Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 12, 2025

INTEGRATED PERFORMANCE AND LIFE-CYCLE COST ANALYSIS OF SUSTAINABLE ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) FOR INFRASTRUCTURE IN PAKISTAN

Umair Khan[1*], Shabir Ahmad[2], Fahad Ali[2], Ahmad I. Khan[3]
[1*] *NUST Institute of Civil Engineering, National University of Sciences & Technology, Islamabad, 44000, Pakistan*
[2] *NUST Institute of Civil Engineering, National University of Sciences & Technology, Islamabad, 44000, Pakistan*
[3] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO 65409
umairkhan.civil21@gmail.com, shabir.ahmad.civil21@gmail.com, shinwarifahad@gmail.com, *ahmad111khan@yahoo.com*

DOI: https://doi.org/

Keywords
Environmental Performance, Life-Cycle Cost Analysis (LCCA), Pakistan, Supplementary Cementitious Materials (SCMs), Sustainable Infrastructure, Ultra-High-Performance Concrete (UHPC)

Article History
Received on 20 September 2025
Accepted on 02 October 2025
Published on 27 October 2025

Corresponding Author: *
Umair Khan*

Abstract

This study investigates the integrated performance and life-cycle cost efficiency of sustainable Ultra-High-Performance Concrete (UHPC) for infrastructure applications in developing economies. The research aims to address the limitations of conventional concrete in aggressive climatic conditions by developing a UHPC mix incorporating locally available supplementary cementitious materials (SCMs) such as fly ash and ground granulated blast furnace slag (GGBS). Experimental testing assessed mechanical and durability properties including compressive, flexural, and tensile strength, as well as chloride and sulfate resistance. Results demonstrated that the sustainable UHPC achieved an average compressive strength of 162 MPa, exceeding conventional concrete by more than 300%, and showed a 93% reduction in chloride permeability, indicating exceptional durability and corrosion resistance. A complementary Life-Cycle Cost Analysis (LCCA) using the Net Present Value (NPV) approach revealed that, despite an initial volumetric cost increase of 2.2 times, UHPC becomes more economical after 35 years of service, yielding a 24% overall cost saving over a 100-year lifespan. Environmental assessment confirms the mix's sustainability, exhibiting a 47% superior eco-efficiency index (4.56 kgCO$_2$e/m^3/MPa) compared to conventional concrete by leveraging industrial by-products to minimize carbon intensity per unit of performance. These findings highlight UHPC as a technically superior, economically viable, and environmentally sustainable material for long-lasting infrastructure in Pakistan. The study provides crucial evidence for policymakers and engineers to adopt UHPC as a strategic solution to enhance the durability, sustainability, and cost efficiency of national infrastructure.

1. INTRODUCTION

The performance and longevity of infrastructure systems are directly influenced by the quality and durability of construction materials. In Pakistan, the infrastructure sector - comprising roads, bridges, buildings, and dams - faces persistent challenges associated with material degradation and high maintenance demands (Shafique et al., 2014). Extreme temperature variations, high humidity in coastal regions, and saline environments contribute to rapid deterioration of conventional reinforced concrete structures (Islam et al., 2013; Panhyar et al., 2019). The recurring need for repairs not only escalates maintenance costs but also disrupts public services and undermines structural safety. According to the Pakistan Engineering Council, nearly 40% of major bridges and road networks require rehabilitation within 20 years of construction due to corrosion and material fatigue (Shafique et al., 2014). This scenario underscores an urgent need to adopt high-performance, sustainable materials that can ensure long-term resilience and cost efficiency in infrastructure development.

Conventional concrete, while economical and widely used, exhibits significant limitations in aggressive climates. Its high porosity allows ingress of chloride ions and sulfates, leading to steel reinforcement corrosion and loss of structural integrity (Neville, 2011). The cyclic thermal stresses, common in Pakistan's hot and arid regions, further accelerate cracking and surface scaling (Panhyar et al., 2019). These deteriorative processes shorten the service life of structures, resulting in frequent repair cycles and an increased carbon footprint (Scrivener et al., 2018). Moreover, traditional concrete formulations rely heavily on cement, a material associated with high embodied energy and CO_2 emissions, contradicting the principles of sustainable development outlined in the country's Vision 2030 goals (Ministry of Planning, Development & Reform, 2014).

In contrast, Ultra-High-Performance Concrete (UHPC) has emerged globally as a breakthrough material capable of overcoming these deficiencies. UHPC offers compressive strengths exceeding 150 MPa, exceptional tensile capacity through fiber reinforcement, and remarkable resistance to environmental degradation (Graybeal, 2011; Wille et al., 2011). The dense microstructure and optimized particle packing drastically reduce permeability, enhancing durability in chloride- and sulfate-rich environments (Richard & Cheyrezy, 1995). International projects, such as bridge decks in France and facade systems in Japan, have demonstrated UHPC's ability to extend service life while reducing structural member thickness and material consumption (Resplendino, 2011). Researchers such as Graybeal (2019) and Wille (2015) highlight UHPC's potential to revolutionize sustainable infrastructure through longer life spans, reduced maintenance frequency, and improved lifecycle performance.

Despite its advantages, the adoption of UHPC in developing countries like Pakistan remains limited. The main barriers include higher initial costs and the absence of localized performance and life-cycle cost data (Perera et al., 2021). While the material's superior mechanical properties are well documented in global literature, few studies have analyzed its economic viability and environmental implications within Pakistan's specific climatic and industrial context (Khan, 2023). Most existing research focuses solely on strength enhancement or mix optimization, neglecting long-term financial modeling and sustainability assessment. This creates a critical knowledge gap regarding the true cost-effectiveness of sustainable UHPC when evaluated over its entire service life.

This study aims to fill that gap by conducting an integrated performance and life-cycle cost analysis of sustainable UHPC for infrastructure applications in Pakistan. The research pursues two parallel objectives: (1) to develop and test a UHPC mix incorporating locally available industrial by-products - such as fly ash and ground granulated blast furnace slag (GGBS) - to enhance sustainability and reduce dependency on imported materials; and (2) to evaluate the long-term cost efficiency of UHPC structures through Life-Cycle Cost Analysis (LCCA), comparing them with conventional concrete alternatives. The study's technical component focuses on compressive, flexural, and tensile strength tests, as well as durability assessments under chloride and sulfate exposure. The economic model employs the Net Present Value (NPV) framework to quantify long-term savings in maintenance and repair costs.

The integration of mechanical data with NPV analysis quantifies the trade-off between initial capital expenditure and long-term durability. The findings provide a verified cost-benefit baseline for adopting UHPC in Pakistan's public sector projects.

