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A Comprehensive Review on Ultra-High Performance Concrete: Composition, Properties, and Applications

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REVIEW

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ABSTRACT

Ultra-High Performance Concrete (UHPC) has emerged as a leading construction material across diverse engineering applications due to its exceptional mechanical properties and durability that exceed those of conventional concrete. This comprehensive review explores UHPC's material composition, production additives, behavior in both fresh and hardened states, and environmental durability characteristics. The low water-to-cement ratio combined with a high binder content and the use of superplasticizers result in a densely compacted microstructure, substantially enhancing UHPC's strength. Pozzolanic additives—including silica fume (SF), metakaolin (MK), fly ash (FA), and ground granulated blast furnace slag (GGBFS)—contribute to reduced cement consumption while improving long-term durability by enhancing permeability resistance, sulfate attack mitigation, and chloride ion durability. The integration of nanomaterials such as nano-silica (NS), carbon nanotubes (CNT), and graphene oxide (GO) increases the reactive surface area within the matrix, leading to a more uniform and denser microstructure. Fiber reinforcements—comprising steel, synthetic, glass, or hybrid fibers—impart ductility to UHPC, significantly boosting tensile and flexural strengths as well as energy absorption capacity, complementing its notable compressive strength. Fresh-state properties such as consistency, slump, and flowability are critical for manufacturability and application quality, with optimized mixtures delivering superior structural performance in terms of impact resistance, fatigue durability, and fracture mechanics. Additionally, UHPC demonstrates outstanding resistance to freeze-thaw cycles, sulfate and acid attacks, and chloride ingress, making it highly suitable for infrastructure exposed to aggressive environments. This review synthesizes the current understanding of UHPC's technical advancements and multifaceted benefits, positioning it as a next-generation sustainable construction material that meets the demanding requirements of modern infrastructure.

Keywords: Ultra-High Performance Concrete (UHPC), Mechanical properties, Durability, Seismic performance, Fiber reinforcement, Sustainability.

INTRODUCTION

Ultra-High Performance Concrete (UHPC) has attracted significant attention in recent years as one of the most innovative and promising materials in civil engineering. Owing to its exceptional mechanical properties, superior durability, low permeability, and advanced microstructure, UHPC offers substantial advantages in complex engineering applications—particularly in high-rise buildings, bridges, infrastructure projects, and marine structures (Azmee & Shafiq, 2018; Cao et al., 2020). The fundamental technical development of UHPC gained momentum in the 1990s with the concrete mixtures developed by de Larrard and Sedran (1994), which achieved compressive strengths exceeding 150 MPa (Fan et al., 2023). The unique properties of UHPC stem from its carefully optimized material composition and chemical structure. The low water-to-cement ratio, the use of superplasticizers, SF, and micro-scale optimized aggregates contribute to the formation of a much more homogeneous and dense cement matrix compared to conventional concrete (Akhnoukh & Buckhalter, 2021; Liew et al., 2016). The material composition and chemistry of UHPC have critical effects not only on its mechanical performance but also on the long-term durability of the concrete (Bahmani & Mostofinejad, 2022). The fresh concrete behavior of UHPC plays a significant role during both the production and application stages. Parameters such as flowability, slump values, and consistency directly influence the workability and quality of application. Thanks to the use of specialized

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admixtures, UHPC mixtures can achieve high flowability, allowing for the easy casting of structural elements with complex geometries (Fan et al., 2023). Among the mechanical properties of UHPC are its high compressive strength, ranging from 125 to 250 MPa, exceptional tensile strength of 5 to 12 MPa, and notable flexural strength reaching up to 48 MPa (Richard & Cheyrezy, 1995). Fiber reinforcement enhances ductility and energy absorption capacity by preventing crack formation, leading to significant performance improvements, especially under impact and dynamic loading condition (Xu et al., 2021; Yang et al., 2022).

In terms of durability and environmental performance, UHPC demonstrates excellent behavior due to its extremely low permeability and high density. Its water absorption rate is approximately 60 times lower than that of conventional concrete, and its carbonation rate is five times slower (Sood & Vesmawala, 2024). As a result, UHPC offers a significant advantage in protecting reinforcing steel against corrosion and substantially increases the service life of structures (Amran et al., 2022). Microstructural characterization is one of the fundamental reasons behind the superior mechanical properties of UHPC. The microstructure of UHPC is optimized through a high packing density of particles and the use of fine binder materials. This dense microstructure enhances the internal integrity of the concrete and significantly reduces the penetration of harmful substances (Bahmani & Mostofinejad, 2022). The production, application, and rheological properties of UHPC are critically important for its effective use in the field. The rheological behavior of UHPC directly influences its performance during mixing, transportation, and placement. Therefore, detailed analysis and optimization of rheological characteristics are essential for the widespread adoption of UHPC in construction practice (Fan et al., 2023).

Sustainability and environmental assessments are becoming increasingly important in the evaluation of modern construction materials. UHPC has the potential to reduce environmental impact through the partial replacement of cement with pozzolanic or other sustainable additives. In this way, it becomes possible to lower carbon emissions associated with material production (Lee et al., 2017). The structural applications and performance evaluation of UHPC are among the most prominent areas of its widespread use. With the growing implementation in the industry, UHPC's potential for use in various engineering projects is gaining increasing recognition. In this context, ongoing research and development efforts aimed at overcoming the current limitations of UHPC and promoting its broader application are attracting significant interest from both academic and industrial communities (Fan et al., 2023).

This review provides a thorough and critical assessment of the existing literature on UHPC, encompassing its fundamental material characteristics, constituent components, and performance in both mechanical and durability aspects. Furthermore, it explores the diverse applications of UHPC across various sectors of civil engineering, highlighting its adaptability and potential to meet the demanding requirements of modern infrastructure projects. The study also addresses the current technological advancements and identifies key challenges that impede the widespread adoption of UHPC, such as cost, standardization, and scalability issues. Finally, future research directions are outlined with an emphasis on optimizing mix designs, enhancing sustainability through innovative material substitutions, and advancing practical implementation techniques to facilitate the transition of UHPC from experimental use to mainstream construction practice. This comprehensive evaluation aims to serve as a valuable resource for researchers, practitioners, and policymakers committed to advancing the development and application of UHPC in sustainable and resilient infrastructure systems.

MATERIAL COMPOSITION AND CHEMISTRY

Definition and Development of UHPC

UHPC is a type of concrete that stands out in modern civil engineering due to its superior strength, durability, and formability. Unlike conventional concrete, UHPC possesses a specially engineered microstructure characterized by an ultra-low water-to-binder ratio, reactive fine materials, and typically fiber reinforcement (Wen et al., 2022). According to the American Concrete Institute (ACI), UHPC is defined as a cementitious composite material with a compressive strength exceeding 150 MPa, exhibiting high ductility and exceptional durability (Wille & Naaman, 2011). The development of UHPC dates to research conducted in the late 1980s by the Bouygues company in France. During this period, various studies were carried out with the aim of developing concrete types exhibiting superior mechanical properties and durability beyond those of conventional concrete. The first commercial UHPC product was introduced on the market in 1996 under the name *Ductal*. This type of concrete stands out not only for its high strength but also for its ability to minimize shrinkage cracks, reduce chloride ion penetration, and provide excellent resistance to freeze-thaw cycles (Wille & Naaman, 2011). One of the most defining features in the development of UHPC is the optimization of its microstructure. This optimization is based on the principle of particle size distribution, which minimizes voids within the concrete and enables the formation of a highly dense matrix. This approach was first introduced through the concept of Reactive Powder Concrete (RPC). In this system, aggregate sizes are selected at the micro-scale, and reactive pozzolans such as quartz powder are incorporated to achieve a compact microstructure (Mala et al., 2021). Another significant advancement in the development of UHPC is the incorporation of fiber reinforcement. Metal or polymer-based fibers are used to enhance the ductility and crack control of UHPC. These fibers not only improve the tensile strength of the concrete but also promote a ductile fracture behavior. Fiber reinforcement is critically important in structural elements, as it helps reduce the risk of sudden failure and ensures greater ductility (Wang et al., 2024).

With advancing technology, the use of nano-scale additives in UHPC formulations has become increasingly widespread. Nano additives such as NS, CNT and GO further densify the microstructure of UHPC, enhancing properties such as strength and impermeability. For instance, the incorporation of NS increases the amount of calcium silicate hydrate (C-S-H) gels formed during cement hydration, resulting in a denser matrix and a significant reduction in porosity (Mala et al., 2021). The global use of UHPC is steadily increasing. Initially applied in bridge decks, this material is now widely used in various areas such as high-rise buildings, nuclear power plants, blast-resistant structures, and architectural elements. In particular, UHPC's high early strength offers significant advantages in precast construction systems by reducing time and labor costs (Wille & Naaman, 2011). In light of all these developments, the future of UHPC appears highly promising. Research on sustainable UHPC production models—supported by AI-assisted mix design, the use of environmentally friendly pozzolans, and recycled fibers—is expected to secure UHPC's long-term role in the construction industry. Furthermore, the integration of UHPC systems with smart sensors enables real-time monitoring and maintenance of structures (Wang et al., 2024; Wen et al., 2022). UHPC is not only a high-strength concrete (HSC) but also a long-lasting, multi-functional construction material with reduced environmental impact. Throughout its development, pioneering research—particularly in countries such as France, Germany, Japan, and the United States—has played a key role in advancing the material to its current state. In this context, UHPC is opening the door to a new era in engineering and redefining the limits of conventional concrete technologies (Wang et al., 2024).

Carboxymethyl cellulose (CMC), a water-soluble polysaccharide derivative, has been increasingly utilized in cementitious systems for its dispersing and suspension-stabilizing capabilities. In UHPC formulations, where low water-to-binder ratios and high fiber contents can lead to poor workability and fiber agglomeration, CMC offers distinct advantages. Recent studies have shown that CMC improves the homogeneity of UHPC mixtures by reducing fiber clumping and enhancing flow properties without compromising mechanical performance. Dehghanpour et al. (2022) demonstrated the effectiveness of CMC as a fiber dispersant in cementitious repair composite, noting significant improvements in the uniform distribution of steel and glass fibers. His research highlighted that even small dosages of CMC contributed to improved fiber-matrix bonding and enhanced compressive and flexural strengths. These findings align with broader literature emphasizing CMC's role in stabilizing particle suspension and preventing segregation. Thus, CMC presents a viable additive for optimizing the fresh and hardened-state properties of UHPCs, especially in fiber-reinforced applications (Dehghanpour et al., 2022).

Influence of Pozzolanic Materials on The Properties of UHPC

Pozzolanic additives are fine-grained minerals that react with cement hydration products to form secondary hydration compounds, thereby improving the mechanical and durability properties of concrete. In UHPC systems, the use of Pozzolanic materials (Figure 1) is of critical importance for enhancing the microstructure and optimizing the binder content. Since UHPC typically contains a high amount of cement, Pozzolanic materials such as FA, SF, MK, and GGBFS are incorporated to make the mixture more environmentally and economically sustainable (Mala et al., 2021). SF is one of the most used Pozzolanic additives in UHPC production. Due to its extremely fine particle size, it fills the voids within the cement matrix, resulting in a denser microstructure and improved durability. Moreover, SF reacts with CH formed during cement hydration to produce additional calcium-silicate-hydrate (C-S-H) gels, which enhance the compressive strength and impermeability of the concrete. For instance, UHPC mixtures containing 20% SF have demonstrated 28-day compressive strengths reaching up to

170 MPa (Abdellatief et al., 2023; Wille & Naaman, 2011). FA, on the other hand, contributes positively to the durability performance of UHPC. Although a slight reduction in early-age strength is observed with the use of FA, long-term improvements in the microstructure lead to increased ultimate strength. Additionally, FA significantly enhances sulfate resistance, mitigates alkali-silica reaction (ASR), and reduces chloride permeability. These properties make FA particularly suitable for the use of UHPC in infrastructure projects (Mala et al., 2021).

MK has emerged as a notable additive in UHPC in recent years due to its high reactivity. High-purity, kaolinite-based MK can partially replace cement thanks to its fine particle size and reactivity, while also promoting the formation of calcium-silicate-hydrate (C-S-H) and increasing matrix density. Moreover, MK is particularly suitable for architectural UHPC applications where color control is desired, as it enables the production of white or light-colored products (Tafraoui et al., 2016; Yeluri et al., 2025). Industrial by-products such as GGBFS are used as sustainable binders in UHPC to reduce its environmental impact. GGBFS enhances the development of hydration products and offers advantages particularly in terms of long-term strength and low heat of hydration. UHPC mixtures incorporating this additive are especially effective in crack control for large-volume castings (Mala et al., 2021). The use of Pozzolanic additives affects not only the mechanical strength but also the durability properties of UHPC. Studies have reported that highly reactive pozzolans such as SF and MK reduce carbonation depth, lower chloride ion penetration, and enhance resistance to freeze-thaw cycles (Abbas & Muntean, 2025; Mala et al., 2021).

Figure 1. Pozzolanic Materials

UHPC with Nanomaterial Additives

In recent years, the use of nanomaterial additives has been extensively studied to further enhance the performance of UHPC systems. These additives aim to improve UHPC properties through various mechanisms such as densification of the microstructure, reduction of permeability, and enhancement of fiber–matrix interaction. Different nanomaterials—such as NS, CNT, nano-calcium carbonate ($CaCO_3$), a GO—have demonstrated significant improvements in both fresh and hardened concrete properties. However, to achieve effective performance, several technical issues must be addressed, including dispersion challenges, interaction mechanisms, and the determination of optimal dosage levels (Yoo et al., 2022). NS is one of the most used active nanomaterials in UHPC. Its high specific surface area and Pozzolanic activity contribute significantly to microstructure densification, promote the formation of calcium-silicate-hydrate (C-S-H), and enhance mechanical strength (Guo et al., 2024). However, the non-uniform dispersion of NS within the cement matrix can lead to agglomeration issues, which may hinder the full realization of its intended effects. To address this problem, Hendrix et al. demonstrated that stabilizing negatively charged NS particles with HCl or PEG improves dispersion quality, thereby enhancing both workability and compressive strength. PEG has proven to be an effective stabilizer in positively charged NS solutions (Hendrix et al., 2024).

In addition to NS, carbon-based nanomaterials also influence UHPC performance from various perspectives. A study by Jung et al. demonstrated that the incorporation of CNT in UHPC not only enhances its mechanical properties but also improves its electromagnetic interference (EMI) shielding capability. CNTs contribute to microcrack bridging, acting similarly to fiber reinforcement, while also imparting electrical conductivity. However, the effectiveness of CNTs largely depends on the dispersion method. When dispersion is improved through techniques such as sonication or high shear mixing, the use of CNTs at low dosages (up to 0.6%) has been shown to yield optimal performance improvements (Jung et al., 2020). In recent years, the electrical conductivity of Ultra-High Performance Concrete (UHPC) has garnered increasing attention from researchers due to its potential in multifunctional applications. The primary aim of such studies is to develop UHPC formulations that combine superior mechanical properties with enhanced electrical performance. This is typically achieved by incorporating conductive fillers such as carbon fibers, carbon nanotubes, or graphite into the

UHPC matrix. Methods include mix design optimization, conductivity measurements (e.g., four-probe method), and microstructural characterization. Electrically conductive UHPCs show promise in structural health monitoring, electromagnetic shielding, and de-icing systems, offering new functionalities for smart and sustainable infrastructure. Electrical conductivity of cementitious materials can be measured by different methods. In Figure 2, the two-point uniaxial measurement method is given as an example (Dehghanpour & Yılmaz, 2020).

