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Ultra-High-Performance Concrete (UHPC) in Bridge Rehabilitation: A Critical Review of Global Practices, Performance, and Life-Cycle Economics

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Abstract

The deteriorating state of global infrastructure presents one of the most significant challenges in civil engineering today, manifesting as ageing bridges in developed economies and an urgent need for new, resilient systems in advanced developing economies like South Africa. Traditional repair methods often provide only short-term solutions. This paper provides a critical review of Ultra-High-Performance Concrete (UHPC) as a transformative material for both the rehabilitation and construction of critical infrastructure. We move beyond a simple summary of material properties to offer a comprehensive, analytical synthesis of UHPC's performance, drawing on international case studies from pioneering nations in Europe, North America, and Asia, while also analyzing its immense potential for nations facing a dual infrastructure challenge. By interrogating the global body of literature, we critically evaluate its superior mechanical properties and exceptional durability. A central focus is the Life-Cycle Cost Analysis (LCCA), which demonstrates that while UHPC has a higher initial cost, its extended service life and minimal maintenance requirements often result in a significantly lower total cost of ownership. The paper identifies key challenges to global adoption, including material costs, the need for specialized expertise, and the harmonization of international design codes, with a particular focus on the barriers to implementation in resource-constrained environments. We conclude by outlining a strategic roadmap for future research to accelerate the adoption of this resilient and economically sustainable solution worldwide.

Keywords: Ultra-High-Performance Concrete (Uhpc); Bridge Rehabilitation; Global Infrastructure; Life-Cycle Cost Analysis (Lcca); Durability; Infrastructure Resilience; Advanced Cementitious Composites; International Design Codes

1. Introduction

A substantial portion of the world's critical bridge inventory, particularly in the developed economies of North America, Europe, and Japan, was constructed in the post-World War II era and is now approaching or has exceeded its original design life. These aging structures are deteriorating under the compounding pressures of increased traffic loads and aggressive environmental conditions. Simultaneously, advanced developing economies like South Africa face a dual imperative: maintaining their own stock of aging infrastructure while also building new, resilient networks to support economic growth and address inequality. The resulting infrastructure deficit, estimated in the trillions of dollars globally, is not merely an economic issue; it is a direct threat to public safety and global supply chain stability.

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Figure 1 Conceptual Framework: The Strategic Case for UHPC in Global Bridge Rehabilitation

However, it is crucial to acknowledge that this conversation about advanced rehabilitation is, for many, a distant one. For a large number of developing nations, including populous countries like Nigeria, the primary challenge is not the preservation of a vast aging inventory, but the construction of fundamental, standardized infrastructure in the first place. With very few high-standard bridges, most of which are concentrated in commercial centers like Lagos, the immediate priority remains the widespread application of reliable, conventional methods. This paper, therefore, operates on two levels: it analyzes the state-of-the-art in advanced economies while simultaneously considering the immense long-term potential and the formidable barriers to adopting such technologies in regions where resilient infrastructure is arguably needed most.

This critical challenge has spurred intense international research into advanced materials that can offer not just a repair, but a long-term, resilient solution. Among the most promising of these is Ultra-High-Performance Concrete (UHPC). Pioneered in Europe in the 1990s, UHPC is an advanced cementitious composite material with mechanical and durability properties that far exceed those of conventional concrete (Schmidt and Fehling, 2005).

While the material science of UHPC is well-established, its application in both new construction and rehabilitation is an area of growing but still fragmented global research (El-Tawil et al., 2019; Semendary and Khodabakhshian, 2020). This paper aims to fill a critical gap by providing a comprehensive review and synthesis of the use of UHPC from an international perspective. We move beyond a simple recitation of material properties to critically analyze its performance in real-world applications and, most importantly, to evaluate its long-term economic viability.

This paper will demonstrate that a narrow focus on initial cost is a profound strategic miscalculation. By synthesizing data from laboratory studies, international field applications, and economic models, we will make the case that the exceptional durability of UHPC leads to a drastically extended service life and minimal maintenance needs, resulting in a lower and more predictable life-cycle cost.