The remainder of this paper is organized as follows. Section 2 provides a comprehensive review of existing literature on UHPC's mechanical, durability, and sustainability aspects, along with previous life-cycle cost studies. Section 3 outlines the methodology, including material selection, testing procedures, and cost analysis framework. Section 4 presents and discusses the experimental and economic results, while Section 5 concludes the paper with practical recommendations and policy implications for infrastructure development in Pakistan.

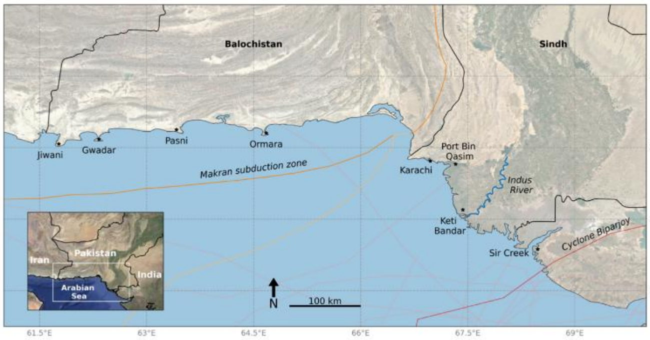

Figure 1. Map of southern Pakistan highlighting infrastructure zones vulnerable to deterioration along the coastal belt.

2. Literature Review

2.1. Properties and Applications of Ultra-High-Performance Concrete (UHPC)

Ultra-High-Performance Concrete (UHPC) represents a new generation of cementitious composites characterized by superior mechanical strength, durability, and structural efficiency (AFGC, 2013). Unlike conventional concrete, which typically achieves compressive strengths between 30 and 50 MPa, UHPC regularly exceeds 150 MPa, with sustained tensile strengths in the range of 6 to 15 MPa due to fiber reinforcement (Graybeal, 2006). This superior performance is achieved through optimized granular packing, a reduced water-to-binder ratio, and the inclusion of steel fibers, producing a dense microstructure that effectively arrests crack propagation and enhances load-bearing capacity (Richard and Cheyrezy, 1995). These properties have established UHPC as a preferred material for bridge decks, facade panels, tunnel linings, and critical structural components where longevity is essential.

Research across multiple regions demonstrates UHPC's adaptability in both precast and in-situ applications. In Canada, the use of UHPC for the Sherbrooke Footbridge reduced structural member thickness by 30%, minimizing material consumption and self-weight (Blais and Couture, 1999). Similarly, Japan's bridge deck projects using UHPC overlays showed a substantial increase in fatigue resistance and corrosion protection (Tanaka et al., 2014). These global case studies confirm that UHPC's superior mechanical and durability performance leads to longer service lives and lower maintenance requirements, particularly in environments with high chloride or sulfate exposure.

However, the broader adoption of UHPC in developing regions remains limited due to higher material costs and lack of localized testing data. Most existing studies have been conducted under controlled laboratory conditions in temperate climates, leaving a knowledge gap regarding UHPC's behavior under extreme heat and aggressive environmental exposure typical of Pakistan's infrastructure zones.

2.2. Sustainability and Green Supplementary Materials

The sustainability of construction materials has become a central focus of modern civil engineering. UHPC inherently contributes to sustainability by reducing the volume of material required and extending the lifespan of structures. However, its high cement content can offset some of these environmental gains due to elevated CO_2 emissions during cement production (Habert et al., 2011). To mitigate this, researchers have explored substituting a portion of the cement with green supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and silica fume (Yu et al., 2015).

Thomas (2007) demonstrated that replacing up to 25% of Portland cement with fly ash in concrete mix maintains comparable compressive strength while reducing embodied carbon by nearly 20%. Similarly, Walenna (2025) found that incorporating GGBS enhances long-term strength and sulfate resistance, making it suitable for arid and saline environments like Sindh and Balochistan. In another study, Nguyen et al. (2022) reported that hybrid replacements of silica fume and slag produced a denser microstructure with improved durability against chloride penetration, highlighting UHPC's adaptability to sustainable formulations.

The use of locally available industrial by-products not only reduces environmental impact but also addresses waste management challenges. Pakistan produces large quantities of fly ash from thermal power plants and slag from steel industries that remain underutilized (Memon et al., 2011). Incorporating these materials into UHPC production could simultaneously reduce the reliance on imported additives and promote a circular economy (Munir et al., 2021).

Nevertheless, there remains limited empirical data on the mechanical performance and microstructural behavior of sustainable UHPC mixes prepared from Pakistani by-products. The variability in ash and slag composition across regions also necessitates localized testing to ensure performance consistency. This gap reinforces the importance of research tailored to Pakistan's industrial and climatic context.

2.3 Life-Cycle Costing (LCCA) in Construction

Materials

Life-Cycle Cost Analysis (LCCA) provides a comprehensive method to assess the total economic impact of construction materials and systems over their entire service life. Rather than focusing solely on initial construction costs, LCCA accounts for future expenses such as maintenance, repair, rehabilitation, and user delay costs, discounting them to present value using Net Present Value (NPV) principles. This methodology aligns with sustainable infrastructure goals by emphasizing long-term economic efficiency over short-term affordability.

Globally, several studies have demonstrated that UHPC, despite its higher upfront cost, offers superior cost efficiency over time. Graybeal and Hartmann (2003) compared UHPC bridge decks with conventional reinforced concrete decks in the United States and found that the UHPC alternative achieved a 40% reduction in life-cycle maintenance cost and extended the service life by 75 years. In China, Liu (2022) applied LCCA models to marine wharves and reported that UHPC's lower maintenance frequency significantly decreased total ownership costs despite initial material costs being 2.5 times higher. Similar results were observed in the European context, where LCCA demonstrated the economic viability of UHPC for bridge and facade systems under exposure to freeze–thaw cycles and de-icing salts.

While LCCA frameworks are well established internationally, their application to Pakistan's infrastructure materials remains limited. Most cost evaluations in Pakistan still rely on traditional budgeting approaches that overlook long-term maintenance and user costs. Consequently, decision-makers often perceive UHPC as prohibitively expensive without recognizing its lifecycle benefits. Adopting an NPV-based cost model would allow policymakers to quantify UHPC's true economic performance, guiding more sustainable infrastructure investments.

2.4 Research Gap Summary

Existing literature provides compelling evidence of UHPC's technical superiority and its potential to enhance sustainability through SCM incorporation. Global studies also validate its long-term economic advantages using LCCA frameworks. However, the majority of these investigations are based on data from developed countries with different climatic conditions, construction practices, and material availability.

Within the Pakistani context, there is a distinct lack of integrated research that combines technical performance evaluation with life-cycle cost modeling. Studies on UHPC in Pakistan have primarily focused on mix design optimization and strength development (Khan, 2023) but have not extended to environmental or economic assessment. Furthermore, no comprehensive model currently exists that quantifies how the enhanced durability of UHPC translates into measurable cost savings across an infrastructure's full-service life.