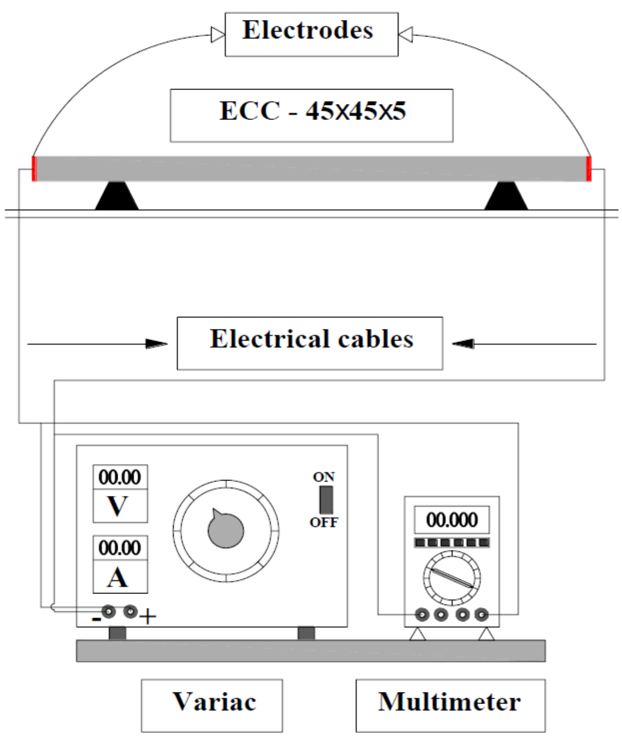

Figure 2. Two-point uniaxial resistivity measurement method example (Dehghanpour & Yılmaz, 2020).

The effects of combining NS with limestone–calcined clay cement (LC3) in UHPC have also gained attention in recent research. Guo et al. reported that the addition of NS to LC3-based UHPC mixtures enhances both the fiber–matrix interfacial bond strength and the overall microstructure. Such combinations offer environmental benefits in the context of sustainable concrete technologies. NS, in particular, plays a role in improving the toughness of UHPC by increasing bond strength in fiber pull-out tests (Guo et al., 2024). Another study by Oh et al. evaluated the effects of substituting SF with NS in UHPC mixtures. The best fiber pull-out performance was achieved when 20% of the SF was replaced with NS. Under this condition, the bond strength increased by approximately 21%, while the pull-out energy improved by about 68%. These results indicate that NS is more effective than SF in terms of both Pozzolanic reactivity and its influence on microstructural refinement (Oh et al., 2022). Overall, the effects of nanomaterial additives on UHPC occur through several mechanisms, including the filling effect, nucleation effect, Pozzolanic reactions, and densification at the fiber–matrix interface. Active nanomaterials (e.g., NS, MK) accelerate cement hydration, whereas inert nanomaterials (e.g., CNT, GNP) primarily contribute to crack bridging and enhanced conductivity. Moreover, maintaining optimal dosage levels, minimizing agglomeration risk, and ensuring compatibility with superplasticizers in the mix design are critical for achieving improved performance (Yoo et al., 2022).

Effects of different fiber types on UHPC

The effects of different fiber additives on UHPC have become a significant area of research in both academic studies and practical applications in recent years. Fiber reinforcement directly influences key properties of UHPC, including mechanical performance, durability, and workability. Through the incorporation of fibers, UHPC gains enhanced crack resistance, improved ductility, and increased resilience under harsh environmental conditions, thereby developing a more robust and multifunctional material identity. Studies have shown that steel, synthetic (e.g., polypropylene (PP), polyvinyl alcohol (PV), polyethylene), and hybrid (the combination of multiple fiber types) fiber systems exhibit different performance characteristics in UHPC. In a review conducted by Yang et al. (2022) it was stated that the contribution of fibers to mechanical strength largely depends on factors such as fiber volume, size, surface geometry, and distribution within the matrix. Steel fibers (SF) have been identified as the most effective in enhancing tensile and flexural strength, and they play a significant role in crack control (Yang et al., 2022).

In a study published by Akeed et al. (2022) the effects of fiber additives on the durability of UHPC were examined in detail. Comparative experiments involving steel and synthetic fibers revealed that SF demonstrated superior resistance to sulfate, chloride, and freeze-thaw cycles. Moreover, mixtures utilizing hybrid systems—combining both steel and synthetic fibers—were reported to achieve optimized performance in terms of both mechanical strength and durability (Akeed et al., 2022). The review study by Gong et al. discusses the overall effects of various fiber types used in UHPC, including polymer, carbon, glass, and SF. It highlights that synthetic fibers offer advantages in properties such as crack bridging and shock absorption. However, SF was found to be more dominant in enhancing tensile strength. The study emphasized that while synthetic fibers alone may be insufficient, their combination with SF results in significantly improved performance (Gong et al., 2022a). In another study conducted by Said, the effect of fiber-reinforced UHPC on shear strength was experimentally investigated. It was observed that the inclusion of fibers significantly enhanced the shear capacity, even in small, unreinforced cubes and prism specimens. These findings demonstrate that fiber reinforcement contributes not only to tensile and flexural strength but also plays a critical role in improving the shear strength of UHPC (Said et al., 2022). The experimental study conducted by Althoey et al. (2023) aimed to optimize both the sustainability and performance of UHPC through fiber reinforcement. In this study, SF and agricultural waste in the form of wheat straw were used. The hybrid system was found to have positive effects on tensile strength, impact resistance, and microstructural refinement, thereby opening the door to more environmentally friendly alternatives (Althoey et al., 2023).

Effect of water-to-cement ratio on UHPC

Optimizing the water-to-cement (w/c) ratio in UHPC plays a critical role in enhancing the material's mechanical and durability properties. The amount of water used in UHPC mixtures directly influences the cement hydration process, microstructure development, and overall durability of the concrete. In this context, various studies have demonstrated that reducing the w/c ratio can significantly improve the mechanical and microstructural characteristics of UHPC. The low w/c ratios typically used in UHPC production range from 0.15 to 0.25, which improves the density and microstructure of the concrete, thereby enhancing its mechanical strength (Amran et al., 2022). In a study conducted by Wang et al., it was observed that increasing the w/c ratio from 0.3 to 0.5 led to higher porosity and reduced compressive strength. When a lower w/c ratio is used, smaller and more isolated pore structures form within the concrete, resulting in a denser and more durable material. Additionally, concretes produced with lower w/c ratios can significantly slow down the penetration of harmful chemicals; for instance, the diffusion rate of chloride ions is reduced, thereby considerably lowering the risk of reinforcement corrosion (Wang et al., 2022). In a study conducted by Ahmad et al. (2024), the effect of the w/c ratio on the fracture toughness of UHPC was investigated. The findings revealed that UHPC mixtures prepared with lower w/c ratios developed a denser matrix that was more resistant to crack propagation. This contributes to enhanced structural strength and durability by preventing or delaying crack formation. The tests also indicated that as the w/c ratio increased, the fracture energy and the material's ability to arrest crack growth decreased (Ahmad et al., 2024).

In terms of UHPC's microstructural development, mixtures prepared with a low w/c ratio tend to exhibit a high degree of hydration, resulting in the formation of a greater amount of hydration products—particularly C–S–H. These hydration products more effectively fill the pore structure of the concrete, leading to a denser microstructure. This compact microstructure not only enhances the mechanical strength of the concrete but also hinders the transport of water and harmful ions, thereby significantly improving its durability (Huang et al., 2023). On the other hand, low w/c ratios can reduce the workability of the mixture, leading to challenges during the mixing process. At this point, the use of high-performance water-reducing agents (superplasticizers) enables the maintenance of adequate flowability despite the low water content. Zhou et al. emphasized the importance of using superplasticizers in mix design, noting that they help regulate the rheological properties of the mixture and allow for effective mixing even at low w/c ratios. This presents a critical advantage for the broader practical application and more efficient production of UHPC (Zhou et al., 2021).

The use of mineral additives such as SF in UHPC production, in combination with a low w/c ratio, creates a synergistic effect that enhances the durability properties of the concrete. SF supports the cement hydration process and contributes to the formation of additional C–S–H. This increases the compactness of the concrete, thereby improving its mechanical properties and reducing the penetration of harmful substances such as water and chloride ions. Thus, optimizing the w/c ratio in conjunction with mineral additives emerges as a critical strategy for achieving the high performance and durability of UHPC (Ahmad et al., 2024). The use of low w/c ratios in UHPC production significantly enhances the concrete's mechanical strength, fracture toughness, and durability. To fully realize these advantages, it is essential to incorporate superplasticizers at appropriate dosages during the mix design stage. Furthermore, the combination of low w/c ratios with mineral additives such as SF has been proven to further improve the overall performance of the concrete. In this context, reducing the w/c ratio and continuously optimizing the mix design will play a key role in maximizing the performance of UHPC.

Fresh Properties of UHPC (Workability, Slump, Flowability)

UHPC has emerged as a prominent material in structural engineering applications due to their superior mechanical strength and exceptional durability. However, achieving these properties requires careful control of the rheological behavior of the fresh mix. Parameters such as workability, slump, and flowability of UHPC are directly influenced by material composition, mix proportions, and the type and dosage of chemical admixtures (Chen et al., 2022). A low water-to-binder ratio (typically < 0.25) is one of the defining features of UHPC. However, this low ratio significantly increases both stress and viscosity, making the fresh mix more difficult to handle. Studies have shown that these adverse effects can be mitigated through optimized particle size distribution (PSD) and the use of high-performance superplasticizers. Specifically, rheological analyses based on the Bingham model indicate that dynamic yield stress may increase by up to 100 times with lower water-to-binder ratios but can be reduced to a tenfold increase when proper particle packing and dispersion-enhancing admixtures are applied (Teng et al., 2025). The sand-to-paste ratio is another critical factor influencing the rheological performance. Chen et al. (2022), reported that selecting a sand ratio between 38% and 41% improves UHPC's consistency while reducing segregation. However, excessive use of fine particles may increase water demand and adversely affect workability (Chen et al., 2022). Yang et al., further observed that in low-carbon UHPC mixes incorporating phosphorous slag (PS), the inclusion of PS improved flowability and reduced early-age autogenous shrinkage as its dosage increased (Yang et al., 2019).

The incorporation of fibers into UHPC has a dual impact on its rheology. Fibers, especially in high volumes, tend to increase yield stress and reduce flowability. It has been shown that flexible fibers such as PP, PVA, or carbon fibers require higher dosages of superplasticizers compared to SF, leading to higher viscosity (Chen et al., 2022). Similarly, Saleem et al., demonstrated that while the addition of SF reduces slump, this adverse effect can be counteracted through adequate superplasticizer dosage and efficient mixing. Systems incorporating CEM-III cement achieved high slump values ranging from 650 mm to 795 mm, indicating self-compacting behavior (Saleem et al., 2024). Slump testing alone may not sufficiently characterize the behavior of fresh UHPC. Yen et al., emphasized the value of using two-point rheometer tests, which align with the Bingham model, to accurately assess parameters such as yield stress and plastic viscosity. When UHPC is conceptualized as a two-phase system composed of matrix and aggregate, the viscosity of the matrix and the volume fraction of aggregates become the dominant factors governing overall flow behavior (Yen et al., 1999).

Additionally, the rheological parameters of UHPC evolve over time. Once mixed, UHPC experiences an increase in static yield stress due to particle flocculation and the formation of early hydration products such as ettringite and C-S-H. This structural build-up becomes particularly significant in time-sensitive applications such as 3D printing, shotcrete, and complex formwork placement (Teng et al., 2025). The fresh behavior of UHPC can be optimized through a careful balance of its low water-to-binder ratio, binder and sand contents, fiber type and volume, and the characteristics of the superplasticizer. Additionally, appropriate admixtures and mixing techniques should be employed with consideration of time-dependent setting and viscosity trends. A proper understanding of these complex interactions is essential to ensure the successful application of UHPC with the desired performance.

MECHANICAL PROPERTIES OF UHPC

Compressive, flexural, and tensile strength

UHPC is an advanced material that demonstrates superior mechanical properties compared to conventional concrete and offers broad application potential within the construction industry. Its high compressive, flexural, and tensile strengths-particularly when enhanced by fiber reinforcement- contribute to the development of more durable and ductile structures (Kusumawardaningsih et al., 2015). A deep understanding of UHPC’s mechanical behavior is essential for its future use in structural applications. As the name suggests, UHPC exhibits remarkably high compressive strength. This strength can be further improved by optimizing components such as aggregate size, quartz powder, SF, and steel fibers. For instance, one study reported that the highest compressive strength was achieved using blended sand. It was also observed that an optimal fiber content of 2%, along with 20% quartz and aggregate sizes ranging from 0.15 to 1.18 mm, significantly increased compressive strength. These findings highlight the significant influence of UHPC formulation on compressive performance. Its high compressive strength makes UHPC particularly attractive for applications that require high load-bearing capacity (Raheem et al., 2019).

One of the most notable characteristics of UHPC is its significantly higher flexural strength and toughness compared to conventional concrete. This enhanced flexural performance is generally achieved through the incorporation of SF. Fiber volume and aspect ratio are key parameters that greatly affect flexural strength. The use of hybrid fiber combinations can yield better flexural behavior than single-fiber systems. For example, a hybrid combination of medium and long SF was found to exhibit superior post-cracking strength, deflection capacity, and toughness compared to other hybrid systems (Jiao et al., 2022).

The Digital Image Correlation (DIC) technique has been employed to observe crack propagation and surface deformation, providing valuable insights into the flexural behavior of UHPC (Jiao et al., 2022; Yao et al., 2021). This technique allows for detailed analysis of the material's behavior during crack initiation and propagation. Additionally, the flexural performance of UHPC under impact loading has been studied, revealing strain-rate-dependent behavior. Dynamic flexural tests have demonstrated the material's high capacity for absorbing impact energy (Yao et al., 2021).

Unlike conventional concrete, UHPC exhibits notable tensile strength, particularly in fiber-reinforced UHPC (UHPFRC), resulting in more ductile behavior. High tensile strength enables UHPC to delay crack development and deform more controllably under load, offering advantages in applications such as earthquake-resistant and blast-resistant structures. One study developed a fracture mechanics-based approach to assess the post-cracking tensile behavior of UHPC and UHPFRC (Kusumawardaningsih et al., 2015). These studies show that the high tensile strength of UHPC enhances the material's ductility and mitigates the brittle nature of conventional concrete. Moreover, tensile strength, like flexural strength, can vary depending on the type and content of fibers. Tensile behavior under impact loading has also been investigated, and UHPC has shown substantial tensile strength even at high strain rates, further confirming its excellent performance under dynamic loading conditions (Yao et al., 2021). Overall, UHPC's high compressive, flexural, and tensile strengths offer a superior performance profile compared to traditional construction materials. These properties—particularly when enhanced by steel fiber reinforcement—improve durability, toughness, and ductility, expanding UHPC's potential for use in diverse engineering applications. A deeper understanding and further optimization of UHPC's mechanical properties will enable significant advancements in the design and construction of future structures.

