

High Performance Concrete Designed Using Industrial Waste: A Review

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Abstract – Ultra-high-performance concrete (UHPC) is renowned for its superior mechanical strength, durability, and minimal permeability, making it an innovative solution for critical infrastructure. Nonetheless, the high consumption of cement and fine powders in conventional UHPC formulations increases both production costs and environmental impact. In recent years, researchers have focused on utilizing industrial waste materials as alternative constituents to enhance the sustainability and cost-effectiveness of UHPC. This review traces the evolution of UHPC and evaluates its advantages, such as long service life, exceptional resilience, and the potential for lighter, thinner structural components. However, the drawbacks including high initial costs, technical complexities, and limited adoption remain significant obstacles. The review further discusses a Fishbone Diagram to systematically analyze these challenges, and highlights the role of supplementary cementitious materials derived from industrial waste in advancing UHPC technology for greener construction practices.

Keywords: Ultra-high-performance concrete (UHPC), Industrial Waste, Cost-effective, Material properties, Structural elements, Structural applications.

1. Introduction

The rapid advancement of infrastructure development has necessitated the introduction of innovative construction materials that can provide enhanced strength, durability, and sustainability compared to conventional alternatives. Concrete, owing to its affordability, ease of use, and global availability, remains the most widely utilized material in civil engineering applications. However, conventional concrete exhibits inherent limitations in mechanical performance, service life, and resilience under harsh environmental conditions. In response to these challenges, research efforts have increasingly focused on devising advanced concrete formulations capable of overcoming such deficiencies. Among these, ultra-high-performance concrete (UHPC) has emerged as a transformative material due to its superior structural

and durability-related characteristics.

UHPC is notable for its exceptional properties, including compressive strengths exceeding 150 MPa, tensile strengths ranging from 5–8 MPa, low permeability, and outstanding resistance to chemical attack and environmental degradation. Such remarkable performance attributes are achieved by optimizing particle packing, employing a higher binder content, and reducing the water-to-binder ratio. These advancements make UHPC particularly valuable for high-performance applications such as bridges, tunnels, marine structures, and the retrofitting of aged infrastructure. Furthermore, its ability to ensure structural continuity and resilience under complex loading conditions positions it as a highly reliable material for addressing modern engineering demands.

Despite its advantages, the widespread adoption of UHPC remains constrained by several challenges. The production of UHPC requires a significantly higher cement content compared to conventional concrete, which not only raises material costs but also contributes to increased carbon emissions. Additionally, the use of ground quartz and silica fume—materials with limited global availability further escalates production expenses and raises sustainability concerns due to the depletion of non-renewable resources. To overcome these limitations, recent investigations have increasingly emphasized the development of sustainable UHPC mixtures through the substitution of traditional constituents with supplementary cementitious materials and locally available industrial by-products. Alternatives such as fly ash, ground granulated blast-furnace slag (GGBS), copper slag, and recycled materials have demonstrated potential in reducing environmental burdens while maintaining or even enhancing the mechanical performance of UHPC.

Another critical factor influencing UHPC performance is the curing regime. Studies conducted by the Federal Highway Administration (FHWA) have highlighted that heat curing can significantly enhance the compressive strength, with improvements of over 50% compared to specimens cured under standard conditions. Such observations underscore the importance of not only mix optimization but also the curing process in attaining the desired performance outcomes. Equally, the incorporation of coarse aggregates into UHPC formulations, although initially avoided to maintain homogeneity, has gained attention for its cost-reduction potential and contribution to sustainability. Nevertheless, the inclusion of industrial waste and coarse aggregates at variable substitution rates may result in inconsistent performance, presenting challenges for the large-scale implementation of these environmentally friendly mixes.