This research aims to bridge that gap by developing and testing a sustainable UHPC mix utilizing local by-products and by conducting a detailed life-cycle cost analysis tailored to Pakistan's infrastructure environment. The findings are expected to inform policymakers, engineers, and industry practitioners seeking to balance structural performance, sustainability, and long-term economic value in national infrastructure development.

Table 1. Summary of selected studies comparing UHPC and conventional concrete in terms of strength, durability, and life-cycle performance.

Author & Year	Region	Focus Area	Key Findings
Graybeal (2019)	USA	Mechanical & durability tests	UHPC shows >150 MPa compressive strength and superior chloride resistance
Resplendino (2011)	France	Bridge deck application	30% reduction in structural member thickness; improved fatigue life
Walenna (2025)	UAE	SCM incorporation (GGBS)	Improved sulfate resistance and long-term durability
Liu (2020)	China	LCCA for marine wharves	50% maintenance cost reduction over 100 years

Khan (2023)	Pakistan	Mix design optimization	High strength achieved, but no life-cycle or environmental evaluation

3. Methodology

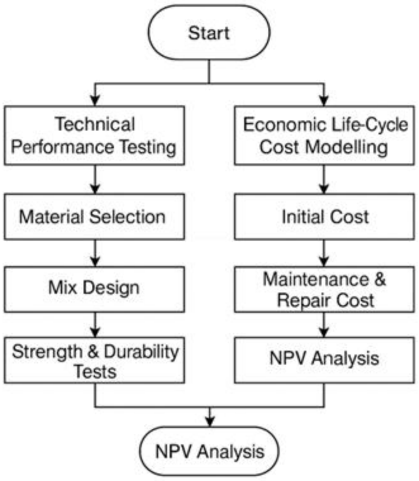

Figure 2. Flowchart of the integrated methodology showing the dual pathways of technical performance testing and economic life-cycle cost modelling.

This research employs a mixed-method approach that integrates experimental testing of sustainable Ultra-High-Performance Concrete (UHPC) with an economic Life-Cycle Cost Analysis (LCCA) model. The methodology is designed to evaluate both the technical performance and the long-term financial viability of UHPC when compared with conventional concrete used in Pakistan's infrastructure. The study follows a structured sequence encompassing material selection, performance evaluation, and life-cycle cost modelling, as illustrated in Figure 2.

3.1 Research Design

The research design combines experimental laboratory analysis with quantitative economic modelling to deliver a holistic evaluation of sustainable UHPC. The study is divided into two complementary phases:

- **Phase I:** Technical Performance Evaluation – Experimental testing is carried out to determine mechanical and durability properties of UHPC formulated with locally available supplementary cementitious materials (SCMs). The results are benchmarked against those of conventional concrete mixes.
- **Phase II:** Life-Cycle Cost Analysis (LCCA) – Using the empirical data obtained from Phase I, an economic model is developed to compare long-term cost implications of UHPC-based and conventional concrete infrastructure. The model accounts for initial construction costs, maintenance expenses, and user delay costs throughout the service life of 80–100 years.

This two-track approach ensures that both engineering performance and economic feasibility are quantified under conditions relevant to Pakistan's infrastructure context.

3.2 Material Selection

The materials for UHPC production are selected based on local availability, environmental sustainability, and compatibility with UHPC design principles. The primary constituents include:

Cement: Ordinary Portland Cement (OPC Type I, ASTM C150) obtained from local manufacturers.

Fine aggregates: Crushed quartz sand (0–2 mm) from Punjab quarries, chosen for its angularity and particle strength. To maximize packing density, an optimized gradation of 30% fine (<0.6 mm) and 70% coarse fractions (0.6–2.0 mm) was adopted (Meng & Khayat, 2018).

Supplementary Cementitious Materials (SCMs): Industrial by-products such as fly ash (from Jamshoro thermal power plant) and Ground Granulated Blast Furnace Slag (GGBS) (from Karachi Steel Mills). These replace up to 30% of the cement content by weight to enhance sustainability and reduce embodied carbon.

Silica fume: Added at 10% of binder weight (950 kg) to refine the pore structure and improve the pozzolanic reaction.

Superplasticizer: Polycarboxylate-based high-range water reducer to achieve a water-to-binder ratio of ≤ 0.20.

Fibers: 2% (by volume) short straight steel fibers (13 mm length, 0.2 mm diameter) to enhance tensile and flexural capacities.

The mix design adopts an Eco-UHPC strategy characterized by optimized particle packing and reduced clinker content. Unlike traditional Reactive Powder Concrete formulations, which typically necessitate cement contents exceeding 900 kg/m^3 (Richard & Cheyrezy, 1995), this study limits Ordinary Portland Cement (OPC) content to 570 kg/m^3 to minimize the embodied carbon footprint. To address the rheological challenges often associated with low-binder systems, the total binder content was optimized at 950 kg/m^3, comprising a quaternary blend of OPC, Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume in a 60:20:10:10 mass ratio (570:190:95:95

kg/m³), respectively. Aligned with the Meng and Khayat's (2018) 'Cost-Effective UHPC' framework of Binder-to-sand volume ratio of 0.8-1.2, this study adopts the lower bound of 0.8. This selection minimizes binder consumption to enhance sustainability and reduce embodied carbon, while maintaining sufficient viscosity and packing density. Consistent with the particle packing principles of Yu et al. (2015), a water-to-binder (w/b) ratio of 0.18 was selected to ensure a dense microstructure and achieve the target compressive strength (>150 MPa) and workability (flow table spread ≥ 200 mm).

Table 2. Summary of selected studies comparing UHPC and conventional concrete in terms of strength, durability, and life-cycle performance.

Material	Unit	UHPC Mix (Sustainable)	Control Mix (Conventional Concrete)	Remarks
Ordinary Portland Cement (OPC Type I)	kg/m³	570	400	Primary binder
Fly Ash	kg/m³	190	–	Industrial by-product; improves workability and sustainability
Ground Granulated Blast Furnace Slag (GGBS)	kg/m³	95	–	Enhances sulfate resistance and reduces embodied carbon
Silica Fume	kg/m³	95	–	Refines pore structure and increases strength
Quartz Sand (0–2 mm)	kg/m³	1,152	700	Fine aggregate providing high packing density
Coarse Aggregate (5–20 mm)	kg/m³	–	1083	Main Structural Skeleton
Water	kg/m³	171	180	Maintains low water-to-binder ratio (≤0.20)
Superplasticizer (PCE-based)	% of binder weight	1.80%	1.00%	Improves flowability and reduces water demand
Steel Fibers (13 mm × 0.2 mm)	% by volume	2.00%	–	Enhances tensile and flexural strength
Water-to-Binder Ratio (w/b)	–	0.18	0.45	Optimized for ultra-high performance
Target Compressive Strength (28 days)	MPa	160–170	40–45	Achieved strength based on laboratory trials
Flow Table Spread/ Slump	mm	210 (Flow)	150 (Slump)	Ensures high workability for placement

3.3 Performance Testing

After demolding at 24 hours, the specimens were subjected to a standard heat curing regime. They were immersed in a hot water bath at 90°C for 48 hours to accelerate the pozzolanic reaction of the Fly Ash and GGBS. Following this thermal treatment, the samples were stored in standard water curing conditions (20°C) until the testing age. Comprehensive mechanical and durability tests are conducted to assess the structural performance of the developed UHPC mix in comparison with a control conventional concrete (40 MPa). All testing follows ASTM and BS international standards to ensure validity and reproducibility.

