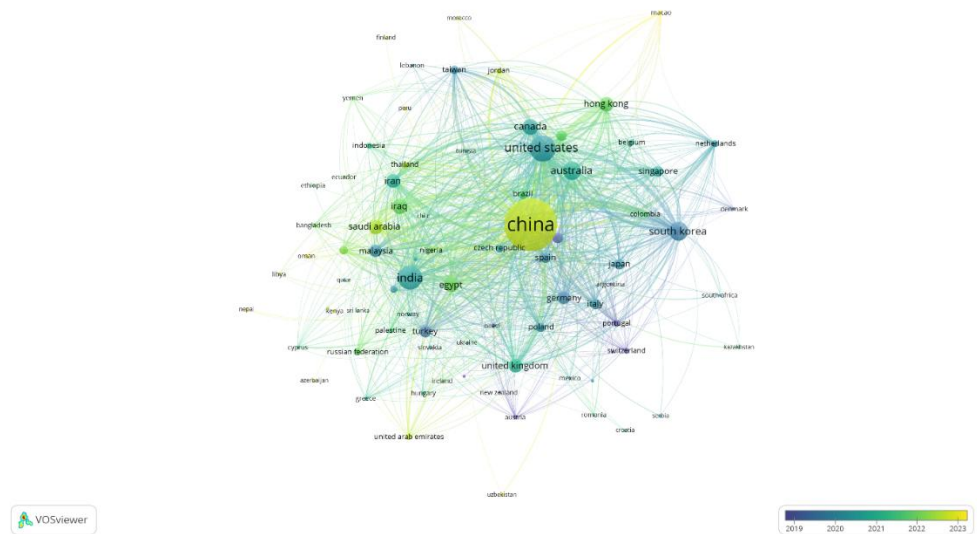


Fig. 2. Country collaboration network in eco-friendly UHPC research visualized

The country collaboration network displays how research and development activities related to UHPC are distributed globally. A very large node representing China dominates the center, as shown in Figure 2, which has many connections to other countries, demonstrating that there is significant collaboration at a global level in relation to UHPC research and development. Research activities were also identified in the United States, South Korea, India, Australia, Germany, and the United Kingdom, which demonstrates a high degree of international cooperation in the development of UHPC. The density of the connections

4.1 Cement Reduction and SCM Integration

Reducing clinker usage is the primary method of enhancing the sustainability of UHPC. Studies from recent years show that using SCMs in place of cement, such as; ground granulated blast furnace slag (GGBS), fly ash, calcined clay, and limestone powder, has been shown to greatly decrease the amount of embodied carbon while maintaining compressive strength greater than 120 MPa. Slag acts as an enhancer of long term strength by reacting as a latent hydraulic, whereas fly ash enhances the workability of UHPC; however, at high replacement levels may decrease the early age strength. The combination of calcined clay and limestone powder generates a refined pore structure through both pozzolanic and carboaluminate reaction processes. Researchers have demonstrated increased use of ternary and quaternary mixes to provide better overall performance related to both reactivity and durability, as well as environmental performance.

Most recent strategies for optimizing binders in UHPC are focused on maximizing binder efficiency and not simply substituting SCMs. Using a tailored multi-SCM system has enabled researchers to achieve reductions in clinker by 40-60 percent with minimal compromises in mechanical performance. These systems also decrease the hydration heat of the binder and improve the resistance of the UHPC to chloride ingress. However, the quality and reactivity of SCMs remain a major issue related to the industrial scale production of UHPC.

4.2 Particle Packing and Microstructure Densification

Binder content reduction in UHPC has been largely driven by development in particle packing optimization technology. Many of the studies on binder content have used the modified Andreasen and Andersen (MAA) model to design continuous particle size distributions that will help to create a minimum amount of void space within the concrete, thereby creating a dense matrix[10]. In many studies, the researchers have optimized the distribution modulus ($q= 0.20 - 0.25$), which resulted in higher packing densities, better rheology, and lower binder contents while still retaining comparable levels of strength. Optimization of fine aggregate gradation and micro-fillers has also contributed to the decrease in capillary porosity and improved the bonding between the fibers and matrix. Micro-structural analysis also confirmed a refinement of the pore structure and an enhancement of the interfacial transition zone in eco-UHPC systems created based upon packing models. This has enabled researchers to retain comparable levels of compressive strength and durability as compared to high binder content UHPC when using less binder content. As such, particle packing represents a key mechanism for optimizing performance per carbon.