In this context, the pursuit of sustainable and economically viable UHPC mix designs has become a central focus of recent research. Developing formulations that balance performance, cost, and environmental impact is essential to advancing the practical adoption of UHPC in widespread infrastructure projects. This paper therefore aims to review the current progress in UHPC research, with particular emphasis on mix design strategies integrating coarse aggregates and industrial by-products. By evaluating their implications for mechanical performance, durability, sustainability, and large-scale feasibility, this study contributes to the ongoing discourse on the optimization and broader application of UHPC in modern civil engineering.

Figure 1 presents an overview of the major trends, market drivers, and growth projections influencing the global Ultra-High-Performance Concrete (UHPC) market. A significant trend identified is the increasing demand for reactive powder concrete, a precursor to UHPC. This demand is driven by its outstanding mechanical properties, superior durability, and ability to withstand aggressive environmental conditions, making it an essential material for high-performance and sustainable infrastructure projects.

Another key trend is the rapid expansion of road and bridge construction activities, particularly in developing economies. Governments and private sectors are investing heavily in durable construction materials to reduce lifecycle costs and enhance safety, where UHPC offers a reliable solution. The Asia-Pacific (APAC) region has emerged as a major market driver, fueled by large-scale urbanization, industrialization, and infrastructure modernization initiatives in countries such as China, Japan, and India.

Market projections further indicate that the global UHPC industry is expected to grow at a Compound Annual Growth Rate (CAGR) of nearly 7% until 2022. This growth reflects the increasing acceptance of UHPC in structural applications and the ongoing research and development efforts to optimize its cost efficiency, mix design, and large-scale implementation in modern construction.



Figure 1: Global UHPC market

1.1 Evolution of Ultra-High-Performance Concrete (UHPC)

The evolution of Ultra-High-Performance Concrete (UHPC) represents a continuous advancement in concrete technology aimed at achieving superior strength and durability. The journey began in 1824 with the development of Portland cement, forming the basis of modern concrete. By 1849, the introduction of reinforced concrete (RC) using metallic reinforcements revolutionized structural design. The 1930s witnessed the creation of concrete with high compressive strength, enhancing material performance.

In the 1970s, focus shifted towards High-Performance Concrete (HPC), integrating improved mechanical and durability properties. This was further refined during the 1980s, achieving even higher strength levels. The breakthrough came in 1994 with the first development of UHPC, a material offering exceptional compressive strength, ductility, and longevity.

Subsequent decades demonstrated UHPC's practical applications, including the first UHPC bridge in Canada (1997) and the first UHPC highway bridge in the USA (2006). By the 2010s, UHPC had gained global recognition, with numerous highway bridges constructed worldwide. Today, UHPC stands as a pivotal innovation driving sustainable, high-performance infrastructure development across the globe. Refer Figure 2.

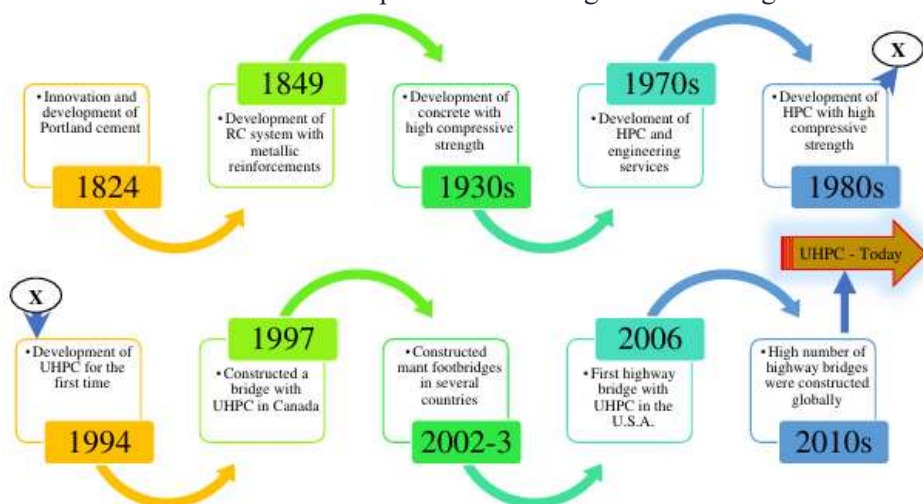


Figure 2: History development trends of UHPC

1.2 Advantage and Disadvantage

The following are the advantages and disadvantages of Ultra high-performance concrete.

