



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ENVIROMENTAL ENGINEERING
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KARTIK POONIA

ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED CONCRETE BRIDGES: APPLICATION AND FUTURE PERSPECTIVES

FINAL MASTER'S THESIS

INNOVATIVE ROAD AND BRIDGE ENGINEERING study programme

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CIVIL ENGINEERING study field

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OBJECTIVES FOR MASTER THESIS

.....No.
Riga and Vilnius

For student: **Kartik Poonia**

Master Thesis title: **ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED
CONCRETE BRIDGES: APPLICATION AND FUTURE PERSPECTIVES**

The master thesis has to be completed by: 1 January, 2025

THE OBJECTIVES:

1. Review existing literature on application of ultra-high-performance fiber reinforced concrete (UHPFRC) in bridge engineering.
2. Conduct a comprehensive review of existing literature on mechanical and physical properties of UHPFRC.
3. Analyse the existing bridges constructed using UHPFRC.
4. Perform comparative analysis of UHPC application in bridge engineering from perspective of cost, strength and durability.
5. Analyse the collected data, draw conclusions, and identify the future directions of UHPFRC application in bridge engineering.

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS
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KELIŲ KATEDRA

Kalba:

Anglų

Anotacija

Magistro darbe nagrinėjamas itin didelio stiprumo pluoštu armuoto betono (UHPFRC) tiltų pritaikymas ir ateities perspektyvos. Remiantis išsamia literatūros apžvalga ir 17 detalių atvejų analize nuo 1997 iki 2023 metų, tyrime nagrinėjama UHPFRC evoliucija tiltų inžinerijoje. Dėmesys sutelkiamas į tris pagrindinius aspektus: ekonominį pagrįstumą, stiprumo charakteristikas ir konstrukcinį efektyvumą.

Ekonominė analizė atskleidžia tendenciją didėjančio ekonominio efektyvumo link, UHPFRC tampa vis konkurencingesnis lyginant su tradicinėmis medžiagomis. Stiprumo charakteristikos rodo įspūdingą nuoseklumą - gniuždomasis stipris per du dešimtmečius nuolat viršija 150 MPa. Konstrukcinis efektyvumas rodo reikšmingą pažangą: perdangų ilgis padidėjo nuo 60 m 1997 m. iki 480 m 2023 m., o perdangos ilgio ir aukščio santykis pasiekė net 50:1.

Darbe daroma išvada, kad UHPFRC tiltai žymi medžiagų naudojimo pokytį tiltų inžinerijoje, derinant itin didelį stiprumą su išskirtiniu konstrukciniu efektyvumu. Magistriniame darbe pabrėžiamas medžiagos potencialas kuriant tvaresnius, ilgaamžiškesnius ir novatoriškesnius tiltų projektus, kartu nurodant sritis, kuriose ateityje reikėtų atlikti tyrimus ir tobulinimus, siekiant pagerinti plastiškumą, tvarumą ir ekonominį efektyvumą.

Šis išsamus tyrimas suteikia vertingų įžvalgų apie dabartinę UHPFRC būklę ir ateities perspektyvas tiltų statyboje, sudarydamas pagrindą tolesnei pažangai šioje srityje.

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Thesis Language

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Annotation

This thesis explores the application and future perspectives of Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) bridges. Through an extensive literature review and analysis of 17 detailed case studies spanning from 1997 to 2023, the research examines the evolution of UHPFRC in bridge engineering. The study focuses on three key aspects: economic viability, strength performance, and structural efficiency.

The economic analysis reveals a trend towards increasing cost-effectiveness, with UHPFRC becoming more competitive compared to traditional materials. Strength performance demonstrates remarkable consistency, with compressive strengths consistently above 150 MPa over two decades. Structural efficiency shows significant advancements, with span lengths increasing from 60m in 1997 to 480m in 2023, and span-to-depth ratios reaching up to 50:1.

The research concludes that UHPFRC bridges represent a paradigm shift in bridge engineering, combining ultra-high strength with exceptional structural efficiency. The thesis highlights the material's potential for creating more sustainable, durable, and innovative bridge designs, while also identifying areas for future research and development in enhancing ductility, sustainability, and cost-effectiveness.

This comprehensive study provides valuable insights into the current state and future prospects of UHPFRC in bridge construction, offering a foundation for further advancements in this field.