1.1. Research Questions

This review is guided by the following core research questions

- What are the fundamental material properties of UHPC that make it particularly suitable for bridge rehabilitation, and how do they compare to traditional repair materials?
- What does the existing evidence from international case studies (from Europe, North America, Asia, and South Africa) reveal about the long-term durability and application of UHPC?
- How does a Life-Cycle Cost Analysis (LCCA) of UHPC strategies compare to conventional methods in different economic and environmental contexts?
- What are the primary challenges, particularly regarding international design standards and local material development, hindering the broader global adoption of UHPC?

1.2. Review Methodology

To ensure a comprehensive and rigorous analysis, this critical review employed a structured literature search and synthesis methodology. The process involved three main stages: literature identification, screening and selection, and thematic synthesis.

1.2.1. Literature Identification

A systematic search was conducted across major academic and engineering databases, including Scopus, Web of Science, the ASCE Library, and Google Scholar. The search utilized a combination of keywords such as "Ultra-High-Performance Concrete," "UHPC," "bridge rehabilitation," "UHPC connections," "life-cycle cost analysis," "UHPC durability," and "advanced cementitious composites." The search was supplemented by a review of technical reports and design guidelines from authoritative national and international bodies, including the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the International Federation for Structural Concrete (fib).

1.2.2. Screening and Selection

Sources were screened based on a set of predefined inclusion and exclusion criteria. To be included, sources had to be peer-reviewed journal articles, major conference proceedings, or technical reports from recognized engineering organizations; focus on the structural or economic aspects of UHPC in bridge applications; and be published in English. The publication date was limited to 2022 and earlier to align with the scope of this review. Excluded were sources that were purely commercial, lacked a clear methodological or empirical basis, or focused on non-structural applications of UHPC.

1.2.3. Thematic Synthesis

The selected literature was analyzed and synthesized using a thematic approach. Rather than summarizing sources chronologically or by author, the information was categorized and organized around the core themes of the research questions: material properties, performance in specific applications, economic viability via LCCA, and challenges to adoption. This thematic structure allows for a more critical and direct comparison of findings across different studies and geographical contexts, forming the basis of the analytical framework presented in this paper.

2. Material Properties of UHPC: A New Paradigm in Concrete Technology

To understand the value of UHPC in rehabilitation, one must first appreciate how it fundamentally differs from conventional concrete. Its superior performance is not an incremental improvement; it is the result of a complete rethinking of concrete mix design at the microstructural level. This paradigm shift is driven by three key compositional principles that work in synergy to create a material that is both exceptionally strong and remarkably durable (Azmee and Shafiq, 2018; Russell and Graybeal, 2013).

First is the Optimized Granular Mixture. Unlike conventional concrete, UHPC mix designs employ a precise, mathematically optimized distribution of fine particles, including fine sand, silica fume, and powdered quartz, to create a densely packed matrix with minimal voids (Haber et al., 2018). This principle of particle packing density is crucial for eliminating the interconnected pore network that plagues conventional concrete, which is the primary pathway for the ingress of water and corrosive agents like chlorides.

Second is the Extremely Low Water-to-Cementitious Materials Ratio (w/cm). With a w/cm ratio typically below 0.20, there is just enough water for the hydration of the cementitious materials. This eliminates the excess water that creates capillary pores during curing, resulting in a dense, crystalline microstructure that is almost impermeable (Russell and Graybeal, 2013). The specific rheology and hydration properties of these mixes have been the subject of extensive research (Meng and Khayat, 2018).

Third is the Steel Microfiber Reinforcement. The addition of a high volume (typically 2-3% by volume) of short, high-strength steel fibers is what gives UHPC its signature mechanical properties (Yoo and Banthia, 2017). These fibers are a critical component in developing high-strength composites (Tayeh et al., 2013). These randomly distributed fibers bridge micro-cracks as they form, providing significant post-cracking tensile strength and ductility. This "crack bridging" mechanism prevents the brittle, sudden failure mode characteristic of unreinforced concrete and allows the material to absorb significant energy before failure, a property crucial for resisting dynamic and fatigue loading from traffic and seismic events (Abbas et al, 2016; Kim and Yoo, 2021).