Advantages:

1. Sustainability and waste use: Effectively uses industrial by-products, like fly ash, slag, silica fume, and metakaolin, reducing landfill waste and environmental pollution.
2. Reduced carbon footprint: Partially replacing cement lowers CO₂ emissions during production.

3. Improved strength and durability: Industrial waste materials enhance the microstructure and lead to higher compressive and flexural strength.
4. Better workability and packing: Fine industrial waste particles fill voids, improving particle packing and lowering porosity.
5. Cost efficiency: Reduces the amount of costly cement and improves the long-term life cycle cost.
6. Resistance to harsh environments: Provides better resistance to chloride attacks, sulfate attacks, and alkali-silica reactions (ASR).
7. Improved sustainability ratings (LEED, GRIHA): Using waste materials helps obtain green building credits.

Disadvantages:

1. Quality variation of waste materials: Industrial by-products differ in chemical makeup and fineness, which affects concrete consistency.
2. Need for careful mix design: Finding the right proportions requires careful mix design and testing.
3. Limited availability in some areas: Some wastes, like silica fume or GGBS, may not be available locally, raising transport costs.
4. Higher initial production cost: Specialized materials and curing methods, such as heat curing, increase initial costs.
5. Workability challenges: A very low water-binder ratio can decrease workability, needing high-range superplasticizers.
6. Lack of standardized guidelines: There are limited codes and design standards for UHPC that uses industrial waste.
7. Complex production process: Requires controlled batching, curing, and mixing conditions to ensure consistent performance.

2. Literature Review

The following are the previous research review based on study of ultra-high-performance concrete designed using industrial waste.

Srinivasan et al. (2015) presented an experimental investigation into modifying Ultra High Strength Concrete (UHSC) by partially replacing cement with the agricultural waste, Bagasse Ash (BA). They motivated their research by pointing to the severe CO₂ emission problem created by the massive consumption of cement, especially in a region generating large amounts of waste BA. The results indicated that incorporating BA not only helped reduce cement reliance but also successfully improved essential characteristics of UHSC, such as workability, resistance to chemical attack, and overall compressive strength [1].

Chandrakar et al. (2017) provided a review focused on achieving M-60 grade High Performance Concrete (HPC) using mineral additions like fly ash and Ground Granulated Blast Furnace Slag (GGBS). They affirmed that replacing a portion of cement with these supplementary materials offers several advantages, including energy and cost savings, environmental protection, and improved concrete properties such as enhanced compressive strength and durability. Specifically, studies reviewed highlighted that GGBS contributes to lower initial strength gain but better long-term strength, and that an optimal replacement percentage, around 20% for GGBS alone, maximizes strength and improves workability [2].

Anandh et al. (2018) investigated replacing cement with Class-F fly ash and silica fume, replacing fine aggregate with copper slag, and reinforcing the mix with plastic fibers made from used bottles. They successfully created multi-component concrete mixes that showcased superior performance for both M-20 and M-35 grades. Their optimal mix achieved substantial improvements over conventional concrete, including a significant increase in compressive strength (up to 5.51%) and notable increases in split tensile and flexural strengths, confirming the potential of this combination for economical and eco-friendly structural applications [3].

Marvila et al. (2021) offered an in-depth review of materials essential for High Performance Concrete (HPC) and Ultra-High-Performance Concrete (UHPC), focusing particularly on future possibilities like alkali-activated cement. They established that conventional UHPC production is expensive due to high cement content and specialized chemical additives, necessitating a shift toward highly reactive SCMs like silica fume and fly ash to ensure strength without the high cost. They heavily endorsed the development of alkali-activated cement as an environmentally

superior binder, capable of utilizing industrial wastes as precursors to achieve comparable strength and even greater long-term durability than traditional OPC based mixes [4].