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INTRODUCTION

In the realm of advanced construction materials, Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) stands as a pinnacle of innovation, seamlessly integrating the strengths of two distinct predecessors: Ultra-High Performance Concrete (UHPC) and Fiber-Reinforced Concrete (FRC). UHPC, recognized for its exceptional compressive strength and durability, has redefined the possibilities in high-performance construction materials. On the other hand, FRC, leveraging the reinforcing properties of fibers, has enhanced tensile strength and crack resistance. This exploration begins by dissecting the individual merits of UHPC and FRC, shedding light on their unique attributes and applications. Subsequently, the narrative converges to unveil the synthesis of these concrete paradigms in UHPFRC—a material that not only inherits the extraordinary compressive strength of UHPC but also



Figure 1 UHPFRC

harnesses the superior tensile strength and ductility bestowed by fiber reinforcement. UHPFRC thus emerges as a material at the forefront of modern construction, offering a harmonious amalgamation of strength, durability, and versatility that transcends the capabilities of its individual predecessors.

AIM OF THESIS

This paper provides an overview of the latest applications of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) in bridge engineering, focusing on the economic impact and viability of using UHPFRC in bridge construction. This review examines the current state, constraints, challenges, and opportunities for further research on Ultra-High-Performance Fiber-Reinforced Concrete in bridge engineering from an economic perspective.

The objective of this research is to enhance the understanding of UHPFRC's economic potential and cost-effectiveness in bridge projects by exploring the following aspects:



Figure 2 Economics for UHPFRC

- **Unique Attributes of UHPFRC:** Understanding how UHPFRC differs from conventional concrete, with a focus on its durability, longevity, and potential to reduce lifecycle costs in bridge construction.
- **Economic Advantages of UHPFRC:** Evaluating the ways in which UHPFRC can yield financial benefits in bridge projects, including reduced maintenance costs, increased durability, and longer service life, ultimately contributing to a more sustainable infrastructure investment.
- **Economic Obstacles:** Identifying the financial challenges and market barriers hindering widespread adoption of UHPFRC in bridge engineering, and exploring potential strategies to overcome these barriers to enable broader implementation.

A comprehensive economic analysis of UHPFRC applications in bridge engineering aims to support its increased market adoption both domestically and globally, fostering a more economically sustainable approach to bridge construction.

1. LITERATURE REVIEW

1.1 ULTRA-HIGH-PERFORMANCE FIBRE-REINFORCED CONCRETE

High-Performance Concrete (HPC), Self-Consolidating Concrete (SCC), and Fiber-Reinforced Concrete (FRC) are distinct types of concrete, each with its unique properties and applications. Combining these technologies can result in a specialized concrete known as Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) (Akeed et al., 2022). This combination leverages the strengths of each concrete type to create a material with exceptional mechanical properties, durability, and versatility.

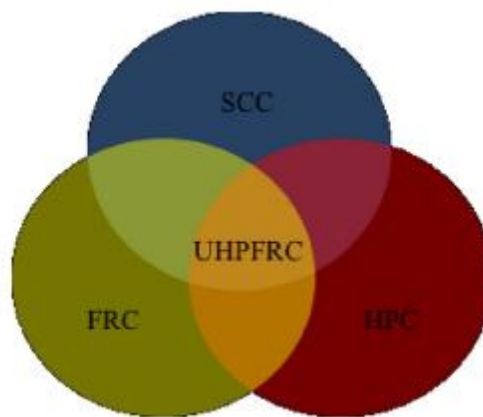


Figure 3 UHPFRC using different types of special concretes (Shafiq et al, 2018)

1. High-Performance Concrete (HPC):

- HPC is characterized by its high compressive strength, excellent durability, and enhanced workability. It typically incorporates advanced admixtures and a well-graded aggregate mix to achieve superior performance. HPC is often used in demanding applications where high strength and durability are critical.

2. Self-Consolidating Concrete (SCC):

- SCC is designed to flow and consolidate on its own under its weight, filling formwork without the need for external vibration. This type of concrete is known for its high workability, ability to flow into complex shapes, and improved consolidation in congested reinforcement areas. SCC is commonly used in applications where ease of placement and reduced labour are essential.

3. Fiber-Reinforced Concrete (FRC):

- FRC incorporates fibers, which can be metallic, synthetic, or natural, to enhance the concrete's tensile and flexural strength. Fiber reinforcement helps control cracking, improve ductility, and increase resistance to impact and dynamic loads. FRC is used in various applications where enhanced toughness is required.

Combination into Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC):

UHPFRC takes the combination of HPC, SCC, and FRC to the next level. By integrating the high compressive strength of HPC, the self-consolidating properties of SCC, and the enhanced toughness of FRC, UHPFRC achieves a unique balance of properties. The mix design often includes ultra-fine particles, high-strength cement, advanced admixtures, and a high dosage of specially selected fibers.

This results in a concrete with exceptional compressive and flexural strength, durability, ductility, and resistance to various types of loads and environmental conditions. It is commonly used in high-stress areas, precast elements, bridge components, architectural elements, and structures that demand a combination of strength, durability, and resilience.