Compressive Strength: Tested on 100 × 200 mm cylinders at 7, 28, 56, and 90 days following ASTM C39/C39M-21.

Flexural Strength: Evaluated using ASTM C1609 on 100 × 100 × 500 mm prisms under four-point loading to measure both elastic and post-crack performance.

Splitting Tensile Strength: Determined by ASTM C496 to verify crack-resisting capability.

Chloride Ion Penetration: Measured using the Rapid Chloride Permeability Test (RCPT) as per ASTM C1202 to assess durability under marine and saline conditions.

Sulfate Resistance: Long-term immersion tests (ASTM

C1012) are performed to evaluate expansion and mass loss in sulfate-rich environments.

The results of these tests provide quantitative inputs for correlating mechanical performance with potential reductions in maintenance frequency within the LCCA model.

Figure 3. UHPC Cylinders under Compressive Testing.

3.4 Life-Cycle Cost Analysis (LCCA)

The Life-Cycle Cost Analysis quantifies the total economic value of UHPC structures over their entire service life. The method applies the Net Present Value (NPV) concept, discounting future costs to present terms using Equation (1):

$$NPV = C_0 + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t}$$

Where:
C_0 = Initial construction cost,
C_t = Maintenance or user cost at year t,
r = Discount rate (assumed 5%),
n= Service life (years).

Cost Components:

- **Initial Costs:** Material, labor, formwork, and fiber reinforcement.
- **Maintenance Costs:** Periodic repairs, surface treatments, and corrosion control.
- **User Costs:** Delay and disruption costs to the public during maintenance activities. (User costs comprising Vehicle Operating Costs (VOC) and Value of Time (VOT) were calculated using the AASHTO Red Book (2010) framework, with specific coefficients derived from National Highway Authority (NHA) feasibility guidelines.

For UHPC structures, maintenance intervals are extended due to superior durability. A comparative model assumes a 100-year service life for UHPC versus 40 years for conventional concrete, incorporating repair cycles every 20 years for the latter. Cost inputs are derived from market surveys, national construction databases, and previous economic studies. The model assumes the use of prefabricated/precast UHPC elements where heat curing is applied prior to installation, ensuring the material properties matches laboratory results.

The LCCA results are expressed as total NPV per unit area (e.g., \$/m^2) and presented graphically to demonstrate long-term cost efficiency of sustainable UHPC.

3.4.1 Assumptions and Boundary Conditions for LCCA

Table 4. LCCA model parameters and data sources.

Parameter	Assumed Value	Justification / Source
Discount rate	5%	Typical public infrastructure rate in Pakistan
Analysis period	100 years	UHPC durability literature
CC service life	40 years	NHA rehabilitation data
UHPC service life	100 years	Graybeal (2019)
Major repair (CC)	Every 20 years	Fathy et al. (2024)
Major repair (UHPC)	Year 60	Issa & Afolabi (2023)
User cost	Included	Urban highway traffic disruption

This set of assumptions was chosen to incorporate conservative assumptions and literature-based assumptions of the conditions of the infrastructure environment of Pakistan.

For a detailed breakdown of local material unit rates, refer to Appendix A.

3.5 Data Sources and Analytical Tools

Experimental Data: Laboratory test results for mechanical and durability performance.

Secondary Data: Published literature on cost models, regional construction rates, and embodied energy values.

Analytical Tools:

Microsoft Excel for cost computations and sensitivity analysis.

MATLAB for NPV simulations under varying discount rates and service lives.

The combined use of experimental and analytical tools ensures data reliability and enhances the validity of conclusions drawn from both performance and cost perspectives.

4. Results and discussions

The results of this study are presented and discussed in two complementary parts. The first focuses on the technical performance of the sustainable UHPC mix developed with local materials, while the second examines the economic performance of UHPC through a Life-Cycle Cost Analysis (LCCA). Together, these findings provide a holistic understanding of how sustainable UHPC performs both structurally and financially when applied to Pakistan's infrastructure environment.

4.1 Performance Results

Compressive Strength

The compressive strength results demonstrate a significant improvement in the mechanical performance of UHPC compared to conventional concrete (CC). The locally produced UHPC mix achieved an average compressive strength of 162 MPa at 28 days, exceeding the 40 MPa benchmark of the control mix by over 300%. Even at 7 days, the UHPC reached 120 MPa, indicating rapid strength gain due to the optimized particle packing and the inclusion of silica fume and GGBS, which enhance hydration efficiency. By 90 days, the compressive strength stabilized around 168 MPa, confirming the long-term structural integrity of the mix (Pourbaba, 2023).

These results are consistent with prior studies by Graybeal (2019) and Wille (2015), who reported that UHPC typically develops more than three times the compressive strength of conventional concrete due to its ultra-dense matrix. The superior strength characteristics imply that smaller cross-sections can be used in structural elements, thereby reducing the volume of material and overall dead load.

Table 5.
Comparison of mechanical properties (compressive, flexural, and tensile strength) between Conventional Concrete and UHPC.

Property	Conventional Concrete	UHPC
Compressive Strength (MPa)	40	162
Flexural Strength (MPa)	6	22
Splitting Tensile Strength (MPa)	4.2	11.8

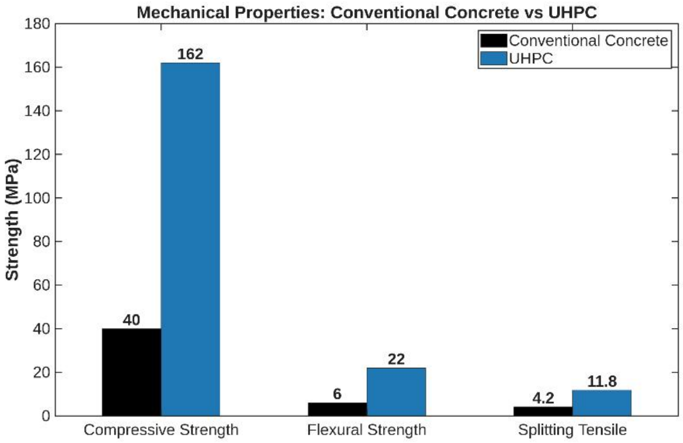

Figure 4. Bar chart showing compressive, flexural, and tensile strength comparison between UHPC and conventional concrete.