Abdellatief et al. (2023) investigated improving UHPC sustainability by extensively replacing cement with waste materials, including Metakaolin (MK), Ground Granulated Blast-Furnace Slag (GGBS), and fly ash (FA). Their findings demonstrated that even with high substitution rates, the material's mechanical performance remained strong, especially with the addition of 15% MK, which notably increased strength beyond the control mix. Overall, incorporating these supplementary cementitious materials (SCMs) successfully reduced the embodied energy consumption and carbon footprint of the UHPC, confirming a path toward cleaner construction products in the near future [5].

He et al. (2023) summarized the research on the interface bond performance between Ultra-High-Performance Concrete (UHPC) and Normal Concrete (NC), a critical issue for the repair and reinforcement of existing structures. They confirmed that the UHPC-NC connection possesses excellent interfacial bonding strength which is significantly influenced by mechanical factors. The study highlighted that maximizing bond strength requires increasing interface roughness and ensuring an appropriate curing system, while the crucial addition of polypropylene fibers enhances the anti-burst performance of UHPC when exposed to high temperatures [6].

Maaty et al. (2023) experimentally demonstrated that high-quality UHPC can be economically and sustainably produced by incorporating industrial wastes as partial cement replacements. They utilized ceramic waste powder (CWP), brick waste powder (BWP), and marble waste powder (MWP), with 10% BWP proving to be the optimal dosage for maximizing compressive strength. Their findings confirmed that while increasing waste content generally reduced workability, the mixes maintained high mechanical performance; notably, adding 2% steel fibers significantly improved mechanical strength and load-carrying capacity by delaying crack initiation [7].

Nagar et al. (2023) investigated replacing cement with Rice Husk Ash (RHA) and replacing sand with Shredded Steel Waste (SSW) to create eco-friendly concrete. Their work confirmed that utilizing these wastes reduces both construction cost and air pollution from cement production. For their specific mixes, they concluded that an optimal replacement of 20% RHA yielded the highest compressive strength, while the combined use of RHA and SSW further increased overall compressive strength. They recommended this combined approach as a sustainable alternative to conventional concrete for structural applications [8].

Liu et al. (2024) emphasize that blast events, whether due to industrial accidents or intentional attacks, pose severe threats to structural safety through direct pressures, fragmentation, and secondary progressive collapse. To address these challenges, recent research has focused on UHPC as a promising material due to its superior mechanical and dynamic response under extreme loading. Experimental, numerical, and theoretical investigations have shown that UHPC structural members such as slabs, beams, and columns, as well as UHPC-based composites like mesh-reinforced UHPC, UHPC-filled steel tubes, and UHPC-strengthened reinforced concrete, significantly enhance blast resistance. Future directions highlight eco-friendly UHPC, 3D printing integration, and machine learning approaches for improved blast-resistant design [9].

Kravanja et al. (2024) Recent literature highlights the significant progress and diverse applications of UHPC, emphasizing its exceptional mechanical strength, durability, and multifunctionality. Historical developments, production methodologies, and mix design innovations are thoroughly explored, along with advancements in nanotechnology and sustainability. UHPC's distinctive properties, including high packing density, low porosity, and minimal permeability, provide superior structural performance compared to conventional concrete. The addition of steel or alternative fibers improves tensile and flexural capacity, shifting failure behavior from brittle to ductile. Despite its benefits, challenges such as high production costs, large-scale mixer inefficiencies, and environmental concerns persist. Current research focuses on sustainable formulations using supplementary cementitious materials, nanoparticles, and industrial by-products to reduce costs, enhance durability, and minimize environmental impact [10].