1.2 FIBERS USED IN UHPFRC

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) utilizes specific types of fibers to enhance its mechanical properties. Not all kinds of fibers can ensure the Ultra High performance which UHPFRC contains. The fibers that are added in the mix are one of the most vital ingredients to ensure the ultimate strength.

Below is a detailed analysis The most commonly used fibers include steel, synthetic (such as polyethylene (PE), polyvinyl alcohol (PVA), polypropylene (PP)), carbon, and basalt fibers.

A. STEEL FIBERS

Steel fibers are widely used in Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) due to their excellent mechanical properties and compatibility with the cement matrix. The material structure of steel fibers plays a crucial role in their performance within UHPFRC.

Composition and Structure

Steel fibers used in UHPFRC are typically made of high-strength steel with the following characteristics:

1. **Material:** High-carbon steel or stainless steel.
2. **Tensile strength:** Generally ranging from 1000 to 3000 MPa.
3. **Diameter:** Usually between 0.1 and 0.6 mm.
4. **Length:** Typically 6 to 60 mm, with optimal lengths between 13 and 20 mm.
5. **Aspect ratio:** The length-to-diameter ratio usually ranges from 30 to 100 (Shehab El-Din et al., 2016).

Types and Shapes

Steel fibers for UHPFRC come in various shapes, each offering specific benefits:

1. **Straight fibers:** Simple cylindrical shape.
2. **Hooked-end fibers:** Ends bent to improve anchorage.
3. **Corrugated fibers:** Wavy along their length for better bonding.
4. **Twisted fibers:** Helical shape for enhanced pull-out resistance (Huang et al, 2024).

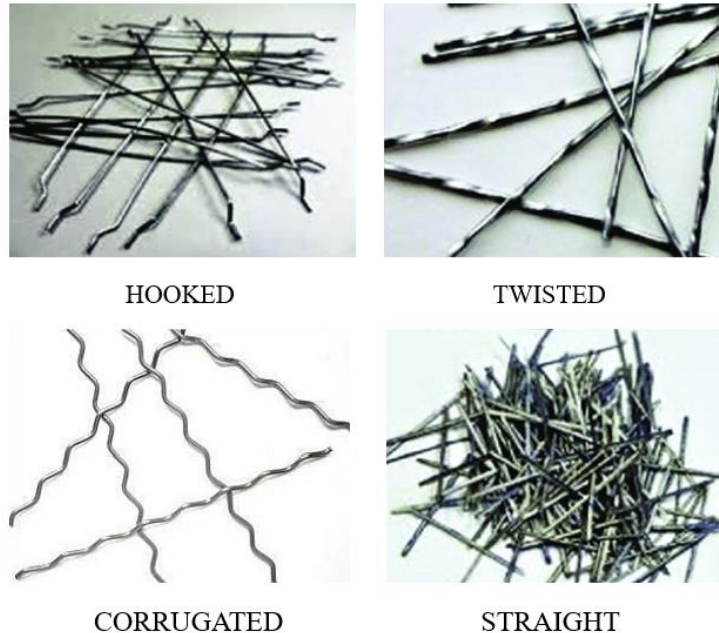


Figure 4 Types of steel fibres

Characteristics and Performance

Steel fibers contribute significantly to UHPFRC's performance:

1. **Strength enhancement:** Steel fibers can increase compressive strength by up to 42% and flexural strength by up to 109.4% compared to unreinforced specimens (Huang et al, 2024).
2. **Ductility improvement:** They significantly enhance the tensile strain capacity of UHPFRC, with some mixtures achieving strain capacities of up to 11% (Shehab El-Din et al., 2016).
3. **Crack bridging:** Steel fibers effectively bridge microcracks, allowing UHPFRC to continue carrying loads after initial cracking (Shehab El-Din et al., 2016).
4. **Pull-out resistance:** The bond strength of straight steel fiber with UHPC matrix is typically in the range of 5–20 MPa with a matrix strength of 100–250 MPa (Soloviev et al, 2023)
5. **Workability impact:** The addition of steel fibers generally reduces workability, with the effect being more pronounced for higher aspect ratios and volume fractions (Shehab El-Din et al., 2016).

Optimal Usage

1. **Fiber content:** The optimal fiber content for UHPFRC typically ranges from 1% to 2% by volume (Huang et al, 2024).
2. **Hybrid systems:** Combining different types of steel fibers (e.g., micro and macro fibers) can optimize performance by addressing both micro and macro cracking (Soloviev et al, 2023).
3. **Orientation:** The orientation of fibers significantly affects performance, with aligned fibers providing better tensile properties (Shehab El-Din et al., 2016).

B. SYNTHETIC FIBERS

While steel fibers are commonly used, synthetic fibers have emerged as promising alternatives, especially in corrosive environments. This includes synthetic fibers used in UHPFRC, focusing on Polyvinyl Alcohol (PVA), Polyethylene (PE), Polypropylene (PP), and Polyoxymethylene (POM) fibers.

i) Polyvinyl Alcohol (PVA) Fibers

PVA fibers are widely used in UHPFRC due to their excellent mechanical properties and strong bond with the cementitious matrix.