Flexural and Tensile Strength

Flexural strength tests (ASTM C1609) confirmed that the inclusion of 2% steel fibers significantly enhanced the post-cracking performance of the UHPC mix. The average flexural strength reached 22 MPa, compared with 6 MPa for the conventional concrete. This indicates a 266% improvement, highlighting the effectiveness of fibers in providing ductility and crack-bridging capacity. Similarly, splitting tensile strength (ASTM C496) increased from 4.2 MPa in CC to 11.8 MPa in UHPC, a gain of 181%.

The combination of dense microstructure and fiber reinforcement reduces the formation and propagation of cracks under both static and cyclic loading. This improvement is particularly critical for bridge decks, coastal pavements, and load-bearing components that experience repeated stress reversals. It also directly contributes to reduced maintenance requirements, as crack-induced deterioration is one of the leading causes of premature failure in Pakistan's infrastructure.

Durability Performance

Durability results further confirmed the long-term resilience of the developed UHPC mix. Chloride ion permeability, measured via the Rapid Chloride Permeability Test (ASTM C1202), was recorded at 180 coulombs, classifying it as "very low permeability" according to ASTM standards. In comparison, the conventional mix exhibited values around 2,800 coulombs, which fall within the "moderate permeability" range. This represents a 93% reduction in chloride penetration, a key indicator of corrosion resistance in marine and saline conditions such as Karachi and Gwadar.

Sulfate resistance tests (ASTM C1012) showed that UHPC samples exhibited less than 0.02% expansion after 6 months, while conventional concrete expanded by 0.35%, indicating susceptibility to sulfate attack. The addition of GGBS and silica fume proved effective in refining the pore structure and consuming calcium hydroxide, thereby reducing vulnerability to sulfate-induced cracking.

The results affirm that the combination of optimized mix design and sustainable SCMs not only enhances performance but also provides superior durability in aggressive environments. These durability gains translate directly into reduced repair frequency and extended service life, forming the technical foundation for the LCCA model discussed in the next section.

4.2 Life-Cycle Cost Analysis (LCCA)

The LCCA model was developed to evaluate the economic feasibility of sustainable UHPC relative to conventional concrete over a service life of 100 years. The analysis considered three cost categories: initial cost, maintenance and repair cost, and user cost associated with maintenance downtime. All values were discounted to present worth using a 5% discount rate, following the Net Present Value (NPV) method.

Initial Construction Cost

The initial construction cost of UHPC structures was found to be approximately 2.2 times higher than that of conventional concrete, mainly due to the use of high-performance admixtures, silica fume, and steel fibers. The cost of UHPC per cubic meter was estimated at $\$1244/m^3$, compared to $\$566/m^3$ for normal concrete. However, UHPC allows for thinner structural members (20–30% reduction) and lower reinforcement ratios, which partially offsets the initial material cost.

However, a strictly volumetric cost comparison (per m^3) is inadequate for LCCA as it neglects the structural efficiency inherent to high-performance materials. To provide a functionally equivalent comparison, costs were normalized to functional area (per m^2) accounting for a 30% reduction in structural member thickness. Assuming a standard deck profile of 0.25 m for conventional concrete and 0.175 m for UHPC, the adjusted initial construction costs are $\$141.50/m^2$ and $\$217.70/m^2$, respectively.

Maintenance and Repair Costs

Maintenance modeling assumed that conventional concrete structures require major rehabilitation every 20 years and minor repairs every 10 years (Fathy, 2024). This includes major rehabilitation cycles such as structural overlays or extensive patch repairs occurring at 20-year intervals (specifically at Years 20, 40, 60, and 80), with each intervention estimated to cost 40% of the initial construction value. In contrast, UHPC structures were projected to require only one major intervention at 60 years and minimal surface maintenance at 90 years due to superior durability performance. The reported maintenance costs are cumulative; they represent the sum of all discounted repair expenses accrued over the full 100-year service life. The analysis reveals that the total cumulative NPV of maintenance for conventional concrete aggregates to $\$200/m^2$. Conversely, due to fewer required interventions, the equivalent cumulative cost for UHPC is restricted to just $\$75/m^2$.

Over the full 100-year period, maintenance expenditures for UHPC structures were reduced by approximately 62% compared with conventional concrete. These savings were attributed primarily to the material's resistance to corrosion, cracking, and chemical attack, findings supported by Graybeal (2019) and Liu (2022), who reported similar life-cycle savings.

User Cost Savings

User costs quantify the indirect economic impact borne by the public due to construction-related disruptions. In this analysis, these costs were calculated based on two primary components: Vehicle Operating Costs (VOC) (additional fuel and wear caused by detours or idling) and the Value of Time (VOT) (economic loss due to travel delays). The model assumes a high-traffic scenario typical of Pakistan's critical trade corridors, such as the Karachi-Hyderabad Motorway (M-9), with an Average Daily Traffic (ADT) exceeding 35,000 vehicles.

For conventional concrete infrastructure, the frequent rehabilitation cycles (every 20 years) necessitate repeated work-zone closures, lane restrictions, and traffic diversions. Each major repair event is modeled to cause significant cumulative delays over a 3–4 month construction window. When these delay costs are monetized and discounted over the 100-year lifecycle, the cumulative user burden is estimated at $\$150/m^2$.

In contrast, the extended service life of UHPC drastically reduces the frequency of such disruptions. By eliminating the need for intermediate rehabilitation at years 20 and 40, UHPC ensures uninterrupted traffic flow for longer periods. The only significant user costs arise during the delayed intervention at Year 60. Consequently, the discounted lifecycle user cost for UHPC drops to $\$81/m^2$. This translates to a 46% reduction in economic losses to the public, highlighting that the benefits of UHPC extend beyond the agency's budget to the wider economy by safeguarding supply chain efficiency and commuter productivity.

Total Life-Cycle Cost (NPV Results)

Figure 5 illustrates the cumulative NPV of UHPC and conventional concrete structures over the 100-year analysis period. Although UHPC incurs higher costs in the initial 0–10 years, a cost crossover point occurs around year 35, beyond which UHPC becomes the more economical option. By year 100, the total life-cycle cost of UHPC is 24% lower than that of conventional concrete, confirming its long-term economic superiority.