Ductility and energy absorption capacity of UHPC

The ductility and energy absorption capacity of UHPC are primarily influenced by factors such as fiber type, volume fraction, aspect ratio, and hybridization strategies (Jiao et al., 2022; Mohammed et al., 2021). The use of fibers such as micro glass fibers (MGF) can improve the mechanical performance and ductility behavior of UHPC. For example, significant increases in compressive and flexural strength have been observed with increased MGF volume in mixtures with a specific water-to-binder ratio. These fibers, particularly when used in higher volumes, enhance the matrix's resistance to crack formation, promoting a more ductile fracture mode (Mohammed et al., 2021). Energy absorption capacity is defined as the amount of energy a material can absorb during deformation before failure and is closely related to toughness (Nguyen et al., 2023). In UHPC, fiber reinforcement significantly enhances this ability. SF, due to their high strength and deformation capacity, notably improve UHPC's energy absorption. Furthermore, hybrid combinations of PP and PVA fibers with SF can optimize energy absorption performance even under elevated temperatures. One study reported that a hybrid of 1% SF and 0.2% PVA fibers achieved the highest energy absorption capacity (5360 N.mm) at room temperature. Different fiber combinations performed best under different temperature ranges, indicating that fiber types and ratios can be tailored to specific environmental conditions (Shahidzadeh Arabani et al., 2025).

Ductility under uniaxial tension is a critical parameter for understanding the performance of UHPC in structural applications. Mix design parameters significantly affect ductility indicators such as strain at peak tensile stress and energy absorption capacity. Machine learning techniques like random forest models have been used to analyze the effects of mix components on UHPC ductility (Abellan-Garcia et al., 2023). Such approaches can help determine the optimal mix design for enhanced ductility. In addition, hybrid use of steel and ultra-high molecular weight polyethylene (UHMWPE) fibers has led to substantial improvements in tensile strain capacity and energy absorption. While the inclusion of UHMWPE fibers showed marginal changes in initial cracking and ultimate tensile strength, it increased tensile toughness and enabled a more ductile response. These properties can be precisely controlled by adjusting fiber length and hybrid ratios (Chu, 2024).

The ductility and energy absorption capacity of UHPC under impact loading have also been extensively studied. At high strain rates, the material's dynamic behavior directly affects its ability to absorb impact energy. Dynamic flexural and tensile tests have demonstrated UHPC's strain-rate-dependent behavior and its ability to absorb high impact energies (Yao et al., 2021). These studies show that UHPC can maintain structural integrity even under sudden and extreme loading conditions. Techniques such as Digital Image Correlation (DIC) allow for detailed observation of micro-scale behaviors like crack propagation and surface deformation, offering deeper insights into the material's energy dissipation mechanisms (Jiao et al., 2022; Yao et al., 2021). With significant improvements achieved through fiber reinforcement, the ductility and energy absorption capacity of UHPC enhanced its potential in modern structural engineering. The fiber type, dosage, and hybridization strategy are critical factors for optimizing these properties. UHPC's high ductility and energy absorption capacity enable the design and construction of safer, more durable, and higher-performance structures.

Mechanical behavior of fiber-reinforced and non-fiber-reinforced UHPC

Fiber reinforcement is one of the most critical factors that fundamentally transform the mechanical behavior of UHPC. While non-fibrous UHPCs exhibit high compressive strength, they are limited in terms of tensile strength, flexural strength, and ductility, and tend to exhibit brittle fracture behavior (Yoo & Banthia, 2016). In contrast, the inclusion of various types of fibers (steel, PVA, UHMWPE, glass, etc.) significantly enhances the post-cracking load-bearing capacity, deformation ability, and energy absorption of UHPC (Gong et al., 2022b; Mohammed et al., 2021). Especially, hybrid fiber use creates synergistic effects in both micro- and macro-crack control, optimizing strength, toughness, and ductility properties (Chu, 2024; Shahidzadeh Arabani et al., 2025). Therefore, comparing the mechanical behavior of fiber-reinforced and non-fiber-reinforced UHPC is of great importance in material selection for engineering applications. Non-fibrous UHPC generally exhibits high compressive strength but shows limited tensile and flexural strength and has a brittle fracture mode. Like conventional concrete, non-fibrous UHPC can crack rapidly under tensile stress and may fail suddenly. This poses significant risks, especially for structures exposed to dynamic loading such as earthquakes, impacts, or explosions. The inclusion of fibers significantly improves this brittle behavior of UHPC, providing post-cracking load-bearing capacity and energy absorption ability (Yoo & Banthia, 2016).

Fiber-reinforced UHPC (UHPFRC) demonstrates significant improvements in mechanical performance due to the addition of steel, polymer (PP, PVA, etc.), or glass fibers (GF) to the matrix (Gong et al., 2022b; Yoo & Banthia, 2016). These fibers distribute randomly within the matrix, delaying crack initiation and propagation, thereby increasing the ductility and toughness of the material. This effect is especially prominent in tensile and flexural strength. For example, in uniaxial tensile tests, unlike non-fibrous UHPC, UHPFRC can exhibit strain-hardening behavior, meaning it can continue to carry load even after initial cracking and can undergo significant deformation. This enhances the material's crack control ability and damage tolerance (Chu, 2024; Yoo & Banthia, 2016). The influence of fibers on mechanical behavior depends on fiber type, volume fraction, aspect ratio, and surface roughness (Gong et al., 2022b). SF are among the most effective in improving the tensile and flexural strength of UHPC due to their high strength and stiffness. Hooked-end SF enhances bond strength with the matrix and increase pull-out resistance, thereby further improving toughness (Muhyaddin, 2023). Polymer fibers, though generally lower in strength and stiffness, can be beneficial for micro-crack control and thermal stability (Shahidzadeh Arabani et al., 2025). Hybrid fiber combinations (e.g., steel and polymer fibers) enable control of cracks at multiple scales and provide synergistic effects to achieve optimal mechanical performance (Chu, 2024; Muhyaddin, 2023; Shahidzadeh Arabani et al., 2025). For instance, hybrid use of steel and ultra-high-molecular-weight polyethylene (UHMWPE) fibers have significantly improved tensile strain capacity and energy dissipation capacity of UHPC (Chu, 2024).

Under dynamic loading, the superiority of fiber-reinforced UHPC becomes even more evident. Under high-speed loads such as impact or explosion, non-fibrous UHPC can fracture suddenly and in a brittle manner, whereas UHPFRC exhibits more resilient behavior due to the energy absorption and distribution capability of fibers. Fibers bridge across crack surfaces, dissipating energy and spreading damage over a wider area. This prevents collapse of structural elements and provides safer performance. The role of SF in impact resistance is especially critical for enhancing the durability of structures under extreme loading conditions (Yao et al., 2021). Ductility is a key feature of fiber-reinforced UHPC and refers to the material's ability to undergo plastic deformation and absorb energy without significant damage (Mohammed et al., 2021). Non-fibrous UHPC has low ductility, making it prone to sudden failure. The addition of fiber increases post-cracking toughness and results in more ductile behavior. This is beneficial for improving the seismic performance of structures or for providing warning before failure under extreme loading (Abellan-Garcia et al., 2023). By fundamentally transforming the mechanical behavior of UHPC, fibers convert a brittle material into a highly ductile and energy-dissipating composite. The presence of fibers provides superior performance compared to non-fibrous UHPC, particularly in tensile strength, flexural toughness, crack control, and resistance to dynamic loads. Therefore, fiber reinforcement is considered an indispensable component in the majority of UHPC applications.

Fatigue behavior of UHPC

The fatigue life of UHPC depends on various factors such as applied stress level, loading frequency, temperature, and the specific characteristics of the material (Islam et al., 2025). Like conventional concrete, an increase in stress level leads to a decrease in fatigue life in UHPC. However, UHPC generally exhibits a longer fatigue life and better fatigue resistance than traditional concrete. Especially, steel fiber reinforcement significantly enhances the fatigue resistance of UHPC. Fibers delay the initiation of fatigue cracks and slow down their propagation, thereby improving the overall toughness and extending the fatigue life of the material (Yoo & Banthia, 2016). Fatigue behavior in UHPC is generally classified into two main categories: compressive fatigue and flexural fatigue. Compressive fatigue refers to deformation accumulation and eventual failure of the material under repeated compressive loads. The uniaxial compressive fatigue behavior of UHPC containing coarse aggregates (UHPC-CA) has been studied. This study focused on the effects of different coarse aggregate contents (10%, 20%, and 30%) on fatigue performance. The results showed that incorporating coarse aggregates significantly affected crack propagation, strain development, and fatigue life due to the formation of weak interfacial transition zones (ITZs) and internal stress concentration. This indicates that coarse aggregates may reduce the fatigue resistance of UHPC, as ITZs create potential weak points for crack initiation (Li et al., 2022).

Flexural fatigue evaluates the behavior of the material under repeated bending loads. The effects of low temperatures on the flexural fatigue performance of UHPC have also been investigated. Exposure to freeze-thaw cycles or cold environments can cause changes in UHPC's microstructure, affecting its fatigue performance. The findings offer valuable insights into how different fiber reinforcements (e.g., SF) and curing conditions influence fatigue life under low-temperature conditions (Tian et al., 2024). Another critical factor affecting the fatigue behavior of UHPC is its composition, particularly the fiber reinforcement strategy. Fiber volume fraction, type (steel, polymer, etc.), and geometry (straight, hooked, etc.) directly influence fatigue resistance (Gong et al., 2022b). High-volume and well-distributed fibers effectively restrain crack growth, prolonging fatigue life. Hybrid fiber combinations can also improve fatigue performance by providing multi-scale crack control (Muhyaddin, 2023).

The fatigue behavior of UHPC is also studied in composite structural elements. Strategic use of UHPC in composite beams with normal-strength concrete (NC) enables more cost-efficient designs. The effects of UHPC layer thickness, reinforcement ratio, type of reinforcement bars, and load level on fatigue performance have been evaluated. Test results showed that increasing the UHPC layer thickness enhanced the fatigue performance of the beam; however, the effectiveness of this reinforcement decreased as the load level increased. These findings highlight the importance of understanding UHPC’s fatigue behavior in complex structural members for optimal design (Wang et al., 2023). From a fatigue mechanism perspective, fatigue damage in UHPC progresses through the formation, propagation, and coalescence of microcracks. Fibers help delay the growth of these microcracks into macrocracks, aiding in energy dissipation. Moreover, as fatigue damage accumulates, the material’s stiffness decreases, and deformations increase. This may lead to sudden failure towards the end of fatigue life (Gong et al., 2022b; Muhyaddin, 2023; Yoo & Banthia, 2016). In addition to its superior mechanical properties, UHPC exhibits enhanced fatigue resistance compared to conventional concretes. Fiber reinforcement is the key to this improved fatigue behavior, increasing ductility, toughness, and crack control capacity. Further investigation into the effects of coarse aggregate content and low temperatures on fatigue performance will help fully realize UHPC’s potential for large-scale and long-lasting structural applications.

Fracture mechanics of UHPCs

The fracture behavior of UHPC is significantly influenced by factors such as the type, volume fraction, and geometry of the incorporated fibers, as well as the matrix microstructure and aggregate characteristics (Ahmad et al., 2024; Dehghanpour et al., 2022; Muhyaddin, 2023). Although fiberless UHPC generally exhibits high compressive strength, it behaves in a brittle manner under tensile stresses and fails rapidly once a crack form (Yoo & Banthia, 2016). This can lead to sudden and unpredictable failures. The incorporation of fibers significantly improves the fracture mechanical properties of UHPC, especially toughness and post-cracking behavior, thereby mitigating its brittleness (Ruifeng et al., 2023; Zhang et al., 2024). Fracture energy is a critical parameter in fracture mechanics that defines the amount of energy a material can absorb per unit area of crack surface (Ahmad et al., 2024; Ruifeng et al., 2023). In fiber-reinforced UHPC (UHPFRC) (Figure 3), fibers bridge across the crack surfaces, resisting crack propagation and absorbing significant amounts of energy. These mechanisms of "fiber pullout" and "fiber bridging" greatly enhance the fracture energy and toughness of the material. In a comprehensive study by Dehghanpour et al. (2022) 18 different UHPC mix formulations containing 0.7%, 1.3%, and 2.0% volume fractions of PVA, GF, and steel fibers (SF) were tested after 18 months of curing. Using Single Edge Notched Beam (SENB) tests, parameters such as fracture energy, dissipated energy, flexural strength, crack resistance index (CRI), and flexibility index (FI) were evaluated in detail. The results clearly showed that SF was the most effective in improving fracture energy and flexural strength due to their high strength and stiffness, which provided superior resistance to crack propagation and greater energy dissipation. It was also noted that increasing fiber volume content led to higher fracture energy (Dehghanpour et al., 2022).

Fracture toughness is another key parameter measuring the resistance of a material to crack propagation. The fracture toughness of UHPC is influenced by mixed proportions such as the water-to-binder ratio, cement content, and steel fiber content (Ahmad et al., 2024). Optimization studies have shown that careful adjustment of these parameters can enhance the crack resistance of UHPC. Furthermore, the steel fiber content significantly affects the dynamic fracture mechanical properties of UHPC (Zhang et al., 2024a). High fiber contents improve resistance to crack initiation and propagation, resulting in better impact performance. The study by Dehghanpour et al. (2022) also showed that dynamic properties such as dynamic modulus of elasticity and damping ratios were influenced by fiber type and volume, contributing to a better understanding of UHPC behavior under dynamic loads. The mechanism of crack propagation plays a central role in understanding the fracture behavior of UHPC. Digital Image Correlation (DIC) is a powerful tool for visualizing and quantitatively analyzing crack initiation and propagation in UHPC (Jiao et al., 2022; Ruifeng et al., 2023; Zhang et al., 2024). This technique provides detailed insights into crack opening, crack speed, and deformation fields, shedding light on the fracture behavior at both macro and micro scales. For instance, the effects of notch depth and curing age on the fracture behavior of UHPC were examined using DIC, and the ratio of total fracture energy to initial fracture energy was found to be a valuable indicator (Ruifeng et al., 2023). The fiber pullout mechanism in UHPC is of particular interest in terms of fracture mechanics. Fiber pullout is a result of the interaction between fibers and the matrix and the bridging action over cracks. This interaction is heavily dependent on the fiber-matrix interface properties. Special fiber geometries such as hooked-end SF can increase the pullout resistance, thereby enhancing the material's toughness and fracture energy (Muhyaddin, 2023). Additionally, hybrid fiber combinations (e.g., a mix of micro steel and GF) can provide effective bridging over cracks of different sizes and stress levels, improving overall fracture resistance (Gong et al., 2022b; Muhyaddin, 2023). Microstructural investigations (SEM) by Dehghanpour et al. confirmed that homogeneous fiber dispersion and a strong fiber-matrix interface are critical for the overall performance of UHPC (Dehghanpour et al., 2022).