Composition and Structure:

PVA fibers are synthetic fibers made from polyvinyl alcohol polymer with a linear molecular structure and hydroxyl groups attached to the carbon backbone.

Characteristics:

- High tensile strength
- Excellent chemical stability
- Strong interfacial bond with cement matrix
- Hydrophilic nature

Performance:

PVA fibers significantly enhance the mechanical properties of UHPFRC, improving tensile strength, flexural strength, and ductility (Xu et al., 2021).

Optimal Usage:

The optimal content of PVA fibers in UHPFRC varies depending on the desired properties. A study found that 0.8% PVA fiber content provided optimal reinforcement for mechanical properties of geopolymer concrete, except for tensile strength, which peaked at 1.0% fiber volume fraction (Xu et al., 2021).

ii) Polyethylene (PE) Fibers

PE fibers are known for their high tensile strength and excellent ductility, making them suitable for UHPFRC applications.

Composition and Structure:

PE fibers are made from polyethylene, a thermoplastic polymer consisting of long chains of ethylene monomers.

Characteristics:

- High tensile strength
- Low density
- Chemical inertness
- Hydrophobic nature

Performance:

PE fibers significantly enhance the tensile and flexural properties of UHPFRC. A study reported that UHPFRC reinforced with 2% (vol.) PE fiber and 1% (vol.) steel fiber achieved the highest f'_{cf_t}/t_w index of $2.45 \text{ MPa}^2/\mu\text{m}$, indicating excellent overall performance (Dai et al., 2021).

Optimal Usage:

The optimal PE fiber content in UHPFRC is typically around 2% by volume, with fiber lengths ranging from 6–19 mm and diameters of 12–29 μm .



PP Synthetic Fibres



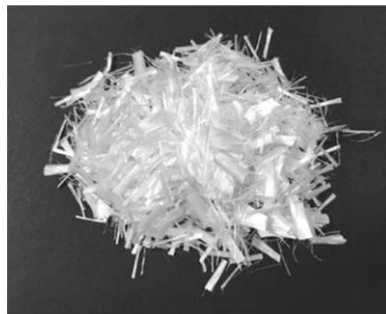
PE Synthetic Fibres

iii) Polypropylene (PP) Fibers

PP fibers are widely used in concrete due to their low cost and ability to control plastic shrinkage cracking.

Composition and Structure:

PP fibers are made from polypropylene, a thermoplastic polymer produced from propylene monomers.



PVA Synthetic Fibres



POM Synthetic Fibres

Figure 5 Types of Synthetic Fibres

Characteristics:

- Low density
- Chemical inertness
- Hydrophobic nature
- Good toughness

Performance:

While PP fibers can improve certain aspects of UHPFRC, their performance is generally not as high as PVA or PE fibers. A study found that PP fiber-reinforced UHPC showed lower mechanical strength, toughness, and impact resistance compared to POM fiber-reinforced UHPC (Tan et al., 2023).

Optimal Usage:

The optimal content of PP fibers in UHPFRC depends on the specific application and desired properties, generally using lower volumes compared to PVA or PE fibers due to their lower performance.

iv) Polyoxymethylene (POM) Fibers

POM fibers are a relatively new addition to the range of synthetic fibers used in UHPFRC, showing promising results in recent studies.

Composition and Structure:

POM fibers are made from polyoxymethylene, a thermoplastic with a chain of alternating carbon and oxygen atoms.

Characteristics:

- High tensile strength
- Good dimensional stability
- Low friction coefficient
- Chemical resistance

Performance:

Recent studies have shown that POM fibers can significantly enhance the mechanical properties of UHPFRC. A study found that increasing POM fiber content improved mechanical strength, flexural toughness, impact, and abrasion resistance of UHPC. At 2% content, the adsorbed-in-fracture energy and abrasion strength of UHPC reached 2670 J and 105 h/(kg/m²), respectively (Tan et al., 2023).

Optimal Usage:

The optimal content of POM fibers in UHPFRC appears to be around 2% by volume, based on recent research. However, more studies are needed to establish definitive guidelines for different applications.

C. CARBON FIBERS

Carbon fibers have emerged as a promising reinforcement material for Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), offering unique advantages in terms of strength, durability, and sustainability. Carbon fibers used in Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) are primarily derived from polyacrylonitrile (PAN) precursors through a complex multi-stage process involving stabilization, carbonization, and graphitization. This results in a material with a unique combination of composition and structural characteristics that significantly enhance the mechanical properties of the concrete matrix.