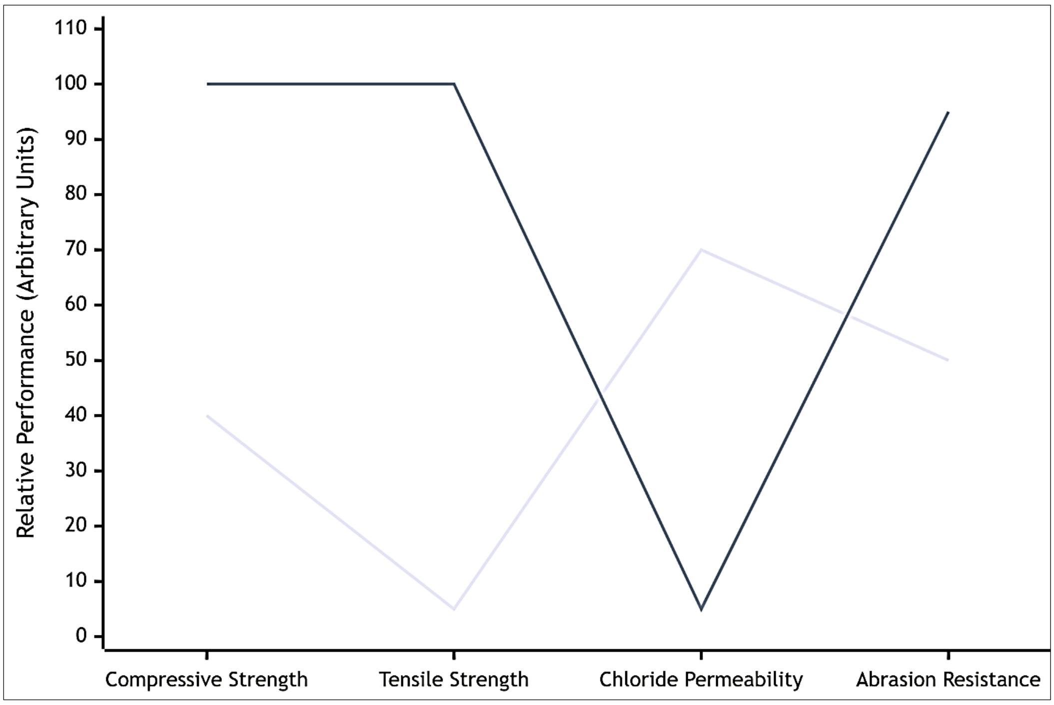

Figure 2 Comparative Mechanical and Durability Properties of Conventional Concrete and UHPC

These compositional principles lead to a suite of emergent properties, detailed in Table 1, that are ideally suited for the harsh and demanding environment of bridge rehabilitation.

Table 1 Comparative Properties of Conventional Concrete vs. UHPC

Property	Conventional Concrete	Ultra-High-Performance Concrete (UHPC)	Implication for Rehabilitation
Compressive Strength	28 - 41 MPa (4-6 ksi)	150 - 200 MPa (22-29 ksi)	Thinner sections can carry higher loads.
Tensile Strength	Negligible	5 - 10 MPa (0.7-1.5 ksi)	High crack resistance and ductility.

Chloride Permeability	Moderate to High	Very Low to Negligible	Exceptional protection against corrosion.
Abrasion Resistance	Moderate	Very High	Superior resistance to wear from traffic.

3. Performance of UHPC in Bridge Rehabilitation: Global Applications

The theoretical benefits of UHPC have been validated in key areas of bridge rehabilitation worldwide, with different regions pioneering different applications based on their specific needs and challenges.

3.1. Bridge Deck Overlays and Preservation (North American Focus)

In North America, the primary driver for UHPC adoption has been the urgent need to combat the rapid deterioration of bridge decks caused by freeze-thaw cycles and the heavy use of de-icing salts. A thin (25-40 mm) UHPC overlay provides a nearly impermeable barrier that protects the underlying conventional concrete from chloride ingress (Graybeal, 2011). This application has been a subject of extensive research and successful field trials (Khedr and Abou-Zeid, 2016). Case studies from states like Iowa and New York have shown that after more than a decade of service, UHPC overlays exhibit minimal wear and no signs of delamination, suggesting a service life that could extend for 50 years or more (Hoisington and Tazarv, 2019). The success of these overlays depends critically on the bond behavior at the UHPC-concrete interface, which has been shown to be exceptionally robust (Qi, Wang, and Ma, 2018). This approach is a cornerstone of the bridge preservation strategy advocated by the Federal Highway Administration (FHWA, 2013).