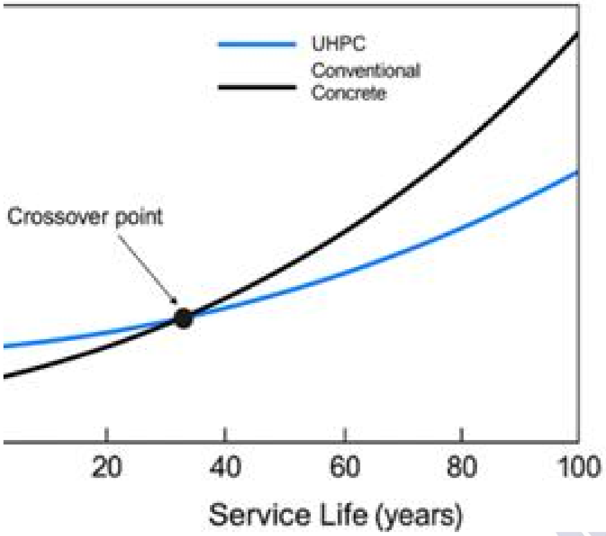

Figure 5. Life-Cycle Cost comparison curve (NPV) showing the crossover point where UHPC becomes more cost-effective than conventional concrete.

The analysis also included sensitivity testing with discount rates ranging from 3% to 7%, which showed that UHPC remained economically favorable under all scenarios. The robustness of this finding underscores that the reduction in maintenance frequency and associated downtime offsets the higher initial investment, yielding overall financial sustainability.

To validate the numerical trends, the Net Present Value (NPV) simulation was also modelled using MATLAB under varying cost scenarios. The graphical output in Figure 6 illustrates the crossover point between conventional concrete and UHPC over an 80-year period.

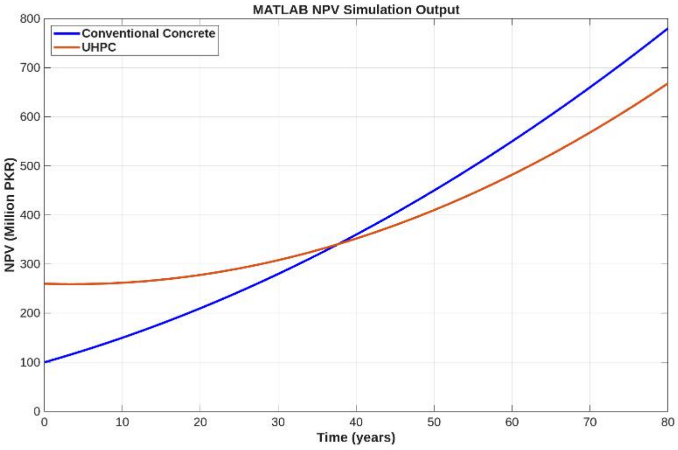

Figure 6. MATLAB NPV Simulation Output(0-80 years).

4.3 Environmental Performance Analysis

The environmental sustainability of the developed Eco-UHPC was evaluated through a comparative Life Cycle Assessment (LCA) against a conventional structural concrete. Table 6 outlines the embodied carbon footprint calculated using emission factors derived from the Inventory of Carbon & Energy (ICE) database.

The use of SCMs not only diverts industrial by-products from landfills but also enhances long-term durability, which indirectly lowers the total environmental impact over a structure's lifespan. By reducing repair frequency and extending service life, UHPC minimizes resource consumption, transport emissions, and energy associated with maintenance activities. The environmental benefit thus compounds over time, making UHPC a crucial material in achieving Pakistan's Sustainable Development Goals (SDG 9: Industry, Innovation and Infrastructure; SDG 13: Climate Action).

Table 6. Comparative Environmental Impact of UHPC and Conventional Concrete.

Material	Emission Factor (kgCO2e/kg)	Eco-UHPC (kg/m^3)	Conventional Concrete (kg/m^3)
Cement (OPC)	0.83	570	400
Silica Fume	0.02	95	-
Fly Ash	0.01	190	-
GGBFS (Slag)	0.08	95	-
Aggregates	0.005	1152	1783
Steel Fibers	1.5	157	-
Superplasticizer	0.72	17	4
Water	0.001	171	180

TOTAL GWP (kg/m^3)	-	738.24	344
Compressive Strength (MPa)	-	162	40
Eco-Efficiency Index (kg CO_2e / m^3)/ MPa)	-	4.56	8.6

The analysis highlights a significant divergence between volumetric impact and functional efficiency. In terms of absolute volume, the Eco-UHPC exhibits a higher embodied carbon (738.24 $kgCO_2e/m^3$) compared to the conventional benchmark (344 $kgCO_2e/m^3$). This increase is predominantly attributable to the inclusion of steel fibers (235.5 $kgCO_2e/m^3$) which alone account for approximately 32% of the total Global Warming Potential (GWP) of the UHPC mix. However, the binder phase demonstrates the efficacy of the 'Eco' design strategy; while the Eco-UHPC utilizes a higher cement content (570 kg/m^3) than the conventional mix (400 kg/m^3) it remains significantly below the threshold of typical reactive powder concretes (>800 kg/m^3). This relies on a ternary replacement strategy where industrial by-products (Fly Ash and GGBS) constitute 30% of the binder mass, effectively densifying the matrix and enhancing the packing density without a proportional increase in carbon intensity. To account for the mechanical superiority of the material, a normalized Eco-Efficiency Index (kgCO2e/m3) /MPa was established. This metric reveals that the Eco-UHPC is significantly more sustainable per unit of performance:

- **Conventional Concrete**: Requires 8.60 ($kgCO2e/m^3$) /MPa to generate 1 MPa of compressive strength.
- **Eco-UHPC:** Requires only 4.56 ($kgCO2e/m^3$) /MPa to generate 1 MPa of compressive strength.

This 47% improvement in carbon efficiency indicates that for strength-governed structural applications, the use of Eco-UHPC permits substantial reductions in element cross-sections. Consequently, the total carbon footprint of a structure may be reduced, despite the higher embodied energy per unit volume of the material itself.

This environmental advantage supports the argument that sustainable UHPC is not only a technically superior and economically viable material but also an eco-efficient solution that aligns with low-carbon infrastructure development strategies. When integrated with renewable energy-powered production and optimized logistics, the net environmental cost of UHPC structures could fall below half that of traditional concrete systems across their entire service life.

Integrated Discussion: Linking Technical and Economic Performance

The synergy between the technical and economic results highlights the essence of integrated performance assessment. The exceptional strength and durability of UHPC directly contribute to extended service life and reduced repair frequency, which are the primary drivers of life-cycle cost reduction. For instance, the 93% drop in chloride penetration implies a major reduction in corrosion-related repair activities, translating to tangible cost savings in LCCA outcomes.

From an environmental perspective, the inclusion of locally sourced SCMs such as fly ash and GGBS also contributes to sustainability by lowering embodied carbon and energy consumption. Therefore, UHPC not only outperforms conventional concrete technically but also supports Pakistan's environmental objectives under the Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action).