Figure 6 Carbon Fibres

Composition and Structure

Carbon fibers used in UHPFRC are typically made from polyacrylonitrile (PAN) precursors, which undergo a series of thermal treatments to achieve their final form. These fibers are characterized by their high carbon content, usually exceeding 90% (Ogi et al., 2016).

The fibers have a diameter ranging from 5 to 15 micrometers and lengths that can vary depending on the specific application, but are generally in the range of 3 to 30 mm for use in UHPFRC (Mastali et al., 2016).

The internal structure of carbon fibers consists of aligned graphene sheets, which contribute to their exceptional mechanical properties. This alignment results in a highly anisotropic material, with superior strength and stiffness in the longitudinal direction (Ogi et al., 2016).

Characteristics and Performance:

- 1) **High Tensile Strength:** Carbon fibers possess superior tensile strength compared to traditional steel fibers. Studies have shown that incorporating carbon fibers can significantly enhance the tensile strength of UHPFRC, with increases of up to 54.9% reported (Wang et al., 2024).

- 2) **Excellent Young's Modulus:** The high stiffness of carbon fibers contributes to improved mechanical properties of the concrete matrix. This characteristic allows for better load transfer and crack bridging within the material (Wang et al., 2024).
- 3) **Low Density:** Carbon fibers are considerably lighter than steel fibers, which can lead to a reduction in the overall weight of UHPFRC structures without compromising strength (Kromoser et al., 2019).
- 4) **Corrosion Resistance:** Unlike steel fibers, carbon fibers are non-corrosive, which enhances the durability and longevity of UHPFRC structures, particularly in aggressive environments (Kromoser et al., 2019).
- 5) **Autogenous Shrinkage Mitigation:** The addition of carbon fibers has been shown to mitigate autogenous shrinkage in UHPFRC, which can help prevent early-age cracking (Wang et al., 2024).
- 6) **Energy Absorption Capacity:** Research has demonstrated that incorporating carbon fibers can significantly improve the energy absorption capacity of UHPFRC, with increases of up to 108.9% observed (Wang et al., 2024).

Optimal Usage

- 1) **Fiber Content:** The optimal fiber content depends on the specific application and desired properties. Studies have shown that even small dosages (e.g., 0.3% by volume) can lead to significant improvements in mechanical properties (Wang et al., 2024).
- 2) **Fiber Distribution:** Achieving uniform dispersion of carbon fibers within the UHPFRC matrix is crucial for optimal performance. Poor distribution can lead to fiber clumping and reduced effectiveness (Nguyen et al., 2022).
- 3) **Fiber Aspect Ratio:** The aspect ratio (length to diameter) of carbon fibers influences their performance in UHPFRC. Higher aspect ratios generally lead to better mechanical properties but may also affect workability (Wang et al., 2024).
- 4) **Matrix Optimization:** The UHPFRC matrix should be optimized to ensure good bonding with carbon fibers. This may involve adjusting the mix design, including the use of supplementary cementitious materials and superplasticizers (Wang et al., 2024).
- 5) **Hybrid Systems:** Some researchers have explored the use of carbon fibers in combination with other fiber types, such as steel fibers, to create hybrid UHPFRC systems with enhanced properties.

D. BASALT FIBERS

Basalt fibers have emerged as a promising reinforcement material for Ultra-High Performance Fiber Reinforced Concrete (UHPFRC), offering several advantages in terms of mechanical properties and durability. A relatively recent addition to the family of reinforcing fibers for UHPFRC, offer a compelling combination of mechanical properties and environmental benefits. Derived from naturally occurring basalt rock, these fibers possess a distinct material structure that influences their performance in concrete applications.

Composition and Structure

Basalt fibers are made from melted basalt rock, a natural volcanic material composed primarily of plagioclase, pyroxene, and olivine minerals (Magdalene and Karthikeyan, 2024). The production process involves melting the basalt rock at high temperatures (around 1400-1700°C) and then extruding the molten material through small nozzles to form continuous filaments (Magdalene and Karthikeyan, 2024).

The resulting fibers have a diameter typically ranging from 9 to 23 μm and lengths that can vary depending on the specific application requirements (Magdalene and Karthikeyan, 2024). Basalt fibers have a smooth surface and are usually coated with plastic before packaging to prevent surface oxidation (Magdalene and Karthikeyan, 2024).