3.2. Field-Cast Connections for Modular Construction (Global Application)

A globally adopted application is the use of UHPC for field-cast connections between precast modular bridge elements, a key component of Accelerated Bridge Construction (ABC) (Shafieifar et al, 2017). These precast systems, which can include deck panels, have been a focus of innovation for decades (Blais and Couture, 2000).

In Europe, early projects in France and Switzerland demonstrated that a small, simple UHPC joint could develop the full strength of the connected elements, eliminating complex reinforcement detailing (Schmidt and Fehling, 2005). The international interest in this application was evident in early symposia on the topic (Kaptijn, 2012). This follows the principles laid out in early French guidelines (AFGC, 2013).

In Japan, this application is critical for seismic resilience. UHPC connections have been shown to provide superior ductility and energy dissipation capacity during an earthquake (Tanaka et al., 2015). This is particularly important for precast bent systems in high seismic regions (Aaleti and Sritharan, 2019) and for bridge columns with pocket connections (Benjamin and Tazarv, 2020).

In the United States, the Federal Highway Administration (FHWA) has championed UHPC connections as a standard solution for ABC projects, with extensive research into their casting procedures and curing behavior (Alkaysi and El-Tawil, 2017; Graybeal, 2014). State-level implementation reports, such as those from Kentucky, have further documented their successful use in superstructure connections (Brunner and Rister, 2019).

3.3. Strengthening and Widening of Existing Structures (European and Asian Focus)

Europe and Japan have been pioneers in using UHPC for strengthening and retrofitting. Because of its exceptional strength-to-weight ratio, a thin layer of UHPC can be added to an existing girder or column to significantly increase its load-carrying capacity with minimal added dead weight (Randl, Steiner, and Ofner, 2014). The famous Millau Viaduct in France, while a new construction, showcased the potential of UHPC to create slender yet incredibly strong structural elements, a principle now applied to rehabilitation (Harris and Roberts-Wollmann, 2015).

3.4. UHPC in Developing Economies: Contrasting Realities in South Africa and Nigeria

While the applications above focus on developed nations, the properties of UHPC offer a compelling but complex case for the distinct challenges faced by developing economies. The strategic calculus for adoption varies dramatically based on a nation's existing infrastructure base and research capacity, a reality vividly illustrated by contrasting South Africa and Nigeria.

In South Africa, the challenge is twofold, mirroring that of many developed nations. The country must maintain a significant inventory of aging, mid-20th-century infrastructure while also expanding its networks to support economic development. As a result, its engineering bodies, such as the Council for Scientific and Industrial Research (CSIR) and the South African National Roads Agency (SANRAL), have actively researched advanced materials for long-term durability. For South Africa, UHPC is a present-day strategic tool for rehabilitating critical economic corridors and building new, resilient structures, with the primary barriers being cost optimization and local production.

In contrast, for many other developing nations like Nigeria, the context is fundamentally different. The primary challenge is a profound infrastructure deficit, not an aging inventory. With a limited number of high-standard bridges, most of which are concentrated in a few commercial hubs like Lagos, the immediate national priority is the large-scale construction of basic, reliable infrastructure using conventional methods. In this environment, UHPC is not yet a tool for widespread application but represents a long-term aspirational goal. Its immediate relevance is in highly specialized, critical applications where its rapid construction time and extreme durability could solve a specific, acute problem that conventional methods cannot. The discussion of UHPC in this context is therefore primarily about future potential and the immense barriers that must be overcome.