The fracture mechanics of UHPC under dynamic loads are also of critical importance. High strain rates affect the dynamic fracture toughness and energy dissipation capacity of the material (Yao et al., 2021; Zhang et al., 2024). Dynamic three-point bending tests showed that fracture toughness increases with strain rate. This strain-rate sensitivity explains UHPC's enhanced resistance to sudden loads such as blasts or impacts. The steel fiber content significantly influences this dynamic fracture performance; higher fiber content provides better crack control and energy absorption under dynamic loads (Zhang et al., 2024a). Fracture mechanics models are also being developed to predict the fracture behavior of UHPC. Cohesive zone models can simulate crack propagation by accounting for fiber bridging effects. These models provide results consistent with experimental data and contribute to a deeper understanding of UHPC's fracture mechanics (Ruifeng et al., 2023). Fracture mechanics of UHPC is a fundamental aspect for the structural reliability and overall performance of the material. Fiber reinforcement significantly mitigates the brittle nature of UHPC by enhancing toughness, fracture energy, and crack control capabilities. Detailed studies such as those conducted by Dehghanpour et al. (2022) have clearly demonstrated the critical role of factors like fiber type, volume fraction, geometry, and matrix characteristics in determining the fracture behavior of UHPC. Advanced testing techniques and modeling approaches enable a deeper understanding of UHPC's complex fracture mechanisms and pave the way for the development of optimized UHPC designs for future high-performance structural applications (Dehghanpour et al., 2022).

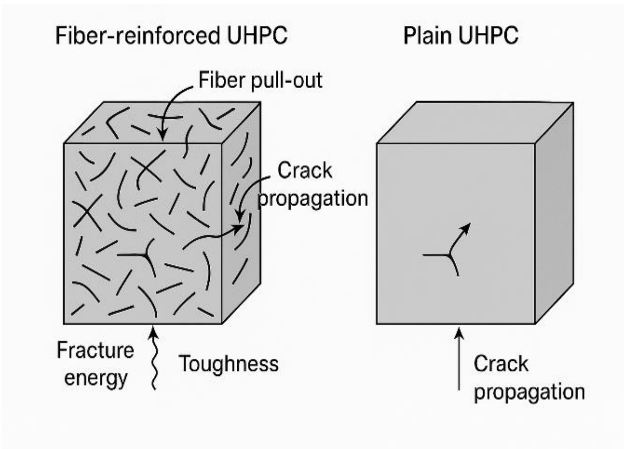

Figure 3. Difference between fiber-reinforced UHPC and plain UHPC

DURABILITY AND ENVIRONMENTAL EFFECTS OF UHPC

The effect of freeze–thaw cycles on UHPC

The freeze-thaw performance of UHPC is generally superior to that of conventional concrete. This enhanced performance is attributed to its dense and low-porosity microstructure. The low water-to-binder ratio of UHPC, optimized particle size distribution, and the typically high volume of binder materials (such as silica fume) contribute to a very fine pore structure. These fine pores limit the expansion potential of free water during freeze-thaw cycles, thereby reducing the formation of internal stresses. The freeze-thaw resistance depends on UHPC's composition, particularly the water-to-binder ratio and the type and quantity of mineral admixtures used. Lower water-to-binder ratios result in a denser matrix, leading to better freeze-thaw resistance (Lu et al., 2021). Additionally, fiber reinforcement significantly influences the freeze-thaw resistance of UHPC. Different fiber types such as steel, PP, and PVA enhance the toughness and ductility of the material by preventing the propagation of microcracks and dissipating energy during freeze-thaw cycles.

This "crack-bridging" effect of fiber slows down freeze-thaw damage progression and helps maintain the integrity of the material over time. For example, hybrid fiber combinations (e.g., steel and PP fibers used together) can enhance UHPC's energy absorption capacity even after exposure to high temperatures, offering additional resistance to freeze-thaw conditions (Shahidzadeh Arabani et al., 2025).

Relative Dynamic Modulus of Elasticity (RDME) is a common parameter used to evaluate freeze-thaw damage. A reduction in RDME indicates internal structural degradation. A study by Kushzhanova et al. (2023) investigated the freeze-thaw resistance of UHPC reinforced with low-volume hybrid fibers and found that these fibers improved both mechanical properties and freeze-thaw durability. Similarly, Wang et al. systematically studied the mechanical and cracking behavior of UHPC under freeze-thaw cycles using Digital Image Correlation (DIC) technology. Such studies provide detailed insights into UHPC's surface deformation and crack development during freeze-thaw exposure (Wang et al., 2023). Freeze-thaw cycles can significantly alter the microstructure of the material. Scanning Electron Microscopy (SEM) and Mercury Intrusion Porosimetry (MIP) tests are used to examine the freeze-thaw mechanism and changes in pore structure. Due to its dense matrix and optimized pore system, UHPC tends to absorb less water compared to conventional concrete, providing natural resistance to freeze-thaw damage (Lu et al., 2021).
Furthermore, some studies have explored the durability of UHPC with pre-existing microcracks under the combined effects of freeze-thaw cycles and chloride salt attacks. Zhong et al. investigated the freeze-thaw and chloride penetration resistance of UHPC containing controlled microcracks under laboratory conditions. Such research is vital for understanding UHPC's long-term performance under complex environmental conditions encountered in structural applications. Features like self-healing capacity further enhance UHPC's resistance against these combined effects (Zhong et al., 2024). Due to its low permeability and dense microstructure, UHPC exhibits superior freeze-thaw resistance compared to conventional concretes. Fiber reinforcement further enhances this resistance by limiting damage during freeze-thaw cycles and improving the overall durability of the material. Ongoing research aims to further optimize UHPC's freeze-thaw performance under varying fiber types, mix proportions, and combined environmental effects (Figure 4).

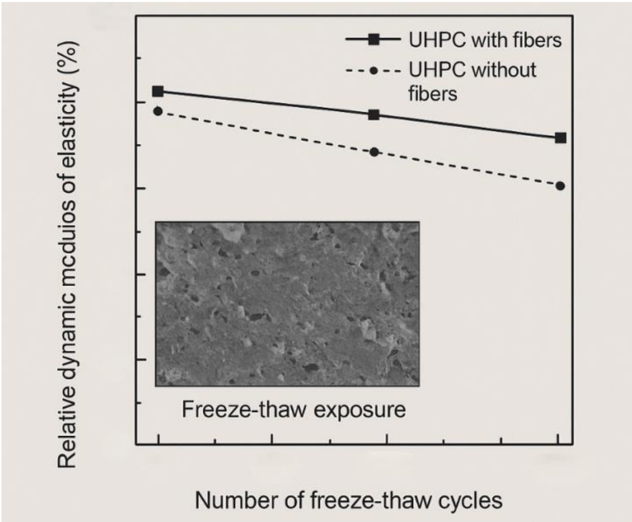

Figure 4. Freeze thaw behavior of UHPCs with and without fibers.

Resistance of UHPCs to sulfate and acid attacks

Sulfate attack is a common degradation mechanism in concrete structures, typically caused by sulfate-containing groundwater, seawater, or industrial wastewater. Sulfate ions react with the hydration products of cement, forming expansive compounds (ettringite and gypsum) that result in volume increase, cracking, spalling, and eventually loss of strength. UHPC's high resistance to sulfate attacks mainly stems from its low water-to-binder ratio, dense matrix, and optimized pore structure. These features significantly hinder the penetration of sulfate ions into the concrete. UHPC, with its low water and binder content, tends to have lower CH content, which is one of the main components reacting during sulfate attacks. Therefore, the specific composition of UHPC provides less reactive surface area for sulfate reactions, enhancing its durability (Wang et al., 2025; Yang et al., 2024). Studies have shown that UHPC experiences significantly less mass loss and compressive strength reduction when exposed to sulfate solutions compared to conventional concretes. For instance, a study by Yang et al. investigated the sulfate resistance of UHPC under dry-wet sulfate cycles and reported that the energy evolution and characteristic stress points of the material were positively affected even under such conditions (Yang et al., 2024). Similarly, Wang et al., evaluated the sulfate resistance and service life prediction of UHPC in saline soil environments and examined the effects of water-to-binder ratio, silica fume content, and fiber type on the deterioration mechanisms (Wang et al., 2025). Mineral admixtures used in UHPC, especially SF, further enhance sulfate resistance. SF contributes to pozzolanic reactions that consume CH and refine the pore structure, thereby reducing concrete permeability. This restricts the penetration of sulfate ions and minimizes harmful reactions (Ahmad et al., 2024). Some studies have also shown that environmentally friendly approaches, such as partially replacing cement with copper mine waste in UHPC production, can improve sulfate resistance (Esmaeili & Oudah AL-Mwanes, 2023).

Acid attacks dissolve the calcium-based components in the cement matrix of concrete, increasing porosity and leading to strength degradation. Like sulfate attacks, UHPC's dense and low-permeability microstructure significantly hinders the penetration of acid ions. UHPC's low water-to-binder ratio and high content of reactive SF or other pozzolanic materials reduce the CH content. Since CH is the primary compound attacked by acids, UHPC with lower CH is more resistant to acid attacks. However, the type and concentration of the acid are critical factors affecting UHPC's performance. Particularly, some acids like hydrofluoric acid can also attack silica-containing materials, requiring UHPC compositions to be specifically optimized for such environments (Ahmad et al., 2024; Esmaeili & Oudah AL-Mwanes, 2023). A study by Esmaeili & AL-Mwanes examined the mass loss and compressive strength resistance of UHPC after exposure to HCl acid solution. Such studies are essential for understanding UHPC's behavior under various acid conditions (Esmaeili & Oudah AL-Mwanes, 2023). UHPC's resistance to sulfate and acid attacks is rooted in its unique microstructure and composition. Its low water-to-binder ratio, dense matrix, optimized pore structure, and the use of mineral admixtures prevent the ingress of aggressive ions and minimize detrimental reactions. These superior durability features make UHPC an ideal material for infrastructure and other structural applications exposed to harsh environmental conditions. Ongoing research continues to focus on better understanding and optimizing UHPC's long-term performance under varying environmental scenarios.

Corrosion resistance of UHPC

UHPCs exhibit significantly higher resistance to corrosion compared to conventional concrete, owing to their superior mechanical properties and dense microstructure. These characteristics make UHPC an ideal material for infrastructure projects requiring durability in aggressive environmental conditions with high corrosion risk (Valcuende et al., 2021). One of the most distinctive features of UHPC is its extremely dense and impermeable microstructure, achieved through a low water-to-binder ratio and optimized aggregate grading (Valcuende et al., 2021). This high density significantly hinders the ingress of aggressive agents such as chloride ions and carbon dioxide into the concrete matrix (Looney et al., 2022). Among these, chloride ions are particularly detrimental, as they disrupt the passive layer on steel reinforcement and initiate corrosion (Angst et al., 2009). The low permeability of UHPC slows down chloride ion diffusion, thereby delaying the onset of corrosion and extending the service life of the structure (Valcuende et al., 2021). Studies have demonstrated that UHPCs exhibit far superior resistance to chloride penetration compared to conventional concretes. For instance, certain UHPC mixtures have consistently outperformed conventional mixes in all tests, particularly excelling in corrosion resistance (Looney et al., 2022).

Carbonation refers to the reaction between atmospheric CO_2 and CH in the concrete pore solution, resulting in a drop in pH and the breakdown of the passive layer on reinforcement. Due to their dense microstructure, UHPCs significantly limit CO_2 diffusion. Accelerated carbonation tests have shown no signs of carbonation in UHPC specimens even after one year of exposure, indicating their high resistance to CO_2-induced corrosion (Valcuende et al., 2021). Electrical resistivity of concrete is considered an indicator of corrosion risk, as high resistivity restricts ion movement and reduces corrosion rate. UHPCs demonstrate much higher electrical resistivity values than conventional concretes. For example, while fiber-free UHPC exhibits resistivity values above 5000 Ohm-m, UHPC with 1% fiber content shows about half this value, and UHPC with 2% fiber content drops to about one-fifth. These findings confirm that UHPC significantly reduces the corrosion rate of steel reinforcement, thereby delaying damage development (Valcuende et al., 2021). SF is commonly used in UHPC to improve mechanical properties; however, their effect on corrosion resistance is more complex. Valcuende et al. (2021) found that increasing fiber content decreases the electrical resistivity of UHPC, suggesting that the fibers might form conductive pathways that facilitate chloride ion transport. Nonetheless, it has also been reported that galvanized SF may provide additional protection against reinforcement corrosion. Therefore, more research is needed to determine the precise influence of fiber content on corrosion resistance (Fan et al., 2019). UHPC is also considered a promising material for repairing damaged concrete structures. When used as a repair material, a phenomenon known as the "halo effect" may occur, where UHPC potentially accelerates corrosion in the surrounding older concrete. However, Looney et al., demonstrated that both proprietary (PUHPC) and non-proprietary (NPUHPC) UHPC repair mixtures showed superior performance in durability tests—such as chloride ion penetration, freeze–thaw resistance, and surface scaling—compared to conventional concretes. Moreover, NPUHPC was reported to perform better than PUHPC in terms of corrosion resistance. These findings indicate that UHPC offers significant advantages in repair applications concerning durability and corrosion protection (Looney et al., 2022).

Recent studies have explored imparting self-healing capabilities to UHPCs to further enhance corrosion resistance. Superabsorbent polymers (SAPs) can promote crack closure and restore impermeability (Hassi et al., 2024). Hassi et al. investigated the effects of sodium polyacrylate and polyacrylate-co-acrylamide SAPs on the corrosion resistance of embedded steel reinforcement in both cracked and uncracked UHPC specimens. Their study revealed that SAPs improved self-healing performance by reducing crack widths and mitigating chloride ingress under marine exposure. Electrochemical impedance spectroscopy (EIS) confirmed the beneficial effects of SAPs on corrosion behavior. These findings highlight the potential of self-healing UHPCs in constructing more durable and corrosion-resistant structures (Hassi et al., 2024). In summary, UHPCs demonstrate markedly superior durability against corrosion compared to conventional concrete due to their dense microstructure, low permeability, and high electrical resistivity. Their high resistance to chloride ion penetration and carbonation significantly delays reinforcement corrosion and prolongs structural service life. Furthermore, the use of UHPCs in repair applications and the development of self-healing capabilities offer promising enhancements to corrosion resistance. Although the effect of fiber content on corrosion behavior warrants further research, UHPC remains a promising material for constructing long-lasting and resilient concrete structures in aggressive environments.

Carbonation Resistance of UHPC

UHPC exhibits superior resistance to carbonation compared to conventional concrete due to its low water-to-binder ratio and dense microstructure. Carbonation is a process in which atmospheric carbon dioxide reacts with CH present in the concrete pore solution to form calcium carbonate, leading to a reduction in the pH of the concrete. This decrease in pH disrupts the passive layer on the reinforcement, thereby initiating corrosion (Angst et al., 2009). The high carbonation resistance of UHPC is therefore critical to extending the service life of reinforced concrete structures. The dense microstructure of UHPC significantly hinders the ingress of carbon dioxide (Valcuende et al., 2021). This low gas permeability slows down or even halts the progression of the carbonation front within the concrete. In an accelerated carbonation test conducted by Valcuende et al. (2021) using an atmosphere containing 3% CO_2, no signs of carbonation were observed in UHPC specimens even after one year. This result clearly demonstrates the exceptional resistance of UHPC to carbonation. Similarly, a comparative study by Sohail et al., reported that UHPC exhibited superior resistance to carbonation front progression compared to both conventional concrete and high-performance concrete (Sohail et al., 2021). The unique dense structure of UHPC and the use of fine aggregates are identified as key factors in limiting CO_2 diffusion (Akeed et al., 2022b).