Figure 7 Basalt Fibers

Characteristics

Basalt fibers possess several notable characteristics that make them suitable for use in UHPFRC:

1. **High tensile strength:** Basalt fibers exhibit excellent tensile strength, contributing to the overall strength of the concrete matrix (Magdalene and Karthikeyan, 2024).
2. **Corrosion resistance:** Unlike steel fibers, basalt fibers are highly resistant to corrosion, making them suitable for aggressive environments (Magdalene and Karthikeyan, 2024).
3. **Thermal stability:** Basalt fibers maintain their properties over a wide range of temperatures, enhancing the concrete's performance in extreme conditions (Magdalene and Karthikeyan, 2024).
4. **Chemical stability:** These fibers show good resistance to various chemical agents, contributing to the durability of the concrete (Magdalene and Karthikeyan, 2024).
5. **Flexibility:** Compared to steel fibers, basalt fibers are more flexible, allowing for better distribution within the concrete matrix (Magdalene and Karthikeyan, 2024).

Performance in UHPFRC

The incorporation of basalt fibers in UHPFRC has shown significant improvements in various aspects of concrete performance:

Mechanical Properties

1. **Compressive Strength:** While the addition of basalt fibers does not significantly impact the compressive strength of UHPFRC, it helps in maintaining the strength by preventing sudden failure (Zhang et al., 2024).

2. **Flexural and Tensile Strength:** Basalt fibers significantly improve the flexural and tensile strength of UHPFRC. Studies have shown increases in flexural strength with increasing fiber content up to an optimal point (Zhang et al., 2024).
3. **Impact Resistance:** The inclusion of basalt fibers enhances the impact resistance of UHPFRC, with improvements in both the number of blows required for failure and the overall impact toughness (Alkaysi et al., 2023).

Durability

1. **Permeability Resistance:** UHPFRC reinforced with basalt fibers shows improved resistance to permeability compared to plain UHPFRC, with the electrical flux being less than 100 C, indicating negligible chloride ion penetration (Magdalene and Karthikeyan, 2024).
2. **Crack Resistance:** Basalt fibers effectively postpone the onset of diagonal cracks in UHPFRC deep beams, enhancing the overall structural integrity (Alkaysi et al., 2023).
3. **Ductility:** The addition of basalt fibers changes the brittle nature of concrete to one of increased ductility, allowing for better energy absorption and deformation before failure (Alkaysi et al., 2023).

Optimal Usage

The optimal usage of basalt fibers in UHPFRC depends on several factors:

1. **Fiber Content:** The ideal basalt fiber content typically ranges from 0.5% to 1.5% by volume of concrete. Higher percentages may lead to workability issues and potential strength reductions (Zhang et al., 2024).
2. **Fiber Length:** The choice of fiber length depends on the specific application, but lengths between 12-24 mm are commonly used in UHPFRC (Magdalene and Karthikeyan, 2024).
3. **Hybrid Systems:** Some studies have explored the use of basalt fibers in combination with steel fibers, finding synergistic effects that enhance both strength and ductility (Zhang et al., 2024).

1.3 MANUFACTURING METHODS OF UHPFRC

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is an advanced cementitious composite material characterized by its exceptional mechanical properties and durability. The manufacturing process of UHPFRC is crucial to achieving its superior performance. Following is a detailed analysis of the manufacturing methods and specific techniques for different fiber types:

General UHPFRC Manufacturing Process

The production of UHPFRC typically involves the following steps:

1. **Material Selection:** UHPFRC uses high-quality materials, including cement, silica fume, fine aggregates, superplasticizers, and fibers (Arora et al, 2016).
2. **Mixing:** The dry components are first mixed thoroughly, followed by the gradual addition of water and superplasticizer. The mixing process is usually longer than for conventional concrete to ensure proper dispersion of fine particles (Puri, 2024).
3. **Fiber Addition:** Fibers are added last and mixed until uniformly distributed. The fiber content typically ranges from 1% to 3% by volume (Maya et al., 2016).
4. **Casting:** The mixture is poured into molds, taking care to maintain proper fiber orientation.
5. **Curing:** UHPFRC often undergoes special curing regimes, including heat treatment, to enhance its properties (Puri, 2024).

Specific Techniques for Different Fiber Types

1. Steel Fibers

Steel fibers are the most commonly used in UHPFRC due to their high strength and modulus.

- **Dosage:** Typically 1-2% by volume (Maya et al., 2016).
- **Mixing Technique:** Steel fibers are usually added last to the mix to prevent balling. Gradual addition with continuous mixing is recommended (Puri, 2024).
- **Orientation:** The casting method significantly influences fiber orientation. Flow-induced orientation can be used to align fibers in the desired direction (Maya et al., 2016).

2. Synthetic Fibers

Synthetic fibers, such as polypropylene or polyvinyl alcohol, are sometimes used in UHPFRC for specific applications.

- **Dosage:** Generally lower than steel fibers, around 0.5-1% by volume.
- **Mixing Technique:** Synthetic fibers can be added earlier in the mixing process due to their lower density and reduced risk of balling (Puri, 2024).
- **Dispersion:** Special attention must be given to ensure uniform dispersion of synthetic fibers throughout the mix.