4. The life-cycle cost analysis (LCCA) imperative

The most significant and frequently cited barrier to the widespread global adoption of Ultra-High-Performance Concrete is its high initial material cost. On a simple per-volume basis, UHPC can be five to ten times more expensive than conventional concrete, a figure that creates a formidable psychological and fiscal barrier for transportation agencies and decision-makers (Russell and Graybeal, 2013). This "sticker shock" has led many to classify UHPC as a niche, prohibitively expensive material, suitable only for specialized or landmark projects with unusually large budgets. This perspective, however, is based on a fundamentally flawed and short-sighted economic analysis that considers only upfront costs. A proper and intellectually honest economic evaluation must transcend this narrow view and employ a comprehensive Life-Cycle Cost Analysis (LCCA). LCCA is a well-established engineering economics methodology that considers all significant costs over the entire service life of an asset, providing a far more accurate picture of its true economic value (Liu and Farzad, 2021).

When viewed through the rigorous lens of an LCCA, the economic case for UHPC becomes not just viable, but compelling. A comprehensive LCCA framework incorporates three distinct categories of cost. The first is the initial construction cost, which includes materials, labor, and equipment; this is where UHPC is at a disadvantage. The second category is future maintenance and rehabilitation costs, which includes all anticipated repairs, overlays, and replacements over the structure's design life. It is in this category that UHPC's superior durability, stemming from its extremely low permeability and resistance to chloride ingress, creates immense long-term savings (Hosseini and Bakhshi, 2022). The third and often most underestimated category is indirect user costs associated with traffic disruption during construction and maintenance activities. These costs, which are borne by the public and the broader economy, include the value of lost time due to traffic delays, increased vehicle operating costs from fuel consumption, higher accident rates in work zones, and the disruption to commercial logistics and supply chains.

The contrast between UHPC and conventional materials becomes stark when these long-term costs are properly quantified. While the initial cost of a UHPC overlay is significantly higher than a conventional repair, its exceptional durability means it may not require any significant maintenance for 50 years or more, as suggested by long-term field performance studies (Hoisington and Tazarv, 2019). In contrast, a conventional concrete or asphalt overlay might need to be completely replaced every 15 to 20 years, or even more frequently in harsh climates. Each of these future repair cycles incurs not only direct construction costs but also triggers massive indirect user costs. In congested urban areas across Europe, North America, and Asia, the economic cost of shutting down lanes on a critical bridge for several weeks can easily run into the millions of dollars per day, often dwarfing the direct cost of the repair itself.

Economic models and LCCA studies from multiple countries have consistently shown that when these essential long-term maintenance and user costs are factored in, the total life-cycle cost of a UHPC solution is often significantly lower than that of its conventional counterparts, as confirmed by recent comprehensive reviews on the topic (Liu and Farzad, 2021; Hosseini and Bakhshi, 2022). For a nation like South Africa, with vast infrastructure networks and significantly constrained long-term public maintenance budgets, this LCCA imperative is particularly acute. Investing more upfront to build or rehabilitate a bridge that will not require major repairs for half a century is a far more sustainable and fiscally responsible strategy than building a cheaper alternative that will demand constant and often unfunded maintenance, inevitably falling into a state of disrepair.

The strategic imperative for transportation agencies worldwide is therefore clear. There must be a fundamental shift in procurement and decision-making frameworks, moving away from a deeply entrenched "lowest initial bid" mentality that prioritizes short-term capital savings and toward a more sophisticated, evidence-based "best long-term value" approach. This requires not only educating engineers and asset managers but also creating the political and institutional will to invest in resilience and durability for the benefit of future generations. Adopting rigorous LCCA is the essential first step in making the powerful, data-driven case for UHPC.

Challenges and Future Research Directions

Despite its clear technical and economic advantages, the global transition of UHPC from a specialized material to a standard tool for bridge rehabilitation is hindered by several significant, interconnected challenges. A critical analysis of the literature reveals that these barriers are not monolithic; they manifest differently across developed, advanced developing, and developing economies, requiring context-specific research priorities and strategic interventions. As the comparative framework in Table 2 illustrates, the path to widespread adoption is not a single highway but a series of parallel journeys. Addressing these barriers is essential for unlocking the full potential of UHPC worldwide.