Suresh et al. (2024) conducted a comprehensive study to evaluate the mechanical behavior of UHPC, targeting compressive strength beyond 150 MPa at 28 days. The research emphasized mix design, material properties, and curing regimes, while assessing stress-strain responses of UHPC cylinders under uniaxial compression. Flexural strength, fracture energy, and crack mouth opening displacement were examined through third-point loading tests, alongside compressive and split tensile strengths. Durability performance was investigated by incorporating varying steel fiber volumes and aspect ratios, revealing significant improvements in strength, toughness, and post-peak response. This work highlights UHPC's potential in India, contributing to its future structural applications and commercialization [11].

Tiwari et al. (2025) conducted an experimental investigation on High-Performance Concrete (HPC) incorporating industrial waste materials such as fly ash and silica fume to enhance durability and sustainability. The study evaluated various mix designs (M70, M80, and M90) with different replacement levels of fly ash (8–21%) and silica fume (4–7%), maintaining a low water–cement ratio (0.24–0.26). Results showed that the inclusion of these supplementary materials improved the compressive, flexural, and tensile strength of concrete, achieving higher performance compared to conventional mixes. Durability assessments through carbonation and water absorption tests confirmed the reduced porosity and enhanced resistance to environmental degradation. The study concluded that partial cement replacement with fly ash and silica fume not only improved mechanical properties but also contributed to sustainable and durable high-performance concrete development [12].

UHPC represents a new generation of cementitious composites characterized by high density and superior compressive strength. **Nadia et al. (2025)** highlight that incorporating locally available materials, particularly coarse aggregates, presents an effective strategy to reduce both the environmental footprint and cost associated with UHPC production. Previous studies have investigated mix design optimization, mixing techniques, fresh concrete testing, and curing methods when integrating materials such as fly ash, ground granulated blast-furnace slag (GGBS), copper slag, and locally sourced aggregates including natural sand, crushed stone, and river sand. Research findings suggest that UHPC mixtures with local materials can achieve compressive strengths up to 150 MPa. Additionally, silica fume, typically used at 10–30%, and fly ash substitutes significantly influence hydration and long-term strength development. Heat curing remains the most effective treatment, achieving higher strengths than moist curing, which can result in approximately 20% strength reduction [13].

Makwana et al. (2025) developed a framework for creating sustainable High-Performance Concrete (HPC) by incorporating both recycled aggregates and Supplementary Cementitious Materials (SCMs). Their study successfully created mixes that maintained comparable mechanical performance to conventional HPC while dramatically reducing the environmental footprint; specifically, they recorded a decrease in CO₂ emissions from 300 kg/m³ to 220 kg/m³. They found that replacing up to 50% of the aggregate with recycled material met all structural requirements, although durability factors like water absorption and chloride penetration showed a modest decline [14].

Mohd Zahid et al. (2025) conducted a detailed review on the potential of various waste materials for developing green UHPC, particularly for on-site rehabilitation work, where specialized properties and normal curing are required. They established that high cement content is the primary driver of UHPC's large CO₂ footprint and energy consumption. The review confirmed that several wastes, such as spent equilibrium catalyst and sugarcane bagasse ash, are promising because they enhance strength and durability while mitigating the crucial issue of autogenous shrinkage, which is essential for improving bond strength with existing concrete substrates [15].

Ultra-high-performance concrete (UHPC) has emerged as a notable advancement in modern concrete technology, offering superior mechanical strength and exceptional durability. According to **Niu et al. (2025)**, its unique material composition and enhanced properties, including compressive, tensile, impact resistance, and long-term durability, contribute significantly to the resilience and service life of structural systems. UHPC has been increasingly applied in engineering domains such as housing, bridges, tunnels, and particularly in underground construction. Its role in shield tunnel segment reinforcement is emphasized, given its ability to optimize structural integrity and resist complex loading conditions. However, further research is required to assess its long-term performance and refine reinforcement methods for broader implementation in tunnel engineering [16].