3. Carbon Fibers

Carbon fibers are less commonly used in UHPFRC but can provide unique properties.

- **Dosage:** Typically lower than steel fibers, around 0.5-1% by volume.

- **Mixing Technique:** Carbon fibers require careful handling to prevent damage. They are often pre-mixed with a portion of the cement or silica fume before being added to the main mix (Puri, 2024).
- **Dispersion:** Ultrasonic dispersion techniques may be employed to ensure proper distribution of carbon fibers.

4. Basalt Fibers

Basalt fibers are gaining attention in UHPFRC production due to their good mechanical properties and chemical stability.

- **Dosage:** Similar to steel fibers, around 1-3% by volume (Vatin et al, 2023).
- **Mixing Technique:** Two main methods are used:
 1. **Direct mixing:** Basalt fibers are separated and directly mixed into the UHPFRC during the mixing process.
 2. **Pre-saturation:** Basalt fibers are first soaked in water to saturate them before being mixed into the RPC mortar (Vatin et al, 2023).
- **Orientation:** The three-dimensional random interweaving of basalt fibers significantly influences the performance of BFRPC (Basalt Fiber Reinforced Polymer Concrete) (Vatin et al, 2023).

Fiber Type	Compressive Strength (MPa)	Tensile Strength (MPa)	Durability	Resistance
Steel Fibers	150-180	20-30	High resistance to freeze-thaw, corrosion	High impact resistance, good crack bridging
Synthetic Fibers	120-150	15-25	Long-term durability, chemical resistance	Good resistance to chemical attacks, water permeability, fire
Carbon Fibers	150-180	30-50	Excellent corrosion resistance, UV stable	Electrical conductivity, thermal stability
Basalt Fibers	150-180	20-30	Superior thermal resistance, dimensional stable	Resistant to alkali-silica reaction, acid, and fire

Table 1 Different UHPFRC characteristics according to fibres

Key Considerations in UHPFRC Manufacturing

1. **Water-to-Binder Ratio:** UHPFRC typically has a very low water-to-binder ratio, usually between 0.16 and 0.20 (Puri, 2024).
2. **Particle Packing:** Achieving maximum packing density of all granular constituents is crucial for UHPFRC performance (Puri, 2024).

3. **Superplasticizer Usage:** A high dosage of superplasticizers is necessary to achieve workable mixtures with such low water content (Puri, 2024).
4. **Curing Regime:** Heat treatment during curing can significantly enhance the properties of UHPFRC by promoting the formation of more hydrates (Puri, 2024).
5. **Fiber Orientation:** The orientation of fibers is a critical parameter in UHPFRC design and is often expressed by orientation factors (K) that consider global and local effects (Puri, 2024).

In conclusion, the manufacturing of UHPFRC requires careful consideration of material selection, mixing procedures, and curing regimes. The specific techniques for different fiber types vary, with each type offering unique advantages and challenges in the production process. Ongoing research continues to refine these methods to optimize UHPFRC performance for various applications.

1.4 COMPARISON OF UHPFRC WITH ORDINARY CONCRETE

Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) represents a significant advancement over ordinary concrete, offering superior mechanical properties, durability, and performance. The following elucidates fundamental characteristics and plausible experimental values associated with UHPFRC when compared with ordinary concrete:

1. Compressive Strength:

- **UHPFRC:** Experimental values for compressive strength in UHPFRC typically range from 150 MPa to well over 200 MPa.
- **Ordinary Concrete:** Ordinary concrete, in comparison, generally has compressive strength values ranging from 20 MPa to 40 MPa. (Karmacharya et al, 2019)

2. Flexural Strength:

- **UHPFRC:** UHPFRC exhibits remarkable flexural strength, often exceeding 30 MPa and occasionally reaching values surpassing 50 MPa.
- **Ordinary Concrete:** Ordinary concrete's flexural strength typically falls in the range of 3 MPa to 5 MPa. (Karmacharya et al, 2019)

3. Tensile Strength:

- **UHPFRC:** UHPFRC demonstrates elevated tensile strength, ranging from 5 MPa to 15 MPa or more, owing to the reinforcing fibers.
- **Ordinary Concrete:** Ordinary concrete's tensile strength is considerably lower, usually in the range of 2 MPa to 5 MPa. (Karmacharya et al, 2019)

4. **Durability:**

- **UHPFRC:** UHPFRC is renowned for its exceptional durability, featuring low permeability that minimizes water and chloride ingress, resulting in superior resistance to environmental factors.
- **Ordinary Concrete:** Ordinary concrete's durability can vary, and while it can withstand typical conditions, it may be susceptible to cracking and degradation over time. (Li et al, 2020)

5. **Ductility:**

- **UHPFRC:** UHPFRC can display ductile behavior, allowing for controlled deformation and energy absorption before failure.
- **Ordinary Concrete:** Ordinary concrete tends to exhibit limited ductility, and its response to deformation is more brittle. (Richard et al, 1995)

6. **Shrinkage:**

- **UHPFRC:** UHPFRC typically demonstrates low shrinkage, mitigating the risk of cracking, even with high compressive strength.
- **Ordinary Concrete:** Ordinary concrete may experience higher shrinkage, contributing to the potential for crack formation.