Research has also focused on improving the carbonation performance of UHPC. For instance, Dixit et al. explored the use of pressurized CO_2 curing applied to fresh UHPC as a method of carbon capture. By partially replacing cement with 30%, 50%, and 70% ground granulated blast-furnace slag (GGBS), their study showed that up to 80 kg of CO_2 per cubic meter could be captured with only 16 hours of curing at 3 bar pressure. The highest carbon uptake was achieved with a 30% GGBS replacement (Dixit et al., 2021). These carbonation curing techniques not only reduce the carbon footprint of UHPC but also have the potential to enhance its dense microstructure and thereby improve carbonation resistance. In addition, new methods combining microwave and wet carbonation curing are being explored to further develop UHPC matrices. These techniques may contribute to sustainability by reducing energy consumption and promoting the use of recycled concrete aggregates, while also improving carbonation resistance (Yuan et al., 2024). Inherently, UHPC demonstrates high resistance to carbonation due to its low permeability and dense microstructure. This property is vital for ensuring the long-term durability of reinforced UHPC structures. Enhancing carbonation resistance through carbon capture and advanced curing techniques increases the appeal of UHPC as a sustainable and long-lasting material for infrastructure applications.

Thermal resistance of UHPC

The primary cause of damage in concrete exposed to high temperatures is the evaporation of water within the concrete and the subsequent increase in vapor pressure in its pores. The extremely dense structure of UHPC hinders the escape of this vapor, leading to critical internal pressure that can result in explosive spalling (Zhu et al., 2021). This spalling manifests as the detachment of surface particles from the concrete, which can severely compromise the load-bearing capacity of the structure. Moreover, high temperatures cause the decomposition of cement hydration products, particularly the dehydration of calcium hydroxide $Ca(OH)_2$ and the deterioration of the C-S-H gel structure. These chemical and physical changes result in a significant reduction in the mechanical properties of concrete (Zhang et al., 2022). Several strategies have been developed to enhance the high-temperature resistance of UHPC. One of these strategies is the incorporation of PP fibers. PP fibers melt at certain temperatures, forming micro-channels within the concrete that allow vapor to escape (Lin et al., 2025). These channels reduce internal vapor pressure, thus decreasing the risk of explosive spalling. A study by Lin et al. demonstrated that PP fibers improve the post-heating mechanical properties of UHPC and effectively prevent spalling. It was particularly noted that PP fibers influence the visual appearance and fracture modes of heat-exposed UHPC (Lin et al., 2025). Another study revealed that the fire resistance of reactive powder concrete (RPC) beams reinforced with hybrid fibers improves when fire insulation measures are applied. This finding suggests that fiber type and concentration, along with fire protection strategies, play a significant role in the high-temperature performance of UHPC. The use of fire-retardant polymer fibers (SFRP) has also emerged as a promising approach to enhance the fire resistance of UHPC (Hou et al., 2019).

Zhang et al. (2022) investigated the use of SFRP fibers incorporating organic-metallic fillers to mitigate thermal damage in UHPC. Their findings showed that SFRP fibers effectively prevented explosive spalling and significantly reduced strength loss in UHPC exposed to temperatures up to 800°C. These fibers can expand at high temperatures, filling internal voids within the concrete and thereby reducing thermal stress (Zhang et al., 2022). The type of aggregate used also influences the high-temperature performance of UHPC. Some studies have shown that certain aggregates, such as bauxite, exhibit superior performance at elevated temperatures. The thermal expansion coefficients and heat resistance of aggregates can affect the overall thermal behavior of concrete. It has been indicated that the use of coarse bauxite aggregate in combination with PP fibers improves the post-heating mechanical properties of UHPC (Lin et al., 2025). To accurately predict the behavior of UHPC exposed to high temperatures, researchers have developed not only experimental studies but also numerical modeling and artificial intelligence-based approaches. For instance, Lin et al. demonstrated that Gaussian Process Regression (GPR) models could predict the mechanical properties of UHPC after thermal exposure more accurately than traditional regression analyses. These models offer valuable tools for understanding complex thermal damage mechanisms and optimizing the performance of UHPC under high-temperature conditions (Lin et al., 2025). Although UHPCs exhibit outstanding mechanical properties, they are still susceptible to explosive spalling when exposed to high temperatures, particularly under fire conditions. This risk is associated with the buildup of vapor pressure due to the dense microstructure of the material. However, material modifications such as PP fibers, fire-retardant polymer fibers, appropriate aggregate selection, and fire insulation measures can significantly enhance the thermal resistance of UHPC. Future research should focus on optimizing these strategies and developing comprehensive solutions to ensure fire safety in critical infrastructure applications using UHPC.

DURABILITY OF UHPC AGAINST AGING AND CHEMICAL DEGRADATION

The primary basis of UHPC's durability lies in its extremely low permeability. In conventional concrete, the pore structure and capillary voids allow the ingress of harmful substances such as water, chloride ions, sulfates, and carbon dioxide. However, in UHPC, these pores are largely eliminated or rendered discontinuous, which significantly restricts the penetration of harmful agents into the concrete matrix. Studies have shown that the chloride ion diffusion coefficient of UHPC is at least one order of magnitude lower than that of conventional or high-performance concrete (Li et al., 2020). This low permeability delays the ingress of chlorides that trigger reinforcement corrosion, thereby extending the service life of reinforced UHPC structures (Valcuende et al., 2021). In a study by Looney et al., both proprietary and non-proprietary UHPC mixtures demonstrated superior resistance to chloride ion penetration compared to conventional concrete (Looney et al., 2022). UHPC also exhibits significant resistance to sulfate attacks. Sulfate ions react with CH and hydrated aluminates in concrete, forming expansive products such as ettringite and gypsum, which cause cracking and deterioration. UHPC's dense matrix and low permeability slow the ingress of sulfate ions, thus minimizing the effects of sulfate attack (Tahwia et al., 2021).

A study by Tahwia et al. (2021) examined the sulfate resistance of environmentally friendly UHPCs produced using high proportions of industrial by-products, confirming the durability of these concretes. Particularly, the partial replacement of cement with binder materials such as (GGBFS or CEM III) and FA enhances sulfate resistance while reducing the environmental impact of UHPC. These additives reduce the portlandite content in the concrete, thereby lowering the amount of reactive material available to interact with sulfate ions and slowing the degradation process (Tahwia et al., 2021). The alkali-aggregate reaction (AAR) is another chemical degradation mechanism in concrete, involving the reaction between reactive aggregates and alkalis, which results in expansion and cracking. UHPC's high binder content and low water-to-binder ratio form a denser matrix around reactive aggregates, restricting the progression of such reactions. Additionally, the widespread use of pozzolanic materials (e.g., silica fume, FA, GGBFS) in UHPC mixtures helps mitigate AAR by consuming free alkalis in cement and forming stable, non-expansive silicate gels that prevent harmful expansion (Akeed et al., 2022b). Resistance to freeze-thaw cycles is also a key factor in the durability of UHPC. Freeze-thaw damage occurs when water inside the concrete freezes and expands, generating stresses that lead to cracking. Due to its extremely dense structure with significantly fewer capillary pores and voids compared to conventional concrete, UHPC shows natural resistance to freeze-thaw damage (Looney et al., 2022). Tests conducted by Looney et al. confirmed that UHPC outperforms traditional concrete in terms of freeze-thaw resistance and surface scaling durability. This supports the suitability of UHPC for long-term applications in cold climates and environments with frequent freeze-thaw cycles (Looney et al., 2022).

To evaluate the long-term aging behavior and performance of UHPC, accelerated aging tests and in-situ performance monitoring under real environmental conditions are essential. A study by Zeng et al. presented a durability assessment of UHPC panels reinforced with fiber-reinforced polymer (FRP) grids in marine environments. Such studies provide critical insights into the long-term aging and degradation behavior of UHPC under various aggressive conditions. Overall, UHPC's dense microstructure and low permeability make it highly resistant to chemical degradation mechanisms and environmental aging effects. This makes UHPC an attractive option for critical infrastructure projects requiring long-lasting and low-maintenance solutions (Zeng et al., 2025). Applying hydrophobic coatings on

UHPC surfaces has been shown to effectively enhance water repellency, thereby improving durability against moisture-induced deterioration. These coatings, often based on silanes, siloxanes, or fluorinated compounds, create a protective barrier that reduces water absorption without significantly affecting the material's breathability or mechanical integrity. Hydrophobic treatment minimizes capillary ingress, chloride penetration, and freeze-thaw damage, making it especially beneficial for UHPC used in harsh environmental conditions. This approach supports long-term performance and extends the service life of UHPC-based structures. An example image of a hydrophobic coating that can be applied on cementitious materials is given in Figure 5 (Doğan & Dehghanpour, 2021).

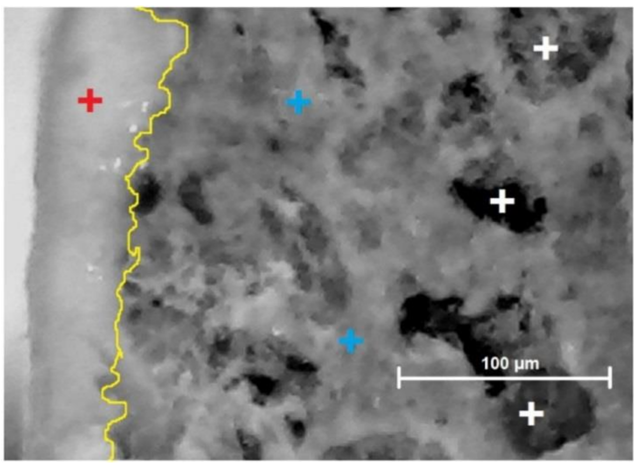

Figure 5. Cross section view of the hydrophobic surface coated concrete sample.

MICROSTRUCTURAL CHARACTERIZATION OF UHPC

Porosity and density of UHPC

UHPC possesses a compact and homogeneous microstructure due to its low water-to-binder ratio, high-quality reactive materials, and the use of superplasticizers (Chen et al., 2019). This dense particle packing significantly reduces the porosity of the concrete, resulting in high density and low permeability (Chu et al., 2022). Porosity is one of the key parameters that determines the durability of UHPC. The size and distribution of pores directly affect the mechanical strength of the concrete and its resistance to environmental factors. In UHPC, pores—especially capillary voids—are minimized, preventing the formation of microcracks. This significantly reduces permeability and blocks the ingress of harmful ions, thereby enhancing durability (Sohail et al., 2021). Various studies have shown that the majority of UHPC's pore sizes are below 500 micrometers. These small pores increase the material's density while reducing internal defects and microcracking (Chen et al., 2019). Furthermore, UHPC's low porosity dramatically limits the penetration of aggressive agents such as chloride ions and carbon dioxide (Sohail et al., 2021). The density of UHPC is a critical parameter that directly affects its mechanical strength and elastic modulus. A dense internal structure increases compressive strength and reduces elastic deformation, resulting in greater stiffness. Studies have shown that UHPC has significantly higher density values compared to conventional concrete, mainly due to the use of fine materials and optimal mix design (Chu et al., 2022). The type of aggregate used in UHPC also influences its density and porosity. For instance, high-modulus aggregates such as alumina micro-powder can further reduce the pore structure, increasing both density and elastic modulus. These aggregates significantly enhance the mechanical performance of the concrete while contributing to a more durable and compact matrix (Chu et al., 2022). Moreover, UHPC's high density and low porosity extend its service life and provide long-term economic benefits. Low porosity greatly delays the corrosion of embedded reinforcement, thus reducing maintenance costs (Sohail et al., 2021). Another important group of materials used in optimizing UHPC's porosity and density includes nano- and micro-level additives such as NS and glass powder. NS significantly reduces pore size and overall porosity, leading to a more homogeneous internal structure. Glass powder, on the other hand, can reduce pore size by up to 90%, substantially improving mechanical properties (Bahmani & Mostofinejad, 2022).

Cement hydration in UHPC leads to the formation of a dense, microcrack-free microstructure. The C-S-H gel produced during hydration densifies the matrix, enhancing mechanical performance and reducing porosity (Chen et al., 2019). Different curing methods applied during UHPC production also have a considerable effect on porosity and density. Steam curing and high temperature curing methods reduce pore size and increase overall microstructural density. High-temperature curing accelerates cement hydration, resulting in a denser C-S-H network. Additionally, such curing methods promote pozzolanic reactions, further improving the mechanical properties of UHPC (Valcuende et al., 2021). The density and porosity of UHPC can also be enhanced through fiber reinforcement. The inclusion of SF improves mechanical properties while restricting the initiation and propagation of microcracks. This contributes to long-term durability and increases the compactness of the matrix. Uniform distribution of SF strengthens the internal structure, reduces pore formation, and improves microstructural density (Valcuende et al., 2021). The porosity and density characteristics of UHPC are key factors behind its superior mechanical performance and long-term durability. These features expand UHPC's range of applications and make it an ideal material for structures exposed to harsh environmental conditions.

Microstructural analyses of UHPCs are essential for understanding and optimizing their superior mechanical and durability properties, and they are conducted using a wide range of characterization techniques. SEM is commonly used to examine the morphological features of aggregates, binder phases, and fibers at the microstructural level. Coupled with SEM, Energy-Dispersive X-ray Spectroscopy (EDS) enables the identification of the chemical composition of UHPC components. X-ray Diffraction (XRD) plays a crucial role in detecting crystalline phases such as cement hydration products and geopolymeric structures. Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) provide insights into thermal stability, binder composition, and the degree of hydration. The pore structure, a key factor in durability, can be characterized using Mercury Intrusion Porosimetry (MIP) to determine pore size distribution and total porosity. Fourier-Transform Infrared Spectroscopy (FTIR) is employed to identify polymeric additives and functional groups in the binder phase. Nuclear Magnetic Resonance (NMR) offers detailed insights into the internal structure of amorphous binder systems. Lastly, X-ray Photoelectron Spectroscopy (XPS) is used to analyze the bonding states and surface chemistry of UHPC. The combined application of these techniques provides a comprehensive understanding of the microstructural behavior of UHPC in both fresh and hardened states, thereby forming a scientific basis for developing performance enhancement strategies (Dehghanpour, 2023). Some microstructure characterization devices are shown in Figure 6.

Figure 6. Sample microstructure characterization devices.