4.3 Alkali-Activated and Geopolymer UHPC

Geopolymers and alkali-activated UHPC systems can provide a viable alternative route for a significant reduction of CO₂ emissions through the elimination or drastic reduction of Portland cement. Most of these systems rely on using slag, fly ash, or metakaolin activated by alkaline solution to achieve similar levels of compressive strength as traditional UHPC and have been shown to reduce embodied CO₂ by 30–70%, depending upon the level of energy required for the activation process. The hybrid fiber reinforcement in geopolymers demonstrates encouraging mechanical properties. However, there are also many barriers to overcome before this type of material is used for structural applications, including early age shrinkage, long term durability, and the behavior of the fiber-matrix interface. The rapid reaction kinetics associated with geopolymers can potentially lead to increased autogenous shrinkage, and additional testing is necessary to verify the long term durability performance

of geopolymers exposed to severe environmental conditions. The standardized mix designs and long term field studies are currently limited; therefore, while geopolymer UHPC has high potential for decarbonizing construction materials, widespread use of this technology will require additional research.

Table 1. Representative Eco-UHPC Mix Designs

Study	Cement (%)	SCM (%)	Fiber Type	Fiber Vol %	f'c (MPa)
Study A (Slag-based UHPC)	60	40 (GGBS)	Steel	2.0	130–145
Study B (Fly ash ternary)	55	45 (Fly ash + Silica fume)	Steel + PP	2.0	125–140
Study C (Calcined clay blend)	50	50 (Calcined clay + Limestone)	Steel	1.5	120–135
Study D (Quaternary SCM mix)	45	55 (Slag + Fly ash + Limestone)	Steel + Basalt	1.8	125–150
Study E (Alkali-activated UHPC)	0 (OPC-free)	100 (Slag/Fly ash activated)	Steel + PP	1.5–2.0	120–140

5 Hybrid Fiber Reinforcement and Multi-Scale Toughening

5.1 Fiber Systems in UHPC

Steel remains the most commonly used reinforcement in UHPC primarily due to its superior tensile properties of high strength and high modulus, along with excellent crack bridging capability, and thus is generally added at volumes of 1 – 3%. The addition of the steel fibers provides load resisting capacity beyond the cracking point of the UHPC and also enhances the strain hardening response[11]. However, a significant increase in the amount of steel fiber is associated with increased cost and an increased complexity in the mixing process, along with an increase in the embodied carbon, which has led to research into hybrid alternatives that may replace all or part of the steel fiber content.

Polypropylene (PP), glass, and basalt fibers have been introduced as micro secondaries to reinforce the UHPC. Polypropylene fibers help to prevent plastic shrinkage and explosive spallation at elevated temperature conditions because melting induced pore pressure reduction can occur. Glass and basalt fibers offer enhanced tensile performance when cracks form at the micro level and will provide corrosion resistant performance over the life of the structure. Hybrids of steel + polypropylene and steel + basalt are being developed to improve multi scale crack control while providing potential reductions in the overall amount of steel fiber.

5.2 Multi-Scale Crack Bridging Mechanism

Hybrid fiber systems function by a hierarchical toughening mechanism. Microfibers (glass, basalt, PP) are used to prevent and limit crack growth and initiate cracking during early stages of cracking and at micro-crack levels. At larger crack widths, macro steel fibers are activated to support load transfer across cracked sections and increase ductility and residual strength. The sequential activation of the different fiber types results in increased energy absorption

compared to a monofibers system. The combination of the two fiber types also increases the number of cracks that develop, decreases the location of the cracks, and will result in improved fatigue performance due to the ability to distribute stresses at various length scales. The use of hybrid systems can improve the structural resiliency of a structure while providing an optimal amount of fiber for a given application. A conceptual example of the hybrid mechanism is shown in Figure 4.