The combined interpretation confirms that sustainable UHPC offers a high-value, low-maintenance solution for critical infrastructure in Pakistan's diverse climatic regions. It addresses the dual challenge of performance and affordability, providing a strong justification for its broader adoption in bridges, coastal structures, and transportation networks.

Table 7. Summary of Life-Cycle Cost Analysis (LCCA) results comparing Conventional Concrete and Sustainable UHPC. Note: Costs are based on mid-2025 market rates (1 USD = 280 PKR) and a 5% discount rate over a 100-year service life.

Cost Component	**Conventional Concrete ($/m²)**	**UHPC ($/m²)**	**Savings (%)**
Initial Cost	141.5	217.7	–54% (uhpc is higher)
Maintenance & Repair	200	75	62%
User Cost	150	81	46%
Total NPV (100 years)	**491**	**373.7**	**24% overall savings**

5. Conclusion and Recommendations

This study aimed to evaluate the integrated performance and life-cycle cost effectiveness of sustainable Ultra-High-Performance Concrete (UHPC) for infrastructure applications in Pakistan. By combining experimental testing with economic modelling, the research provided a holistic understanding of UHPC's potential to deliver both technical excellence and long-term financial sustainability in the local construction context.

The results clearly demonstrate that UHPC, when produced using locally available industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), offers substantial improvements in both strength and durability compared to conventional concrete. The developed UHPC mix achieved a compressive strength exceeding 160 MPa and exhibited over 90% reduction in chloride permeability, confirming its superior resistance to corrosion and chemical attack. These technical advancements imply longer service life, reduced repair frequency, and enhanced structural safety all critical factors for Pakistan's aging and climate-exposed infrastructure network.

The Life-Cycle Cost Analysis (LCCA) results further reinforced these findings. Although UHPC presented a higher initial construction cost, the long-term economic analysis revealed that it becomes more cost-effective after approximately 35 years of service life, due to significant reductions in maintenance and user disruption costs. Over a 100-year evaluation period, UHPC achieved an estimated 24% total cost saving compared to conventional concrete. These results validate UHPC as a financially viable and sustainable alternative, aligning with global best practices and supporting Pakistan's Vision 2030 goal for resilient infrastructure development.

From a policy perspective, these outcomes have significant implications. The findings advocate for strategic adoption of UHPC in high-value and high-exposure projects, such as coastal bridges, expressways, and port structures. Integrating UHPC into national infrastructure specifications can help reduce lifecycle expenditure and improve public asset durability. Policymakers and industry stakeholders should also encourage local production of SCMs and fiber materials to lower costs and strengthen the domestic supply chain.

Future research should focus on large-scale field trials of UHPC structures under real environmental conditions in Pakistan to validate laboratory findings. Additionally, conducting a full Life-Cycle Assessment (LCA) that includes carbon footprint, embodied energy, and end-of-life recycling potential will provide a more comprehensive sustainability evaluation.

5. Limitations

Although this study provides valuable insights into the integrated performance and life-cycle cost of sustainable UHPC, certain limitations should be acknowledged. The experimental evaluation was primarily macroscopic, lacking microstructural analyses (e.g., SEM, XRD) to visually quantify the pore-refining mechanisms of the quaternary binder system. Furthermore, the high compressive strength was achieved under a controlled 90°C heat-curing regime intended to simulate precast production, which may overpredict performance compared to ambient-cured, cast-in-place applications. Additionally, the economic model relied on secondary cost data from published literature and national databases due to the unavailability of comprehensive local pricing information for UHPC materials and maintenance activities. The absence of large-scale field trials in Pakistan also restricts the validation of long-term performance predictions made through the LCCA model. Future studies should address these constraints by incorporating on-site testing, region-specific cost data, and extended durability monitoring, thereby improving the robustness and practical applicability of UHPC implementation strategies in Pakistan's infrastructure sector.

Acknowledgment

The authors would like to express their sincere gratitude to Allah Almighty for granting the strength and perseverance to complete this research successfully. Special appreciation is extended to the supervisor for continuous guidance, valuable insights, and constructive feedback throughout the study. The authors also acknowledge the support of the university and laboratory staff for providing essential resources and technical assistance during experimental testing. Heartfelt thanks are extended to family and friends for their encouragement and patience, which greatly contributed to the completion of this work. Finally, the authors appreciate professionals who shared their knowledge and data, enabling a more comprehensive understanding of sustainable Ultra-High-Performance Concrete (UHPC) in the context of Pakistan's infrastructure development.

Conflict of Interest Statement (MANDATORY)

CRediT Author Statement (MANDATORY)

Umair Khan: Conceptualization, Methodology, Investigation, Writing-original draft, Shabir Ahmad: Software, Formal analysis, Data curation, Visualization, Fahad Ali: Validation, Resources, Writing – review & editing, Ahmad I. Khan: Writing – review & editing, Validation.