Table 2 Key Challenges and Strategic Research Directions for UHPC in Rehabilitation

Challenge	Developed Economies (e.g., USA)	Advanced Developing (e.g., South Africa)	Developing Economies (e.g., Nigeria)
Cost	Barrier: High Upfront Cost Priority: Standardize LCCA	Barrier: Imported Materials Priority: Develop Local Mixes	Barrier: Prohibitive First Cost Priority: Research Ultra-Low-Cost Mixes
Expertise	Barrier: Scaling Specialized Teams Priority: Advanced Certification	Barrier: Limited Local Experts Priority: Local Capacity Building	Barrier: Lack of Foundational Skills Priority: Knowledge Transfer
Standards	Barrier: Complex Code Integration Priority: Finalize National Codes	Barrier: Code Adaptation Priority: Create National Annexes	Barrier: No Existing Codes Priority: Adopt Simplified Guidelines

4.1. The Cost Barrier: From Justification to Feasibility

The first and most frequently cited barrier is the high initial cost. In developed economies like the United States, where public funds are available but highly scrutinized, the primary challenge is institutional. Public agencies often operate under strict annual budgets and "lowest initial bid" procurement models that prioritize minimizing upfront capital expenditure (Russell and Graybeal, 2013). The key research priority, therefore, is the development and standardization of widely accepted LCCA models that can formally and legally justify the long-term economic benefits of a higher initial investment, a field of study that has gained significant traction (Liu and Farzad, 2021; Hosseini and Bakhshi, 2022).

In contrast, for an advanced developing economy like South Africa, the challenge shifts from justification to supply chain. The primary barrier is the high cost driven by a reliance on expensive, imported proprietary materials for UHPC mixes. A critical research imperative is therefore the development of cost-effective UHPC mix designs that can utilize locally sourced pozzolans, aggregates, and industrial byproducts (such as those from its extensive mining sector), creating a domestic supply chain and reducing material costs.

The barrier becomes even more fundamental in developing nations like Nigeria. Here, the challenge is the prohibitive first cost of UHPC relative to the urgent need for widespread basic infrastructure. For these nations, UHPC remains a long-term aspirational goal. The most critical long-term research direction is the pursuit of ultra-low-cost formulations that could one day compete on a first-cost basis with conventional materials.

4.2. The Expertise Barrier: From Scaling to Foundational Training

The second challenge relates to quality control and field expertise. UHPC is a highly specialized material that is sensitive to mixing, placement, and curing procedures (Alkaysi and El-Tawil, 2017). In developed economies, a base of specialized contractors exists, but the barrier is scaling this expertise to meet broader demand. The priority is creating advanced training and certification programs to ensure that the exceptional properties of UHPC are reliably achieved on a large scale.

In South Africa, the challenge is a limited pool of local experts familiar with the nuances of UHPC technology. The priority is therefore a dedicated focus on local capacity building and technology transfer through partnerships between universities, research institutions like the CSIR, and international experts to empower a new generation of local engineers and contractors.

For a nation like Nigeria, the barrier is a more foundational lack of the specialized equipment and skills required for advanced material science. The immediate priority is not advanced certification, but fundamental knowledge transfer, likely through international development partnerships and pilot projects focused on basic, high-impact applications.

4.3. The Standards Barrier: From Integration to Adoption

A third significant challenge is the lack of fully integrated and harmonized design codes, which creates uncertainty for engineers worldwide. In the United States and Europe, the barrier is the complex process of integrating UHPC into mature and legally entrenched national codes like AASHTO and Eurocode (AASHTO, 2018). The priority is accelerating this detailed codification process to provide clear guidance for designers (Chen and Graybeal, 2012).

In South Africa, the challenge is one of adaptation. The country has a robust set of national standards, and the priority is to create national annexes or specific guidelines that adapt the principles of international codes to local materials and conditions.

In Nigeria and many other developing nations, there are often no existing national codes for such advanced materials. The most practical and immediate priority is to adopt simplified, internationally recognized guidelines, perhaps from an organization like fib (2019) or based on the French recommendations (AFGC, 2013), to provide a safe and reliable starting point for initial projects.