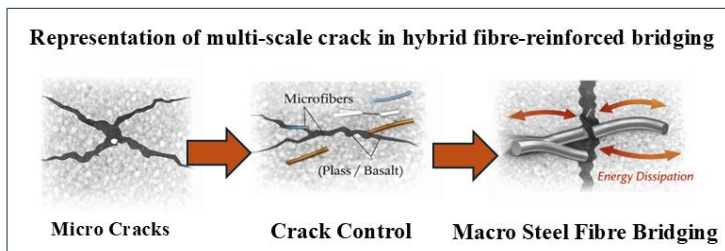


Fig. 4. Hybrid Fiber Mechanism Schematic

5.3 Mechanical Performance Enhancement

Hybrid fibers have a relatively small impact on compressive strength and typically increase the strength from 0-10%, primarily because of the confining effect created by the hybrid system. In contrast, the hybrid fiber combination significantly improves both the flexural strength and post-crack performance compared to the non-fibrous mixes[1]. A common increase in flexural strength as high as 20-50% above that for non-fibrous mixes can be seen in comparison studies. The toughness and residual strength performance under bending and impact loads improve substantially. Hybrid fiber combinations generally exhibit superior crack resistance and deformability than single type steel fiber combinations when using similar total amounts of steel fiber[12]. Thus, it is possible to optimize performance while reducing the amount of steel used and providing an environmental benefit through reduced use of this material. The performance of hybrid fiber composites is heavily dependent upon the hybrid fiber volume fraction, length-to-width ratio of each hybrid fiber, degree of fiber dispersion, and the nature of the fiber-matrix interface.

Table 2. Mechanical Performance Comparison

Fiber System	Compressive Strength (MPa)	Flexural Strength (MPa)	Residual Performance
No Fiber	120–150	8–12	Brittle failure, low energy absorption
Steel (2%)	125–155	18–25	High post-cracking strength, strain hardening
Steel + PP	125–150	20–28	Improved crack control, enhanced fire resistance
Steel + Basalt	130–155	22–30	Higher ductility, improved durability
Steel + Glass	125–150	20–27	Improved tensile behavior, corrosion resistance

6 Durability and High-Temperature Performance

6.1 Chloride Migration Resistance

The material properties of UHPC have an inherent very low permeability to chlorides. This is mainly due to both the high density of the microstructure and the fine porosity. The addition of high volume SCMs, including slag and calcined clay, will further reduce the ability of chlorides to migrate through the matrix by improving secondary C-S-H formation and also by refining the porosity. The results from testing for chloride migration coefficients for optimized eco-UHPC indicate that they are substantially lower than those for conventional high strength concrete; this indicates their potential for use in marine and other highly aggressive environments[13]. While there may be a limited effect of hybrid fiber reinforcement on the diffusion of chlorides directly, it can have an indirect effect by limiting crack width and thus limiting the potential for cracks to be connected. Improved crack distribution within hybrid systems minimizes the paths available to ions entering the material, and therefore enhances long term durability performance.

6.2 Freeze–Thaw Performance

The low permeability & limited capillary porosity in UHPC provide strong resistance to freeze-thaw cycles. Most eco-UHPC mixtures that incorporate SCMs retain high relative dynamic modulus values following repeated freeze-thaw exposure, provided that the microstructure is dense and well-graded. Lower water absorption and smaller pore networks limit internal hydraulic pressure development. Hybrid fiber systems further enhance freeze-thaw durability by mitigating crack propagation during cyclic loading. Distributed crack control provided by hybrid reinforcement reduces scaling and surface deterioration, thus supporting long-term durability under cold climate conditions.