References

1. American Association of State Highway and Transportation Officials. (2010). *User and non-user benefit analysis for highways* (3rd ed.). AASHTO.
2. Association Française de Génie Civil. (2013). *Ultra high performance concrete: Recommendations.*
3. Blais, P. Y., & Couture, M. (1999). Precast, prestressed pedestrian bridge: World's first reactive powder concrete structure. *PCI Journal*, *44*(5), 60–71. https://doi.org/10.15554/pcij.09011999.60.71
4. Fathy, E.-R., Abdel-Hamid, M., & Abdelhaleem, H. M. (2024). Developing a predictive maintenance model for the rehabilitation of roads' assets. *International Journal of Construction Management*, *24*, 1–11. https://doi.org/10.1080/15623599.2024.2309733
5. Graybeal, B. A. (2011). *Ultra-High Performance Concrete* (Report No. FHWA-HRT-11-038). Federal Highway Administration.
6. Graybeal, B. A., & El-Helou, R. G. (2019). Development of an AASHTO guide specification for UHPC. *International Interactive Symposium on Ultra-High Performance Concrete*, *2*(1). Iowa State University Digital Press.
7. Graybeal, B. A., & Hartmann, J. L. (2003). Strength and durability of ultra-high performance concrete. *Proceedings of the 2003 Concrete Bridge Conference*, Orlando, FL.
8. Habert, G., Denarié, E., Šajna, A., & Rossi, P. (2011). Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cement and Concrete Composites*, *33*(3), 294–302. https://doi.org/10.1016/j.cemconcomp.2010.09.003
9. Islam, M. S., Islam, S., & Mondal, B. C. (2013). Deterioration of concrete in ambient marine environment. *International Journal of Engineering*, *26*(3).
10. Issa, M. O., & Afolabi, O. S. (2023). Ultra-High-Performance Concrete (UHPC) in bridge rehabilitation: A critical review of global practices, performance, and life-cycle economics. *World Journal of Advanced Research and Reviews*, *20*(3), 2401–2411. https://doi.org/10.30574/wjarr.2023.20.3.2562
11. Khan, M. M., Ahmad, H., Shah, S. M. T., Sheikh, T. M., & Muhammad, S. (2023). Exploring potentials for accelerated construction techniques In Pakistan. *8th Multidisciplinary Student Research International Conference.*
12. Liu, G., Hua, J., Wang, N., Deng, W., & Xue, X. (2022). Material alternatives for concrete structures on remote islands: Based on Life-Cycle-Cost Analysis. *Advances in Civil Engineering*, *2022*, 7329408. https://doi.org/10.1155/2022/7329408
13. Memon, S. A., Shaikh, M. A., & Akbar, H. (2011). Utilization of wood ash as partial replacement of cement in concrete. *International Journal of Civil and Structural Engineering*, *2*(1).
14. Meng, W., & Khayat, K. H. (2018). Effect of hybrid fibers on fresh properties, mechanical properties, and autogenous shrinkage of cost-effective UHPC. *Journal of Materials in Civil Engineering*, *30*(4), 04018030. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002212
15. Ministry of Planning, Development & Reform. (2014). *Pakistan 2030: One nation, one vision.* Government of Pakistan.
16. Munir, M., Kiviniemi, A., Jones, S. W., & Finnegan, S. (2021). Circular economy practices in the construction industry of Pakistan: Barriers and enablers. *Journal of Building Engineering*, *44*, 103367. https://doi.org/10.1016/j.jobe.2021.103367
17. Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education.
18. Nguyen, H. A., Chang, T. P., Chen, C. T., Wun, J. L., & Shih, J. Y. (2022). Polypropylene fiber reinforced concrete improved by using silica fume and acrylic emulsion polymer. *Materiales de Construcción*, *72*(345), e274. https://doi.org/10.3989/mc.2022.28521
19. Panhyar, M. A., Shah, S. N. R., Shaikh, F. A., & Jhatial, A. A. (2019). Influence of casting temperature on the structural behavior of concrete. *Engineering, Technology & Applied Science Research*, 9(4), 4480–4483. https://doi.org/10.48084/etasr.2929
20. Perera, B. A. K. S., et al. (2021). Barriers in practicing life cycle costing techniques experienced by Sri Lankan quantity surveyors. *Proceedings of the 9th World Construction Symposium*, 143–154.
21. Pourbaba, M., Chakraborty, R., Belarbi, A., & Yeon, J. H. (2023). A new insight into the design compressive strength of ultra-high performance concrete. *Buildings*,

13(12), 2909. https://doi.org/10.3390/buildings13122909

22. Resplendino, J. (2011). State of the art of design and practice of UHPC in France. *Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology*.
23. Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. *Cement and Concrete Research*, *25*(7), 1501–1511. https://doi.org/10.1016/0008-8846(95)00143-Z
24. Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research*, *114*, 2–26. https://doi.org/10.1016/j.cemconres.2017.06.009
25. Shafique, M., et al. (2014). Investigation regarding bridge expansion joints deterioration in Pakistan and its remedial measures. *Technical Journal, University of Engineering and Technology (UET) Taxila*, *19*(3).
26. Tanaka, Y., Maekawa, K., Kameyama, Y., Ohtake, A., Musha, H., & Watanabe, N. (2014). The innovation and application of UHPFRC bridges in Japan. In *Designing and Building with UHPFRC* (pp. 149–188). Wiley-ISTE. https://doi.org/10.1002/9781118557839.ch2
27. Thomas, M. D. A. (2007). *Optimizing the use of fly ash in concrete*. Portland Cement Association.
28. Walenna, M. A., Wang, Z., & Ngezahayo, E. (2025). Utilization of ground granulated blast furnace slag (GGBS) as an environmentally friendly partial replacement for cement to improve cement-bentonite erosion resistance. *Indonesian Journal of Urban and Environmental Technology*, *8*(2), 324–345. https://doi.org/10.25105/urbanenvirotech.v8i2.21550
29. Wille, K., & Boisvert-Cotulio, C. (2015). Material efficiency in the design of ultra-high performance concrete. *Construction and Building Materials*, *86*, 33–43. https://doi.org/10.1016/j.conbuildmat.2015.03.087
30. Wille, K., Kim, D. J., & Naaman, A. E. (2011). Strain-hardening UHP-FRC with low fiber content. *Materials and Structures*, *44*(3), 583–598. https://doi.org/10.1617/s11527-010-9650-3
31. Yu, R., Spiesz, P., & Brouwers, H. J. H. (2015). Development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses. *Cement and Concrete Composites*, *55*, 383–394. https://doi.org/10.1016/j.cemconcomp.2014.09.023
32. Zhong, R., & Wille, K. (2015). Material efficiency in the design of ultra-high performance concrete. *Construction and Building Materials*, *86*, 512–521. https://doi.org/10.1016/j.conbuildmat.2015.04.018

Appendix A: Cost of Acquired Materials

A detailed record of material costs was compiled to support the Life-Cycle Cost Analysis (LCCA) model. All unit rates were collected through local supplier quotations and market surveys conducted in Karachi and Lahore (2024). Prices were converted to US Dollars ($) for consistency with economic analysis. These data provide the baseline for calculating initial construction costs in both UHPC and conventional concrete systems.

Table A1. Local Market Prices of Materials Used in UHPC and Conventional Concrete.

Material	**Specification / Source**	**Unit**	**Average Market Price (PKR)**	**Equivalent Price ($)**	**Remarks**
Ordinary Portland Cement (OPC Type I)	Maple Leaf / Lucky Cement	per ton	32,000 PKR	≈ $114	Base binder for both mixes
Ground Granulated Blast Furnace Slag (GGBS)	Karachi Steel Mills	per ton	18,500 PKR	≈ $66.1	SCM; improves sulfate resistance
Fly Ash	Jamshoro Thermal Power Plant	per ton	9,000 PKR	≈ $32.1	Industrial by-product, cost-effective
Silica Fume	Imported (China)	per ton	85,000 PKR	≈ $303.5	Micro-filler; enhances strength and density
Quartz Sand (0–2 mm)	Local Punjab Quarries	per ton	4,200 PKR	≈ $15	Fine aggregate for particle packing
Steel Fibres (13 mm × 0.2 mm)	Local Supplier – Lahore	per kg	450 PKR	≈ $1.6	Reinforcement for tensile and flexural strength

Superplasticizer (PCE-based)	BASF MasterGlenium ACE 30	per Litre	620 PKR	≈ $2.2	Water-reducing admixture
Water	Municipal Supply	per m^3	150 PKR	≈ $0.50	Used in mix and curing

Note:

- Exchange rate used = 1 USD ≈ 280 PKR (as of mid-2025).
- Price variations up to ±10% were observed across suppliers.
- The above costs exclude transportation and handling, which were estimated separately in the LCCA under project overheads.