SEM, XRD, TGA and FTIR

UHPC is a special type of concrete that is extensively studied using advanced analytical techniques. The primary methods used to understand its microstructural properties include SEM, XRD, TGA and FTIR (Fourier Transform Infrared Spectroscopy). Data obtained from these techniques reveal the microstructural mechanisms that underlie UHPC's superior mechanical and durability properties. SEM analysis provides a detailed examination of phase distributions and the fiber–matrix interface in the microstructure of UHPC. Through SEM, the distribution of microcracks, the interaction between fibers and the cementitious matrix, and the overall pore structure can be observed. Uniform fiber dispersion and strong interfacial bonding significantly enhance the mechanical performance of UHPC (Dong et al., 2023). Moreover, SEM helps track the development and distribution of hydration products from cement and mineral additives, revealing the homogeneity of the internal structure (Qian et al., 2025). XRD analysis is critical for identifying crystalline phases within UHPC and tracking phase transformations. It allows the detection of hydration phases such as C-S-H, portlandite $Ca(OH)_2$, and ettringite, which are essential components influencing mechanical strength and durability. In UHPC, which often contains high amounts of amorphous silica, the degree of crystallinity and distribution of C-S-H gel formed during hydration can be thoroughly analyzed using XRD (Dong et al., 2023). Additionally, XRD clarifies the hydration reactions of mineral additives (e.g., SF and FA) and the formation of amorphous phases, helping explain UHPC's chemical durability (Huang et al., 2024).

TGA evaluates the thermal stability of UHPC and the decomposition behavior of hydration products. This method quantifies the amount of bound water, C-S-H gel, portlandite, and carbonated products. The thermal stability of hydration phases provides critical insights into UHPC's behavior at elevated temperatures, relevant for fire resistance and long-term performance (Dong et al., 2023). TGA data are also used to assess the degree of hydration, pore structure, and thus the material's long-term durability (Li et al., 2023). FTIR analysis identifies chemical bonds and functional groups within UHPC, enabling the monitoring of hydration processes and chemical reactions. FTIR spectra clearly shows the presence of silicate bonds, carbonate formations, and other hydration products. These spectra help to better understand the mechanisms of cement hydration and contribute to the optimization of hydration processes (Qian et al., 2025). FTIR also allows the evaluation of polymeric additives and their effects on hydration, providing deeper insights into UHPC's chemical stability. When used together, SEM and FTIR analyses can reveal the influence of surface chemical treatments and physical changes on fiber–matrix interfacial bonding, which is critical to UHPC performance. These methods are instrumental in explaining mechanical anchoring and chemical adhesion mechanisms and optimizing the effectiveness of fiber reinforcements (Qian et al., 2025). Notably, SEM, XRD, TGA, and FTIR are employed to optimize processes related to UHPC mixing, curing, and long-term performance. For example, these methods show the effects of curing temperature and duration on microstructural development (Qian et al., 2025). They also investigate the impact of various mineral additives used in concrete production, such as limestone powder and calcined clay, and analyze their hydration mechanisms in detail (Dong et al., 2023).

The effective utilization of sustainable materials in UHPC, such as recycled concrete fines, red mud, and ceramic polishing waste, is also evaluated using SEM, XRD, TGA, and FTIR. These analyses determine the positive or negative effects of waste materials on hydration processes and mechanical properties, contributing significantly to sustainable concrete production (Yuan et al., 2024). Overall, analytical methods such as SEM, XRD, TGA, and FTIR allow for an in-depth understanding of UHPC's complex microstructure. These techniques provide essential information for improving UHPC's design, enhancing its mechanical properties, and extending its service life. Such comprehensive analyses offer valuable insights for optimizing every stage of UHPC production, from material selection to curing processes, thereby greatly enhancing the engineering performance of the material.

Fiber–Matrix Interface and Microcrack Development in UHPC

UHPC is an advanced construction material known for its exceptional strength and long service life. One of the key factors that contribute to these properties is the complex mechanical interactions occurring at the fiber–matrix interface. In UHPC, this interface enables effective mechanical anchorage between fibers and the matrix, slowing crack propagation and enhancing ductility and energy absorption capacity. In particular, the bond strength at the interface plays a decisive role in the tensile strength, impact resistance, and multiple cracking behavior of

UHPC (Du et al., 2023; Ji et al., 2024). Recent studies have shown that when the interfacial bond strength reaches values as high as 14 MPa, the load transfer capacity of the fibers increases significantly, promoting the formation of multiple cracks within the matrix. This interaction is one of the core mechanisms that reinforces UHPC's performance (Du et al., 2023). The random orientation and distribution of fibers within the matrix are critical parameters in terms of tensile strength and crack control. Aligned fibers provide maximum bridging effect along the loading direction and improve the fiber pull-out behavior (Ji et al., 2024). Micromechanical mechanisms such as snubbing and matrix debonding enhance the fiber's load-carrying capacity within the matrix, enabling fibers to sustain crack-bridging over longer periods (Du et al., 2023). Surface modifications of fibers using nano-coatings such as nano-SiO_2 can further increase the bond strength at the interfacial transition zone (ITZ), preventing crack propagation and enhancing ductility (Hannawi et al., 2016; Kim & Yoo, 2019).

Another important factor influencing UHPC's multiple cracking behavior is the compatibility between matrix strength and interfacial bond strength. Research indicates that when the bond strength is below 10 MPa, matrix strength has a limited effect on the final strength of UHPC. However, once the bond strength exceeds this threshold, the matrix strength becomes a critical factor. This finding highlights the necessity of optimizing both matrix composition and fiber–matrix interaction in UHPC design (Du et al., 2023). Moreover, during UHPC production, fiber alignment and matrix homogeneity must be carefully controlled from the mixing stage. The alignment of fibers along the flow direction can improve tensile and flexural strength by 30–50% (Wang et al., 2017). In addition, multi-scale reinforcement systems—using nano, micro, and macro fibers—can provide optimal bonding at the fiber–matrix interface, effectively controlling both microcrack formation and macrocrack propagation (Hannawi et al., 2016; Ji et al., 2024). The mechanical performance and crack control capability of UHPC depend on the interaction of several parameters, including fiber–matrix bond strength, fiber orientation, and the distribution of matrix strength. Enhancements at the interface achieved through physical and chemical modifications can significantly improve the overall performance of UHPC, enabling the production of long-lasting, high-strength structural elements (Du et al., 2023; Ji et al., 2024). These findings provide a solid scientific and technical foundation for the advanced application of UHPC in the construction industry.

PRODUCTION, APPLICATION, AND RHEOLOGY OF UHPC

Rheological Properties and Workability of UHPC

UHPC is increasingly utilized in modern structural engineering due to its outstanding mechanical performance and long-term durability (Teng et al., 2025). The rheological properties of UHPC are crucial for both the workability of the fresh mix and the ultimate mechanical performance of the hardened material. These properties are defined by parameters such as yield stress, plastic viscosity, thixotropy, and structural build-up. Rheology directly influences the effectiveness of the fiber–matrix interface and the uniformity of the microstructure, which in turn determine the final performance of UHPC (Meng & Khayat, 2017). In UHPC, yield stress represents the energy required to initiate flow in the mixture. This parameter plays a critical role in achieving uniform fiber dispersion and preventing segregation (Li et al., 2025a). Plastic viscosity refers to the resistance to flow once the yield stress is overcome and is essential for workability. In fiber-reinforced concretes, maintaining plastic viscosity within an optimal range improves fiber orientation and distribution, thereby enhancing the ultimate strength (Meng & Khayat, 2017). Thixotropy, the time-dependent structural build-up of concrete, is particularly advantageous in applications requiring rapid setting, such as 3D printing (Arunothayan et al., 2023).

The low water-to-binder ratio and high fine particle content in UHPC can make uniform fiber dispersion and matrix homogeneity difficult to achieve. Therefore, polycarboxylate-based superplasticizers and viscosity-modifying agents are used in UHPC mixtures to reduce yield stress while keeping plastic viscosity at optimal levels (Meng & Khayat, 2017). Additionally, nano-additives such as nano-clays and graphene improve rheological behavior, increase mix stability, and enhance mechanical strength. For example, graphene optimizes stress and viscosity, improving flow behavior and fiber dispersion (Li et al., 2025a). UHPC's rheological properties are not only important in laboratory settings but also critical in practical applications. 3D printing is one of the most sensitive areas in terms of UHPC rheology. In 3D printing, low dynamic yield stress facilitates smooth extrusion from the nozzle, while high static yield stress supports the structural stability of printed layers (Arunothayan et al., 2023). In contrast, for shotcrete applications, a rapid increase in yield stress during spraying reduces the risk of sagging and ensures a more uniform application (Teng et al., 2025).

Accurate measurement of UHPC's rheological properties is typically conducted using high-precision devices such as coaxial cylinder rheometers, which determine parameters like yield stress and viscosity by measuring torque and rotational speed (Khayat et al., 2019). However, the thixotropic nature of UHPC mixes can increase the risk of measurement errors. To enhance accuracy, procedures such as pre-shearing are implemented to prevent structural rebuilding during testing (Arunothayan et al., 2023). Another key factor affecting UHPC rheology is fiber content and distribution. Fiber alignment along the flow direction can improve tensile and flexural performance by up to 30% (Meng & Khayat, 2017). However, as fiber content increases, so do flow resistance and the risk of segregation, requiring a careful balance of rheological parameters (Li et al., 2025b). Rheological properties play a decisive role in the effectiveness of the fiber–matrix interface and the homogeneity of the microstructure. Well-controlled rheological parameters ensure uniform fiber dispersion and optimal mechanical performance of UHPC (Meng & Khayat, 2017; Teng et al., 2025). Therefore, rheology control strategies must be carefully applied and optimized according to the specific application conditions. In this way, UHPC's high-performance potential can be utilized to its fullest extent.

Design of UHPC for 3D printing applications

UHPC, when combined with the opportunities presented by 3D printing technologies in the modern construction industry, offers extraordinary possibilities in both design and application. Recent studies have shown that the rheological properties and fiber orientation in UHPC have a direct impact on its performance in 3D printing applications (Arunothayan et al., 2020; Chen et al., 2025). A theoretical model developed by Dong et al., demonstrated how fiber alignment in 3D printed UHPC is influenced by factors such as nozzle shape, fiber content, and the "flattening effect" during extrusion. The model revealed that improved alignment of fibers along the printing direction can enhance flexural strength by up to 20%. This alignment is particularly supported by the boundary effects of the nozzle, which guide fiber orientation during extrusion (Dong et al., 2024). Jia et al., found that the addition of limestone powder (LP) to UHPC mixes significantly affects rheological properties and printability. LP reduces the yield stress of the mix, improving extrudability, but excessive dosages can compromise mechanical strength. UHPC, with 10% LP, achieved compressive strengths up to 153.1 MPa and flexural strengths up to 24.7 MPa. However, LP contents above 15% may improve workability at the cost of reduced final strength, highlighting the need for precise optimization of admixture ratios (Jia et al., 2024). The shape stability of UHPC during 3D printing also depends on the extrusion system and nozzle design used. Gomaa et al., showed that different printing systems (e.g., piston extruders versus screw-based systems) significantly influence the stability of the mix during printing. Screw-based systems tend to apply lower pressure, reducing deformation after extrusion. Furthermore, circular nozzles help the material to be deposited more uniformly along the printing path (Gomaa et al., 2024).

The use of recycled steel fibers (RSF) in 3D-printed UHPC has gained attention for both cost-effectiveness and environmental sustainability. Chen et al. (2025) investigated the rheological and mechanical properties of RSF-reinforced UHPC and reported that increasing RSF content from 1% to 3% raised the yield stress by 27.37%, improving shape retention during printing. This indicates that RSF can offer both economic and sustainable advantages in 3D printing applications (Chen et al., 2025). Another crucial parameter for enhancing UHPC's suitability for 3D printing is thixotropy. Thixotropic behavior strengthens the bonding between layers and prevents deformation during the printing process. This is especially beneficial for large-scale or geometrically complex structures (Arunothayan et al., 2020). Therefore, balancing thixotropy and flowability is essential to ensure both print performance and structural integrity. The design of UHPC for 3D printing requires the optimization of rheological parameters (yield stress, viscosity, thixotropy), admixture contents, and printing parameters. Elements such as nano-additives, polycarboxylate-based superplasticizers, recycled fibers, and nozzle geometry play a significant role in improving the workability and final performance of UHPC (Dong et al., 2024; Gosselin et al., 2016). These integrated approaches enable the full utilization of UHPC's potential in 3D printing while contributing to the development of sustainable and aesthetically innovative structures.

Effect of curing conditions on the performance of UHPC

The hydration kinetics, microstructural development, and mechanical performance of UHPC are highly influenced by curing conditions. Accelerated curing regimes such as steam curing and autoclave curing are commonly used to promote early-age strength development (Dong et al., 2024; Xu et al., 2023). Curing temperature is one of the primary factors affecting the hydration of cementitious materials and supplementary cementitious materials (SCMs). High-temperature curing accelerates the pozzolanic reaction of SF and other SCMs, thereby increasing the degree of hydration. This leads to the formation of a denser and more homogeneous microstructure. For instance, UHPC specimens subjected to steam curing at 90 °C for 48 hours can reach compressive strengths exceeding 170 MPa within a few days—higher than the strength typically achieved after 28 days under standard curing conditions (Hamada et al., 2022; Rai & Wille, 2024). The impact of steam curing on UHPC's microstructure is also significant. Mercury intrusion porosimetry (MIP) tests have shown that steam curing can reduce total porosity by up to 30% and refine the pore size distribution. This reduction in porosity is mainly attributed to the increased formation of C-S-H phases. The greater presence of C-S-H in the matrix enhances the material's density and thus its mechanical strength (Dong et al., 2024; Xu et al., 2023). Steam curing not only improves compressive strength but also flexural strength and overall durability (Shen et al., 2019). In UHPC, C-S-H is the primary hydration product responsible for strength and durability. Due to the low water-to-binder ratio and high pozzolanic content (e.g., silica fume), UHPC forms a dense, low-porosity matrix rich in secondary C-S-H. The Ca/Si ratio typically ranges between 1.2 and 1.5, lower than in conventional concrete, indicating a more polymerized and compact gel structure. This refined C-S-H phase enhances mechanical performance and reduces permeability, contributing to UHPC's superior long-term durability. Figure 7 shows the C-S-H products displayed in cementitious materials of a study (Doğan et al., 2022).