Girmay (2025) Ultra-high-performance concrete (UHPC) and ultra-high-performance fiber-reinforced concrete (UHPFRC) represent a new generation of advanced construction materials, offering superior mechanical characteristics, durability, and sustainability compared to conventional concrete. Recent studies highlight that UHPC/UHPFRC demonstrates exceptional compressive, flexural, and tensile strengths, with fiber incorporation significantly enhancing ductility, toughness, and resistance to crack propagation. Their outstanding durability against chloride ingress, freeze-thaw cycles, and chemical attacks further supports their long-term application in bridges, tunnels, high-rise buildings, and protective structures. Additionally, their high strength-to-weight ratio allows for lighter and more efficient structural designs. Despite the challenges associated with high cement content and environmental impact, innovations such as recycled materials, eco-friendly curing, digital technologies, and smart monitoring systems indicate strong potential for UHPC/UHPFRC in sustainable, intelligent infrastructure development [17].

3. Fishbone Diagram for Ultra-high-performance concrete (UHPC)

The Fishbone Diagram (Ishikawa Diagram) presented in Figure 3 systematically illustrates the key factors influencing the performance and quality of Ultra-High-Performance Concrete (UHPC). The major categories include Materials, Methods, Machinery, Measurement, Environment, and People, each representing a critical dimension in UHPC production and application.

1. Materials such as binders, fibers, aggregates, and admixtures directly impact the strength, durability, and workability of UHPC. Proper selection and proportioning are vital to achieving target performance.
2. Methods encompass mixing, casting, curing, and mix design procedures, which govern the homogeneity and mechanical properties of the final product.
3. Machinery focuses on equipment efficiency, including mixer functionality, testing apparatus, and control sensors that ensure consistency and accuracy in production.
4. Measurement includes quality control practices, dimensional checks, and monitoring equipment to maintain precision throughout production and testing.
5. Environment factors such as temperature, humidity, and exposure conditions significantly affect curing behavior and long-term durability.
6. People represent the human element skills, training, communication, and supervision which play a decisive role in maintaining procedural accuracy and minimizing variability.

Overall, the diagram highlights that UHPC quality is a multifactorial outcome, requiring optimization and coordination across materials, processes, equipment, and human expertise.

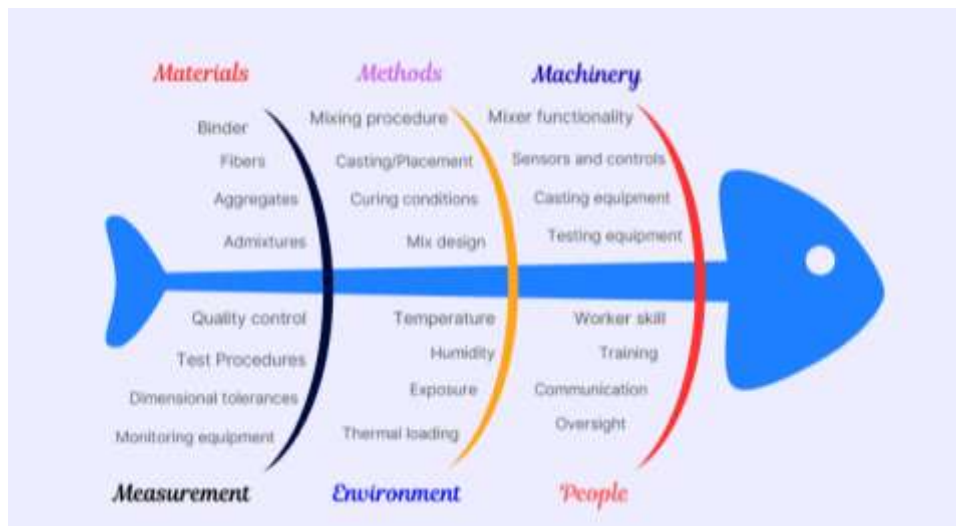


Figure 3: Fishbone Diagram for Ultra-high-performance concrete (UHPC)

4. Supplementary Cementitious Materials in UHPC

The most commonly used supplementary cementitious materials (SCMs) (Refer Table 1) are such as fly ash (FA), ground granulated blast-furnace slag (GGBS), silica fume, metakaolin, limestone powder, steel slag powder and rice husk ash.