6.3 Fire Resistance and Residual Strength

Fire performance remains a critical concern for UHPC due to its dense microstructure, which can lead to explosive spalling under rapid heating. Hybrid fiber systems, particularly those incorporating polypropylene fibers, significantly reduce spalling risk. Polypropylene fibers melt at elevated temperatures, creating vapor escape channels that relieve internal pore pressure. Steel fibers contribute to residual load-bearing capacity after thermal exposure by maintaining crack bridging even at elevated temperatures. Hybrid combinations therefore, provide both spalling mitigation and post-fire structural integrity. Residual compressive and flexural strengths of hybrid UHPC after exposure to 400–600°C are generally higher than mono-fiber systems, although strength degradation becomes significant beyond 800°C.

Table 3. Durability Performance

Mix Type	Chloride Resistance	Freeze–Thaw Resistance	Fire Resistance
Conventional UHPC (Steel)	Very low permeability	Excellent	Spalling risk under rapid heating
High-SCM UHPC	Extremely low diffusion coefficient	Excellent	Similar to conventional; spalling possible

Steel + PP Hybrid	Very low; improved crack control	Excellent; reduced surface scaling	Reduced spalling; improved residual strength
Steel + Basalt Hybrid	Very low	Excellent	Improved crack stability at moderate temperatures
Alkali-Activated UHPC	Low to moderate (matrix-dependent)	Good to excellent	Requires further validation; shrinkage concerns

7 Sustainability Assessment and Life Cycle Implications

7.1 Embodied Carbon Contributors

The environmental footprint of UHPC is dominated by cement production, which typically accounts for 60–80% of total cradle-to-gate global warming potential (GWP) due to high clinker content. The large binder dosage required to achieve ultra-dense microstructures significantly amplifies this contribution. Steel fibers represent the second major carbon source, particularly at volume fractions above 2%, owing to energy-intensive steel manufacturing[14]. Although used in smaller quantities, their impact per kilogram is high compared to cementitious materials. Transport, grinding, and processing of fine powders and specialty admixtures also contribute to embodied emissions, particularly when silica fume or imported materials are used. Consequently, sustainability evaluation of UHPC must consider not only cement reduction but also fiber dosage, supply-chain logistics, and processing energy.

7.2 Carbon Reduction Pathways

High-volume SCM replacement remains the most effective strategy for lowering embodied carbon in UHPC. Replacement levels of 40–60% using slag, fly ash, or calcined clay have demonstrated substantial GWP reductions while maintaining target mechanical performance. Ternary and quaternary systems further optimize reactivity and packing density, improving strength efficiency per unit binder. Hybrid fiber optimization provides an additional pathway by enhancing crack control and toughness while potentially reducing total steel fiber content. By combining microfibers with lower steel dosages, comparable structural performance can be achieved with reduced environmental impact. Local sourcing of SCMs and aggregates further minimizes transport-related emissions, improving overall life cycle performance.

7.3 Integrated Mechanical–Environmental Optimization

Recent studies have shown the shift from a traditional strength based approach to designing mixes of ultra-high-performance concrete to a multi objective optimization framework which combines both the mechanical properties and durability of the concrete with its environmental impact and cost. The use of metrics like the strength to carbon ratio or performance per CO₂ allows for the direct comparison of traditional UHPC systems and their eco optimized counterparts. In addition, this will support a rational approach to making decisions regarding reducing carbon emissions versus simply reducing carbon emissions through individual optimizations.

The future will see LCA used in an increasing number of cases in early stage mix design, utilizing data driven models and optimization techniques. Integrated frameworks combining all aspects of concrete production, including LCA, are critical to enabling the scale up of eco

friendly hybrid UHPC systems. These frameworks are also important in order to ensure that the long term durability and mechanical reliability of the ecofriendly UHPC systems are not sacrificed during the process of reducing carbon emissions.