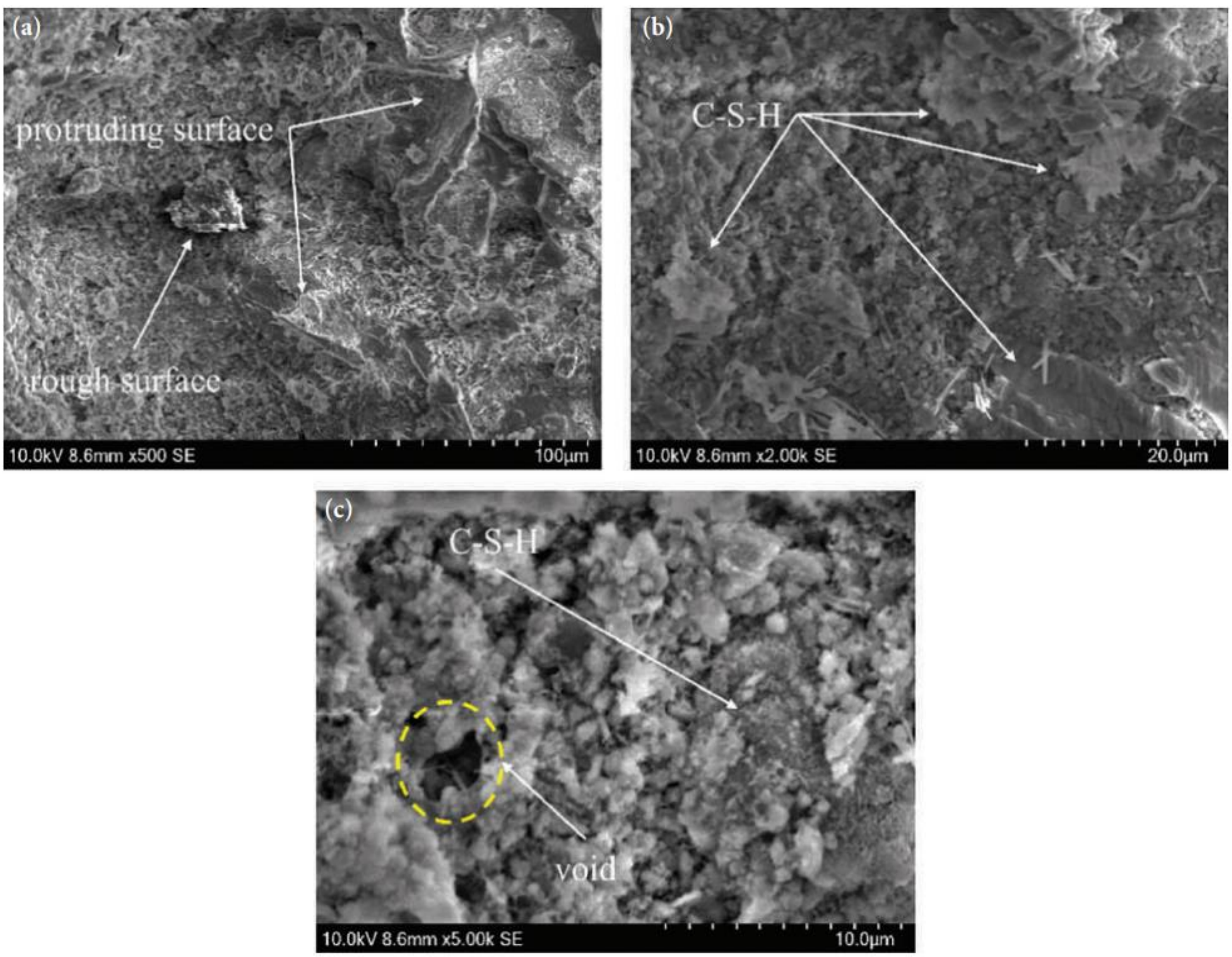

Figure 7. C-S-H products displayed in cementitious materials (Doğan et al., 2022).

However, curing parameters must be carefully controlled. Excessively high curing temperatures may lead to internal microcracking and coarsening of the pore structure. Temperatures above 250 °C, for example, can damage the mechanical properties of UHPC and negatively affect long-term performance (Dong et al., 2024). Therefore, curing parameters such as preset time, heating rate, and cooling duration must be optimized. A properly designed steam curing process enhances both early-age and long-term durability while minimizing thermal damage risks (Hamada et al., 2022; Xu et al., 2023). The effects of curing are not limited to compressive strength alone. Steam-cured UHPC also shows improved dynamic properties. Characteristics such as energy absorption capacity, impact resistance, and dynamic modulus of elasticity benefit significantly from high-temperature curing (Shen et al., 2019; Xu et al., 2023). In steel fiber-reinforced UHPC, steam curing strengthens the fiber–matrix interface, allowing fibers to carry more tensile load, thereby enhancing the toughness and ductility of the material (Dong et al., 2024).

From a hydration standpoint, high-temperature curing increases both the quantity and chain length of C-S-H phases. For example, quartz and SF undergo enhanced pozzolanic reactions at elevated temperatures, resulting in more secondary hydration products. Among these are high-temperature phases such as tobermorite and xonotlite, which contribute to the densification of UHPC's microstructure and the improvement of its compressive and flexural strength (Dong et al., 2024). Furthermore, steam curing improves UHPC's durability characteristics. Steam-cured UHPC exhibits greater resistance to chloride ion penetration and higher electrical surface resistivity. This is particularly advantageous for UHPC used in marine environments or other aggressive conditions. UHPC cured at 90 °C for 48 hours has demonstrated surface resistivity values exceeding 1000 kΩ-cm and shrinkage rates below 0.04%, far surpassing those achieved under standard curing (Hamada et al., 2022; Rai & Wille, 2024).

The effects of early thermal curing on UHPC also depend on factors such as cement type, SCM content, and fiber type and dosage. Some studies have reported that elevated temperatures at early ages promote the formation of more amorphous C-S-H, which reduces porosity and enhances strength (Shen et al., 2019; Xu et al., 2023). The three-stage steam curing cycle—initial delay, temperature rise, and constant temperature phase—is especially important, and optimizing these stages is key to achieving the desired performance of UHPC (Dong et al., 2024). Selecting the appropriate curing regime is critical to maximizing UHPC's performance. High-temperature regimes like steam and autoclave curing facilitate rapid early-age strength gain and improve long-term mechanical and durability performance. However, if they are not properly managed, these processes can lead to microstructural damage and performance loss. Therefore, precise control of curing parameters and thoughtful curing design are essential to fully realize the potential of UHPC (Dong et al., 2024; Hamada et al., 2022; Xu et al., 2023).

Precast and Cast-in-Place Applications of UHPC

Due to its high strength capacity, exceptional durability, and superior microstructural characteristics, UHPC has rapidly gained prominence as an advanced material in structural engineering. These outstanding properties make UHPC an attractive option particularly for precast and cast-in-place applications (Zhang et al., 2023). Recent studies have shown that both precast UHPC elements and cast-in-place UHPC systems enhance structural performance while accelerating construction processes (Liu et al., 2024). Precast UHPC elements are produced under controlled factory conditions, ensuring high quality and material uniformity. These elements are widely used in structural components such as bridge decks, columns, beams, and façade panels (Weng et al., 2025). The use of precast UHPC panels as permanent formwork offers long-term durability by reducing chloride ion penetration, especially in marine and bridge structures exposed to harsh environmental conditions (Chen et al., 2025). Additionally, precast UHPC allows for flexibility in shaping complex architectural components, enabling the combination of aesthetic and structural performance (Shi et al., 2022).

Alongside these advantages, the lightweight nature and high strength of precast UHPC elements facilitate easier transport and installation. For instance, Zhang et al. (2023) demonstrated that precast FRP–UHPC hybrid beams achieved up to 40% higher load capacity compared to conventional concrete members. This performance gain, coupled with faster on-site assembly compared to cast-in-place concrete, offers significant cost benefits (Zhang et al., 2023). Cast-in-place UHPC applications enable the formation of hybrid systems combining precast elements with cast-in-place normal concrete. These hybrid systems are particularly beneficial for structural elements with complex load transfer mechanisms, such as bridge girders and slab-to-column connections (Liu et al., 2024). A critical aspect of cast-in-place UHPC use is the interfacial performance between precast UHPC components and the in-situ concrete (Chen et al., 2025). Interface characteristics such as surface roughness, fiber content, and concrete quality directly affect load transfer capacity. Liu et al. found that grooved connection details improved bond strength in precast slab–cast-in-place UHPC joints. Their study also noted that connection height and steel bar anchorage length significantly contributed to shear capacity (Liu et al., 2024).

Weng et al. (2025) through push-out tests on precast UHPC–cast-in-place concrete interfaces, identified three typical failure modes: pure interface failure, composite interface–NC failure, and concrete splitting. The study showed that the use of triangular shear keys at the interface significantly increased shear resistance, offering the highest performance among the tested geometries (Weng et al., 2025). An experimental study by Semendary and Svecova (2020), emphasized that bond strength at the interface between precast concrete and cast-in-place UHPC is influenced by factors such as aggregate type, concrete strength class, surface preparation, and moisture condition. Saturated surface-dry (SSD) conditions improved bond strength by up to 22.7%, preventing the formation of weak zones at the interface (Semendary & Svecova, 2020). In the design of cast-in-place UHPC applications, numerical modeling is as critical as experimental findings. Chen et al., developed predictive methods to estimate the bond strength of UHPC–NC interfaces and demonstrated strong agreement with experimental results. These methods consider parameters such as steel fiber content, surface roughness, and NC compressive strength, enabling more reliable predictions in the design process (Chen et al., 2025). Both precast and cast-in-place applications of UHPC offer significant advantages in terms of durability and sustainability in modern construction. While precast UHPC components provide high strength and long service life, cast-in-place UHPC improves structural integrity through enhanced bond strength at the interface. However, the performance of such systems relies heavily on careful control of interface preparation, material properties, and detailed design parameters. Future research is recommended to focus on long-term performance evaluations of interface roughness and fiber-reinforced hybrid systems.

SUSTAINABILITY AND ENVIRONMENTAL ASSESSMENTS

Carbon footprint and environmental impacts of UHPC

UHPC offers significantly higher compressive strength and superior durability compared to conventional concrete. However, these advantages come with environmentally costly raw materials—particularly high cement content (800–1100 kg/m³) and energy-intensive SF. Cement production alone accounts for approximately 7–8% of global CO_2 emissions, releasing about 0.8–0.9 tons of CO_2 per ton of cement produced. In the literature, it is widely noted that a substantial portion of UHPC's carbon emissions stems from these two components (Lande & Terje Thorstensen, 2023; Zhang et al., 2024). Therefore, reducing the environmental burden of these constituents is essential for improving UHPC's sustainability. A primary strategy is the partial replacement of cement. Using SCMs such as GGBFS, FA, and MK can significantly lower the carbon load associated with cement. For example, Moula et al. demonstrated that replacing 30% of cement with GGBFS preserved the mechanical performance of UHPC while significantly reducing its carbon footprint (Moula et al., 2023). Similarly, Ji et al. and Salas et al. reported that using geopolymer binders as low-carbon clinker alternatives could reduce emissions by 30–60% (Ji et al., 2022; Salas et al., 2018).

Another advancement is the emergence of geopolymer-based UHPC (UHPGC) systems. These materials incorporate industrial by-products such as GGBFS and FA, activated with sodium silicate and NaOH, and can achieve compressive strengths of over 120 MPa. Studies report that these systems can reduce the carbon footprint by 32–45%, although water and energy consumption remain high. Some commercial geopolymer systems have even been shown to reduce CO_2 emissions by up to 80% (Glanz et al., 2023). Life Cycle Assessment (LCA) is crucial in evaluating UHPC's environmental impact. Cement and steel fiber content are the most dominant contributors to UHPC's carbon burden in LCA analyses. Case studies by Li et al. (2022) indicated that these parameters account for up to 90% of total emissions. Ji et al. (2022) found that off-site production combined with 50 °C water bath curing offered environmental benefits over traditional methods, making UHPC more sustainable throughout its service life. Conversely, on-site curing may increase energy demands by up to 50%, while high-performance of off-site cured UHPC can help mitigate this impact (Ji et al., 2022; Li et al., 2025a).

Alternative fibers also play a role in shaping UHPC's environmental profile. While SF improves ductility and tensile strength, their production is energy intensive. Researchers such as Lande and Thorstensen suggest partial replacement with waste-derived plastic or rubber fibers, although these alternatives have not yet fully matched the performance of SF. Nevertheless, such waste fibers show promising potential for future emission reductions (Lande & Terje Thorstensen, 2023). The use of recycled aggregates is also receiving increased attention. Materials like glass powder or crushed concrete can offer additional environmental benefits in UHPC mixes. However, some studies note that their impact is less significant than that of cement replacement, serving more as complementary solutions (Zhang et al., 2024b).

When examining the life cycle of geopolymer systems, it is observed that the production of activators such as NaOH and Na_2SiO_3 contributes significantly to carbon and energy footprints. Nevertheless, the environmental load is partially offset by using industrial by-products such as GGBFS and FA, making the net carbon footprint of geopolymer UHPC lower than that of traditional Portland-based UHPC. However, geopolymer UHPC tends to consume more water and energy, particularly due to the high-water demand of Na_2SiO_3, leading to a trade-off between reduced climate impact and increased resource consumption (Salas et al., 2018). Strategic approaches to reducing the carbon footprint of UHPC include high-volume cement replacement (GGBFS, FA, MK), use of geopolymer binders, substitution of SF with environmentally friendlier alternatives, integration of recycled aggregates, and implementation of sustainable curing methods. When applied collectively, these strategies can reduce UHPC's carbon footprint by 30–80%, while maintaining its high-performance potential. However, comprehensive life cycle assessments are needed to evaluate trade-offs such as increased energy and water use. Ongoing research in this field highlights the need for multi-dimensional analyses to optimize UHPC for both engineering and environmental performance. Future UHPC formulations are expected to prioritize low-carbon production methods, recycled raw materials, and energy-efficient curing technologies.

Use of Waste and Recycled Materials in UHPC Production

Studies have shown that recycled fine aggregates (RFA) obtained from construction and demolition (C&D) waste can improve both the mechanical and environmental performance of UHPC. Particularly, replacing 20% of quartz sand with RFA particles sized between 1.18–2.36 mm has been shown to reduce autogenous shrinkage by 78.5% due to improved internal moisture retention, while increasing 28-day compressive strength by 7.1%. Moreover, RFA had no adverse effect on the flowability or chloride ion resistance of UHPC; in fact, it improved the microstructure and reduced the presence of large pores. Environmentally, this approach resulted in a 7% reduction in carbon emissions and 7.8% less energy consumption (Chen et al., 2024). Other waste materials such as recycled concrete powder (RCP) and iron ore tailing sand (IOTS) have also been successfully utilized in UHPC production. In one study, a mixture containing 10% RCP and 45% IOTS achieved a 28-day compressive strength of 144 MPa, with a 5.8% increase in ultra-dense hydrated calcium silicate gel content. Additionally, this combination reduced carbon emissions by 28.5% and fossil energy consumption by 25.4% (Luan et al., 2024).

Another notable approach involves the use of recycled coarse aggregates (RCA) after accelerated carbonation. Research has demonstrated that carbonated RCA (CRCA) provides better mechanical and volumetric stability than natural aggregates, improves resistance to chloride ion penetration, and contributes to CO_2 emission reduction. The carbonation process reduces RCA porosity, lowers water absorption, and enhances the bond with the binder, thereby increasing strength—an advantage particularly beneficial in long-lasting infrastructure applications (Leng et al., 2023). The use of waste and recycled materials in UHPC production not only enhances mechanical properties but also offers considerable environmental and economic benefits. For example, recycled materials reduce natural resource consumption and transportation distances, thereby minimizing environmental footprints (Tran et al., 2025). These materials also help address waste management challenges and support sustainable construction practices. The incorporation of industrial by-products such as FA, rice husk ash (RHA), and steel mill dust has shown promise in reducing both cost and environmental burden (Tran et al., 2025; Van Tuan et al., 2011). Similarly, the use of waste glass powder and ceramic waste in UHPC mixes has been explored with promising results.