Table 1: Supplementary Cementitious Materials in UHPC

SCM Type	Properties	Applications	Advantages	Limitations	Challenges
Fly Ash	Fine spherical particles; available in Type F (pozzolanic) and Type C (cementitious + pozzolanic); improves packing density and	UHPC structural members, bridge decks, precast panels	Reduces water demand, improves workability, enhances long-term strength and durability	Slow early strength development; variability in composition	Ensuring consistent quality and supply; compatibility with superplasticizers

	workability				
Ground Granulated Blast-Furnace Slag (GGBS)	Latent hydraulic SCM with high CaO and SiO ₂ ; replaces 30–60% cement	Durable UHPC infrastructure, marine/bridge construction	Improves sulfate resistance, lowers heat of hydration, enhances durability	May reduce early-age strength; requires activation	Controlled curing needed for reactivity activation; cost of fine grinding
Silica Fume	Extremely fine amorphous SiO ₂ (0.1 μm); highly reactive	Fiber-reinforced UHPC, thin precast elements	Enhances compressive and tensile strength, reduces permeability, refines pore structure	Reduces workability due to high surface area; requires high-range admixtures	Uniform dispersion; mitigating autogenous shrinkage
Rice Husk Ash (RHA)	Agricultural by-product; high amorphous silica (70–80% SiO ₂)	Sustainable UHPC, rural infrastructure projects	Substitute's silica fume; improves impermeability and durability; reduces autogenous shrinkage	High water absorption; reduced workability	Requires controlled combustion for amorphous structure; consistency control
Metakaolin	Calcined clay (Al ₂ O ₃ ·2SiO ₂); highly pozzolanic	Eco-friendly UHPC, sustainable architectural concrete	Improves early strength, reduces porosity, enhances durability and color uniformity	Costly compared to fly ash or slag; increases water demand	Maintaining uniform fineness; limited large-scale supply
Steel Slag Powder	By-product of steel industry; rich in CaO and Fe ₂ O ₃	Structural UHPC, eco-efficient concrete	Reduces CO ₂ footprint, improves modulus and microstructure	Potential volume instability due to free lime; variable composition	Pre-treatment required to stabilize slag; variability in supply
Limestone Powder	Finely ground CaCO ₃ ; acts as filler and accelerant	UHPC pavements, precast blocks, lightweight structures	Improves packing density, accelerates hydration, reduces shrinkage	Limited chemical reactivity; possible reduction in later strength	Optimization of replacement level to balance strength and durability

UHPC exhibits compressive strengths above 150 MPa and superior durability, largely due to SCM incorporation that densifies its microstructure and enhances sustainability. Each SCM contributes distinct benefits silica fume and GGBS for durability, fly ash and metakaolin for workability and strength, and rice husk ash and limestone powder for eco-efficiency. Challenges primarily relate to mix optimization, material variability, and cost-performance balance essential for UHPC scalability in construction applications.

5. Conclusions

Based on the reviewed literature, several key insights can be drawn regarding the challenges and opportunities in ultra-high-performance concrete within the construction sector:

1. UHPC is established as a high-performance and durable material with significant potential in modern infrastructure.
2. Its widespread adoption is limited by high cement content and associated production costs.

3. Incorporating industrial wastes such as fly ash, GGBS, silica fume, rice husk ash, glass powder, and metakaolin improves sustainability and reduces costs.
4. These waste-based SCMs also enhance microstructural refinement and durability properties of UHPC.
5. Challenges remain in terms of standardized mix designs, workability adjustments, and large-scale implementation.
6. Research confirms UHPC-SCM mixes can achieve compressive strengths exceeding 150 MPa with superior durability.
7. Technological advances such as 3D printing, AI-based mix design, and sustainable curing methods will further support adoption.
8. UHPC incorporating industrial waste offers strong potential to drive sustainable, high-performance infrastructure development globally.

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