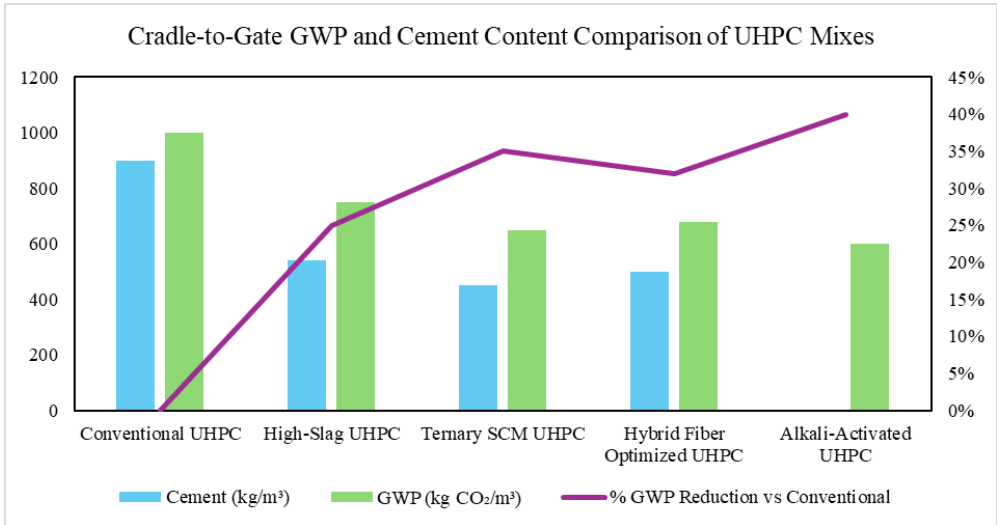


Fig. 5. Cradle-to-Gate global warming potential of conventional and eco-optimized uhpc systems.

Table 4. LCA Comparison of UHPC Mixes

Mix Type	Cement (kg/m³)	Fiber (kg/m³)	GWP (kg CO ₂ /m³)	% Reduction vs Conventional
Conventional UHPC (2% Steel)	900	157	950–1050	–
High-Slag UHPC (40% GGBS)	540	157	700–780	20–30%
Ternary SCM UHPC (50% replacement)	450	140	600–700	30–40%
Hybrid Fiber UHPC (Reduced Steel + PP)	500	120 (Steel + PP)	620–720	25–35%
Alkali-Activated UHPC	0 (OPC-free)	130	500–650*	35–50%

8 Challenges in Scaling Eco-Friendly Hybrid UHPC

While research has shown great potential for the use of sustainable hybrid UHPC at the lab scale, there are many reasons why this technology is limited in its application at a larger scale. One major reason for the limitation of the application of sustainable hybrid UHPC at a larger scale is variability in raw materials, particularly those used as SCMs such as slag, fly ash, or calcined clay[15]. Variability in SCMs can arise from differences in their chemical composition, particle size (fineness), and rate of reaction, which will affect the rate of hydration, ultimate strength, and durability of the resulting structure. As SCM's are utilized in increasing amounts, variability in SCM quality will make it increasingly difficult to

standardize mixes and control quality, particularly if the goal is to utilize SCMs at a level greater than 40% in the overall mix.

Further challenges exist for fiber dispersion and workability of sustainable hybrid UHPC during industrial production. Higher powder content and lower water/binder ratios create more viscous mixtures that become much harder to uniformly distribute fiber in larger capacity mixers. Common problems with the use of fibers include the formation of "fiber balls," separation of fibers within the mix, and poor pumpability, especially when using hybrid combinations of fibers. Microfibers provide excellent crack resistance but may cause an increase in plastic viscosity, leading to poor flow and castability of the fresh mix. To achieve a stable rheology of the fresh mix while maintaining acceptable mechanical characteristics, the admixture and mixing protocol for sustainable hybrid UHPC needs to be carefully developed and optimized, which has not been standardized for the majority of hybrid eco-UHPC systems.