4.4. The Long-Term Performance Barrier: From Promise to Proof

Finally, while early results from structures in service for over a decade are extremely promising, most UHPC applications are still relatively young in the context of a 75–100-year design life (Hoisington and Tazarv, 2019). There remains a critical need for more long-term performance data from structures that have been in service for multiple decades to definitively validate durability models. The establishment of well-funded, international long-term structural health monitoring (SHM) programs for existing UHPC rehabilitations is essential to build the comprehensive, multi-decade database needed (D'Alessandro et al, 2019). This data is the final piece of evidence required to refine our long-term durability and life-cycle cost models and move from confident projections to proven facts.

Scope and Limitations of the Study

It is important to acknowledge the precise boundaries of this analysis to provide a clear understanding of its contributions and constraints. The scope of this paper is to provide a critical literature review on the use of Ultra-High-Performance Concrete (UHPC) in bridge rehabilitation and construction applications. Its focus is specifically on performance, durability, and the overarching economic argument as framed by Life-Cycle Cost Analysis (LCCA). The methodology involves a synthesis and critical evaluation of existing peer-reviewed articles, international conference proceedings, and technical reports from transportation agencies and global engineering bodies. This paper does not present new experimental data; rather, its primary contribution lies in the thematic organization and analytical interrogation of the existing body of knowledge to build a cohesive, global narrative on the state of UHPC adoption.

This study has several inherent limitations that must be recognized. First, as a review, its findings and conclusions are contingent upon the quality, accuracy, and availability of the published research. While we have endeavored to be comprehensive by including a wide range of international sources, the rapidly evolving nature of the field means that new research on UHPC mix designs and field applications is constantly emerging.

Second, the LCCA data presented and discussed is based on economic models and case studies that are highly sensitive to a wide range of local and time-dependent variables. Factors such as regional labor costs, the price and availability of raw materials, traffic volumes, and the discount rates used in economic calculations can significantly alter the outcome of an LCCA. Therefore, the specific Return on Investment (ROI) in any given project will vary, and the figures presented in this paper should be understood as illustrative models designed to demonstrate a principle, not as a guarantee of a specific financial return.

Moreover, this review highlights a general and critical limitation of the field itself: the scarcity of very long-term (e.g., 50+ year) field performance data for UHPC applications. While accelerated laboratory testing and results from the first few decades of service are extremely promising, the material is still relatively new in the grand timeline of infrastructure. The definitive validation of its long-term durability and the ultimate refinement of our life-cycle cost models will require the continued monitoring of existing structures and a sustained, multi-decade international effort to build a comprehensive database of in-service performance.

5. Conclusion

The preservation of our aging global infrastructure, and the concurrent need to build new, resilient networks in developing economies, demands a fundamental paradigm shift. We must move away from the short-term, reactive repair strategies of the past and toward a new model of long-term, sustainable infrastructure management. This critical review has demonstrated that Ultra-High-Performance Concrete is not merely an incremental improvement over conventional materials; it is a transformative technology with the potential to fundamentally change how we approach bridge engineering worldwide.

This paper has made the case that the primary barrier to its adoption, its high initial cost, is based on an incomplete and flawed economic analysis. A comprehensive Life-Cycle Cost Analysis reveals that UHPC is often the most economically prudent choice, a finding that is particularly critical for nations with constrained long-term maintenance budgets. Its superior durability provides an unparalleled defense against environmental and mechanical stressors, and its use in applications like field-cast connections is a key enabler of safer, more efficient construction methods globally.

However, this review has also demonstrated that the path to widespread adoption is not monolithic but is, in fact, a series of parallel journeys that are highly dependent on local economic and institutional contexts. While developed economies must focus on standardizing LCCA models to justify upfront costs, advanced developing nations like South Africa must prioritize the development of local material supply chains. For many other developing nations like Nigeria, the challenge is more fundamental, requiring long-term research into ultra-low-cost formulations. The path forward, therefore, is not a single roadmap but a multi-faceted global strategy. It requires targeted research, context-specific training, and the development of adaptable international standards that can support widespread adoption. By embracing this nuanced approach, we can leverage the power of UHPC to build a more durable, more resilient, and more economically sustainable transportation infrastructure for the 21st century.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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