However, careful quality control and processing are essential when using such materials in UHPC. Characteristics such as porosity, water absorption capacity, and chemical composition of waste materials used as aggregate or binder can directly influence the final performance of UHPC (Chen et al., 2024; Luan et al., 2024). For example, the presence of residual mortar on RFA surfaces can retain internal moisture and help reduce autogenous shrinkage. Furthermore, some studies emphasize the necessity of pre-treatment methods such as grinding, thermal processing, and chemical activation to enhance the reactivity of these recycled materials. Optimizing the binding properties of these materials can further improve UHPC performance (Gonzalez-Corominas

& Etxeberria, 2016). Using waste and recycled materials in UHPC production not only mitigates environmental impacts but also enhances long-term performance. However, it is essential to determine optimal mix proportions, thoroughly characterize material properties, and validate results through long-term field applications. Research in this direction holds significant potential for developing environmentally friendly and economically sustainable solutions in UHPC manufacturing.

Environmental Assessment through Life Cycle Analysis (LCA)

UHPC stands out in the construction industry with its high compressive strength and superior durability, enabling the construction of longer-lasting structures compared to conventional concrete (Al-Ameen et al., 2024). However, the high cement content and energy intensity involved in UHPC production result in a relatively large initial environmental footprint (Ghahsareh et al., 2025). At this point, the long-term advantages of UHPC become apparent: it significantly reduces maintenance and repair needs over the structure's lifespan, thereby lowering overall carbon emissions and costs (Al-Ameen et al., 2024; Shang et al., 2023). Research indicates that UHPC can offer 25–48% lower carbon emissions compared to conventional concrete, presenting a more sustainable alternative. For instance, Ghahsareh et al. (2025) found that UHPC beams could reduce lifetime maintenance costs by up to 55% and carbon emissions by up to 58%. These figures rise to 76% when partial removal of steel reinforcement is incorporated. Similarly, Fan et al. reported that beams designed with UHPC produced 48% less life cycle carbon emissions compared to conventional concrete beams, and despite a 13% increase in material cost, they offered long-term economic savings (Fan et al., 2024).

Another important finding is the environmental benefit of incorporating waste and recycled materials into UHPC production. The inclusion of materials such as FA, slag, waste glass powder, and ceramic waste significantly reduces both material costs and carbon emissions (Ghahsareh et al., 2025; Shang et al., 2023). For example, Xia et al. showed that using 25% ceramic waste resulted in a 12% reduction in material cost and a 15% decrease in carbon emissions (Xia et al., 2021).. This approach not only optimizes resource usage but also promotes the reuse of waste materials in the construction industry (Ghahsareh et al., 2025). Furthermore, a study by Al-Ameen et al. (2024) revealed that Sprayed-UHPC Sandwich Panels (SUHPC-SP) provide up to 500% lower environmental impact and reduce economic costs by up to 180% compared to traditional brick-wall construction. This highlights that UHPC's environmental performance can be improved not only through its material properties but also through innovative structural applications (Al-Ameen et al., 2024). In addition, research by Shang et al. has demonstrated that new curing techniques, such as accelerated carbonation, can further reduce the ecological footprint of UHPC production (Shang et al., 2023).

Studies emphasize the critical role of durability in UHPC's life cycle performance (Shang et al., 2023). Crack development directly affects maintenance intervals, and the use of advanced sensors such as Digital Image Correlation (DIC) and Distributed Fiber Optic Sensing (DFOS) enables more accurate maintenance planning (Ghahsareh et al., 2025). These monitoring technologies optimize maintenance needs, thereby reducing both carbon emissions and economic burden. Taken together, these findings show that the environmental sustainability potential of UHPC should not be assessed based solely on production-stage emissions. Instead, a comprehensive evaluation that includes maintenance, repair, and service life emissions is required (Al-Ameen et al., 2024; Shang et al., 2023). Replacing the "cradle-to-gate" approach with a "cradle-to-grave" system boundary more accurately reflects the true sustainability potential of innovative construction materials like UHPC (Ghahsareh et al., 2025). Although UHPC entails high initial environmental costs, these are balanced out by its long service life, reduced maintenance demands, and the integration of recycled materials, making it an indispensable part of sustainable construction. Therefore, it is recommended that UHPC's potential be further explored through comprehensive LCA studies and long-term field applications.

STRUCTURAL APPLICATIONS AND PERFORMANCE

Use of UHPC in Bridges, Facades, and Column–Beam Elements

The application of UHPC in bridges, facades, and column–beam elements represent a major advancement in modern structural engineering by enhancing durability, aesthetics, and reducing maintenance costs (Abdal et al., 2023). In bridge construction, UHPC is especially appealing due to its high strength and low maintenance requirements. Offering approximately four times the compressive strength of conventional concrete, UHPC enables longer spans and greater flexibility in architectural design (Schmidt & Fehling, 2005). Its use in prestressed systems allows for the design of slender beams and decks capable of spanning greater distances (El-Helou & Graybeal, 2022). UHPC also offers significant advantages in connection zones. While traditional concrete joints tend to deteriorate over time, UHPC-filled joints provide long-term integrity thanks to their high strength and low permeability (Abdal et al., 2023). Abdal et al. (2023) demonstrated that UHPC connection systems can reduce maintenance costs by 30–40%, significantly lowering life cycle costs. Moreover, these connections enhance seismic performance, offering benefits in earthquake-prone regions (Abdal et al., 2023). The use of UHPC in column–beam elements provide a resilient and ductile system, particularly effective under seismic loads. According to Kravanja et al., UHPC-jacketed beam–column joints demonstrated a 40–60% increase in elastic modulus, which helped limit crack propagation. This enables a reduction in column cross-sections while enhancing structural stability and seismic performance (Kravanja et al., 2024). Experimental studies conducted in seismic zones have shown that UHPC-wrapped joints can dissipate twice as much energy as conventional reinforced concrete systems (El-Helou & Graybeal, 2022).

In façade systems, UHPC allows for modern architectural expression. The thin-section precast UHPC panels provide high-resolution surface finishes, meeting aesthetic demands (Schmidt & Fehling, 2005). Thanks to their low water absorption and chemical resistance, these panels require minimal maintenance throughout their service life (Abdal et al., 2023). In high-rise buildings, UHPC façade panels offer a lightweight yet high-strength solution against wind loads, thereby optimizing both structural and architectural performance (Kravanja et al., 2024). UHPC's dense microstructure and ultra-low permeability offer long-term durability against freeze–thaw cycles and aggressive environmental conditions (Abdal et al., 2023). These properties enhance the performance of bridges and facades exposed to harsh environments and extend maintenance intervals (Zhou et al., 2018). Chemical stability provides superior protection against saltwater and industrial pollutants, making it ideal for long-term use in coastal and chemically aggressive environments (El-Helou & Graybeal, 2022). The use of UHPC in bridges, façades, and column–beam systems provides exceptional load-carrying capacity, long service life, reduced maintenance needs, architectural flexibility, and seismic resilience—features that are shaping the future of structural design (Abdal et al., 2023; El-Helou & Graybeal, 2022; Kravanja et al., 2024; Schmidt & Fehling, 2005; Zhou et al., 2018). With all these advantages, UHPC has become a key material for creating sustainable, economical, and safe solutions in modern structural engineering and architecture.

Hybrid material systems with UHPC (Steel–UHPC, ceramic–UHPC, polymer–UHPC)

Although traditional UHPC mixtures typically rely solely on SF, hybrid reinforcements combining different fiber types have emerged as an effective strategy to improve both the mechanical behavior and environmental durability of UHPC (Ravichandran et al., 2022). In this context, integrating steel, polymer, vegetal, and inorganic fibers into UHPC in a hybrid form can enhance strength, ductility, and particularly performance under high-temperature conditions. Kim et al., investigated the hybrid use of steel and polyethylene (PE) fibers in an alkali-activated cement-free UHPC system and evaluated its effect on mechanical properties. The study revealed that the inclusion of PE fibers alongside SF led to greater microcrack formation and lower density compared to mixtures with only SF. However, in hybrid systems, especially with a moderate fine aggregate-to-binder ratio of 0.32, optimal performance in tensile ductility and energy absorption was achieved. The hybrid reinforcement system offered a more balanced and multidimensional strength profile due to the combination of different fiber pull-out and rupture mechanisms (Kim et al., 2023). Moreover, fiber aspect ratio and the interfacial area between fibers and binder were identified as critical factors for understanding strength mechanisms in the interfacial transition zone (ITZ). Similarly, Ren et al. examined hybrid UHPC systems incorporating natural sisal and SF in terms of their high-temperature performance. In this study, sisal fibers decomposed at lower temperatures, creating microchannels that facilitated vapor escape and thus prevented explosive spalling. An optimal residual compressive and flexural strength was obtained with 0.6 vol-% sisal fibers. Considering the sustainability and low cost of vegetal fibers, hybrid steel–vegetal fiber systems can be regarded as cost-effective and eco-friendly UHPC alternatives (Ren et al., 2022). This approach provides a promising solution in response to increasing demand for carbon footprint reduction and use of recyclable materials.

Khan et al. explored the post-fire behavior of UHPC systems incorporating both steel and basalt fibers. Basalt fibers demonstrated superior heat resistance compared to organic polymer fibers, and when combined with SF, UHPC's resistance to explosive spalling significantly improved. Microstructural analyses supported by XRD, TGA, and FTIR tests showed that basalt fibers positively influenced hydration products and porosity structure. Unlike organic fibers that degrade around 400°C, basalt fibers contributed to structural integrity and durability (Khan et al., 2024). Their natural origin and non-toxic profile further enhance their value as a sustainable option. Complementing these findings, the review by Ravichandran et al. systematically analyzed the influence of hybrid fiber systems on UHPC. The study categorized the effects of fiber geometry, volume, orientation, and interaction with the binder on both fresh-state rheology and hardened-state strength. It emphasized that straight SF contribute to flexural strength, twisted and hooked fibers enhance crack resistance, and polymer fibers improve energy dissipation capacity. Furthermore, hybrid systems with SF exhibited significant advantages in crack control, impact resistance, and energy absorption. The distribution and orientation of fibers in the mixture were identified as critical performance factors, especially for three-dimensional structural elements (Ravichandran et al., 2022).

Hybrid fiber use in UHPC, especially combinations of steel with polymeric, vegetal, or inorganic fibers, significantly enhances the material's performance to meet diverse engineering demands. Improved resistance to spalling under elevated temperatures, enhanced ductility, and the inclusion of sustainable fibers are among the key advantages of such hybrid systems. The general trend in literature supports the idea that combining fibers with different physical and chemical characteristics leads to meaningful improvements in UHPC performance. Future research should focus on optimizing fiber proportions and investigating fiber–matrix interactions at the microscale to further advance UHPC technology. Additionally, aligning these advancements with carbon reduction goals in construction materials will strengthen UHPC’s role in sustainable building technologies (Ravichandran et al., 2022).

Seismic Performance of UHPC and Its Use in Low-Energy Buildings

Recent studies on the seismic performance of UHPC reveal its significant potential for enhancing structural safety against earthquake effects. Due to its high strength, ductility, and low permeability, UHPC emerges as a promising material for structures in earthquake-prone regions. The seismic behavior of UHPC under dynamic loads has been extensively examined through both experimental and numerical studies on various structural components such as columns, beams, joints, and walls (Elmorsy & Hassan, 2021). Elmorsy and Hassan (2021) systematically analyzed 142 experimental tests from the literature and demonstrated UHPC's superior resistance to seismic loads and deformation capacity. Their study concluded that UHPC delayed crack propagation, enhanced stiffness, and promoted ductile behavior. Additionally, its high energy dissipation capacity significantly contributes to damage control during seismic events. The use of UHPC in composite systems has also shown favorable outcomes in terms of seismic performance. In an experimental study by Zhang et al. (2024b) a precast frame system composed of UHPC beams and HSC columns was compared to a fully cast-in-place concrete system. Results indicated that the UHPC–HSC system exhibited 15.78% higher load-carrying capacity and superior energy dissipation/deformation behavior. These advantages were largely attributed to improved stiffness and reduced damage to the connection zones. Moreover, this system showed enhanced post-earthquake reparability and structural integrity, making it particularly advantageous in areas requiring rapid recovery (Zhang et al., 2024b).

Combining UHPC with FRPs has also led to significant performance improvements. Ma et al. analyzed UHPC columns reinforced with GFRP bars under multi-directional loading and found that this system limited crack development, maintained consistent performance regardless of loading direction, and preserved load capacity with less deformation compared to conventional concrete columns. These characteristics make UHPC–GFRP columns advantageous under complex seismic demands (Ma et al., 2023). Numerical modeling and artificial intelligence-based approaches are increasingly used to evaluate UHPC’s potential. He et al., investigated seismic performance improvements in RC frames through the addition of UHPC zones, using both finite element modeling and deep learning simulations. Their results showed that localized application of UHPC—especially at column ends—reduced maximum story drift by an average of 38% and significantly enhanced overall stiffness. This proves that even targeted use of UHPC can increase ductility and strength. Furthermore, the use of deep learning models enabled testing thousands of design strategies, allowing for faster and more efficient development of low-energy, high-performance structures (He et al., 2025). Finally, an experimental study by Li et al. (2024) evaluated the performance of two-story precast frame systems with UHPC-based joints. The results showed a 9% increase in load-bearing capacity and a 10%

improvement in displacement ductility. Additionally, stiffness degradation remained lower than in traditional monolithic frames. These findings indicate that UHPC not only enhances seismic performance during earthquakes but also contributes to post-event functionality. Thanks to its compact and high-strength structure, UHPC provides energy efficiency benefits during both construction and operational phases, making it highly suitable for low-energy building concepts (Li et al., 2024).

CONCLUSION

This study provided an in-depth review of UHPC, focusing on its material composition, fresh and hardened properties, mechanical performance, and long-term durability. Characterized by compressive strengths typically ranging from 125 to 250 MPa, along with significantly enhanced tensile and flexural capacities due to fiber reinforcement, UHPC demonstrates a dense microstructure achieved through low water-to-binder ratios, superplasticizers, and advanced additives such as SF, FA, and NMs.

Despite its impressive mechanical and durability characteristics, several barriers hinder the widespread use of UHPC. Chief among these are its high production costs—largely attributed to the inclusion of premium materials like steel fibers and nanoscale additives—as well as challenges related to workability during large-scale construction. Additionally, limited long-term field performance data and the absence of universally accepted design codes further restrict its adoption across mainstream infrastructure projects.

To support broader implementation, future research should prioritize life-cycle assessments to evaluate UHPC's environmental impact relative to conventional concrete. Investigations into its performance under combined hazards, such as seismic activity followed by fire exposure, and extended monitoring of real-world applications are also essential. Innovations in mix optimization using artificial intelligence, incorporation of recycled or locally sourced materials, and development of self-healing or multifunctional properties could further improve both the sustainability and practicality of UHPC systems.

In summary, while UHPC presents a compelling solution for durable, high-performance infrastructure, its full potential can only be realized through continued interdisciplinary collaboration aimed at addressing current economic, technical, and regulatory limitations.

DECLARATIONS

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Consent to publish

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Competing interests

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