The economic and regulatory issues also limit the ability to apply sustainable hybrid UHPC at a larger scale. Currently, the cost of steel fibers, high-performance admixtures, and the specialized equipment required to process sustainable hybrid UHPC are significantly more expensive than traditional concrete. Although SCM substitution can reduce the cost of cement and decrease the environmental footprint associated with cement production, these reductions in cost and environmental footprint may be offset by increased costs associated with processing complex mixes and controlling the quality of sustainable hybrid UHPC. Sustainable hybrid UHPC also lacks universally accepted performance-based design specifications and standards, limiting acceptance of sustainable hybrid UHPC in structural applications. The industry faces additional constraints related to energy consumption required to produce sustainable hybrid UHPC in commercial quantities, the distance that sustainable hybrid UHPC must be pumped to reach the construction site, and the lack of established and widely accepted field placement techniques for sustainable hybrid UHPC. All of these challenges need to be addressed through the coordination of material standardization, the development of commercially viable and efficient methods for producing sustainable hybrid UHPC, and the establishment of regulatory frameworks to ensure the safe and economically feasible use of sustainable hybrid UHPC.

9 Opportunities and Future Research Directions

A large amount of future work for developing sustainable hybrid UHPC will involve the development of combined optimization methods that evaluate mechanical performance, environmental impact, and cost. Methods for optimizing multiple objectives relative to each other with respect to embodied carbon and economic feasibility will enable the comparison of different combinations of performance characteristics on a per unit of carbon basis. The use of recycled steel fibers generated from industrial waste or end-of-life products represents a potentially significant opportunity to reduce the environmental impacts associated with UHPC production, especially if the geometric consistency and mechanical property consistency of the fibers is maintained. Standardization of environmental inventory data for fiber reinforced UHPC is also important to ensure that comparative life cycle assessments are reliable and consistent.

The increased use of data driven and computationally based tools is anticipated to enhance the process of designing new UHPC mixes. The integration of artificial intelligence with machine learning algorithms has the potential to quickly determine the relationship between UHPC mix composition, strength, durability, and embodied carbon. These relationships can then be used to significantly reduce the number of experimental trials needed to develop new UHPC mixes. In addition, the emerging capability of advanced manufacturing technologies, including 3-D printing, will provide the ability to control fiber orientation and distribution

within the matrix of UHPC. This will have the potential to increase the structural efficiency of UHPC while simultaneously reducing the volume of materials required to produce the same structural properties.

The development of multi-scale micromechanical models that couple the effects of hydration kinetics, pore structure evolution, and fiber/matrix interactions, at the microscopic scale, will provide the fundamental understanding necessary to accurately predict the long term behavior of eco-UHPC. Laboratory testing of UHPC should be supported by long term field testing of UHPC structures exposed to real environmental conditions. Only through the collection of reliable long term service life data will there be sufficient evidence to support the development of performance based codes for eco-UHPC and acceptance of the technology by the construction industry. The research areas will contribute to advancing hybrid UHPC from an experimentally feasible technology toward a standardized, scalable, and sustainable technology.

10 Conclusion

The study highlights that hybrid fiber reinforcement plays a central role in enhancing the structural reliability of eco-friendly UHPC systems. While compressive strength improvements are generally modest, significant gains are observed in flexural performance, crack control, toughness, and residual strength under thermal exposure. The integration of micro- and macro-scale fibers enables multi-level crack bridging, improving durability and mitigating spalling risks. Concurrently, high-volume incorporation of supplementary cementitious materials such as slag, fly ash, calcined clay, and limestone powder has proven essential for reducing clinker dependency and lowering embodied carbon without compromising target strength levels. Bibliometric mapping indicates a marked increase in sustainability-oriented UHPC research after 2018, with growing emphasis on hybrid reinforcement, life cycle assessment, and alternative binder systems. Despite promising laboratory findings, large-scale implementation remains constrained by material variability, fiber dispersion challenges, cost considerations, and the absence of unified performance-based codes. Advancing eco-friendly hybrid UHPC requires integrated mechanical–environmental optimization frameworks, standardized LCA databases, and validated field performance data to support reliable and scalable adoption in infrastructure applications.

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