7. **Workability:**

- **UHPFRC:** UHPFRC mixtures can be designed for good workability, aided by the strategic use of superplasticizers and other admixtures.
- **Ordinary Concrete:** Ordinary concrete generally has good workability, but the addition of admixtures may be required for specific applications.

8. **Curing Requirements:**

- **UHPFRC:** UHPFRC often requires specific curing protocols to achieve optimal strength and durability, which may involve steam curing or meticulous moist curing.
- **Ordinary Concrete:** Ordinary concrete also requires curing, but the protocols may be less stringent compared to UHPFRC. (Tayeh et al, 2019)

These comparisons highlight the significant differences in mechanical properties between UHPFRC and ordinary concrete, with UHPFRC consistently exhibiting superior strength, durability, and performance in various aspects. Its adoption is still limited by higher initial costs and the need for specialized production techniques. However, its potential for creating more sustainable and resilient infrastructure makes it an increasingly attractive option for specific applications in modern construction.

It's important to note that the selection of concrete type depends on the specific requirements and conditions of a given construction project too.

1.4 APPLICATIONS OF UHPFRC IN CONSTRUCTION TILL DATE



Figure 8 UHPFRC Bridge Girders

Currently, the use of UHPFRC has been extensively applied in bridge construction (Lei Voo et al, 2014).

The applications of UHPFRC as a material for repairing concrete structures, including both the rehabilitation and strengthening process, has been increasingly explored in various situations (Abdal et al, 2023).

Bridge Girders: The expensive cost of developed Ultra-High Performance Concrete (UHPC) mixes significantly limits its usage in both domestic and global markets.

The initial use of UHPC in North America occurred in 1997 when it was utilized for the construction of a pedestrian bridge in Quebec, Canada. UHPC was introduced to the commercial market in the United States in the year 2000.

It was utilized in the construction of the Mars Hill Bridge, which is the first girder bridge made of UHPC. This bridge is located in Wapello County, Iowa. The bridge was constructed



Figure 9 Mars Hill UHPC bridge in Wapello County, Iowa (sourced from Google)

in 2006 as a direct outcome of five years of cooperative research conducted by the Federal Highway Administration (FHWA) and Iowa Department of Transportation. The Mars Hill bridge is a bridge that consists of a single span and has a cross-section with three beams. The span of the bridge measures 33.5 meters (Aitcin, 2000). (fig. 9)

Moreover, based on a recent study conducted by the Federal Highway Administration (FHWA), about 200 bridge expansion (BE) projects between 2006 and 2018 employed a particular high-performance concrete (UHPC) mixture on a specific level. These projects included both the maintenance of existing BE structures and the construction of new BE structures within the state Department of Transportation (DOT) BE network. Table 2 displays a comprehensive list of UHPC projects that have been successfully finished on a global scale (Middendorf et al, 2019).

Year	App	Location	Advantages
1997	Pedestrian BE	Sherbrooke, Canada	The first UHPC structure.
2004	Foot BE	Seonyu, Seoul, South Korea	Reduced-segment arch BE.
2004	Roof	Shawnessy LRT Station, Canada	Simple to build and requires very little maintenance work, lightweight.
2005	Road BE	Bourg-les-Valence, France	Steel reinforcing costs are reduced by 90 percent. Lighter construction with a 66 percent weight reduction over CC.
2006	Road BE	Mars Hill BE, United States	The first UHPC highway BE in the United States had a simple structure. There is no shear reinforcement.
2013	Column and Façade	MUCEM, Marseille, France	Y-formed column with a 'Transparent' façade.
2013	Roof and Façade	Jean Bouin Stadium, Paris	Pre-cast UHPC components, waterproof roof and façade, slim construction with distinctive design.
2014	Cladding UHPCpanels	Foundation Louis Vuitton, France	Creative design

Table 2 Completed UHPC projects worldwide (Middendorf et al, 2019)

Bridge deck overlays: UHPC is being employed in the application of bridge deck overlays to enhance the state of bridge decks. Currently, there is a significant need for efficient and long-lasting restoration of bridge decks that have been damaged due to factors such as the rise in vehicle volume, heavier vehicle loads, freeze-thaw cycles, cracking of the deck, separation of the concrete cover, and corrosion of the reinforcing steel. The approach to bridge deck repair is contingent upon the allocated budget and the intended longevity of the restored structure.

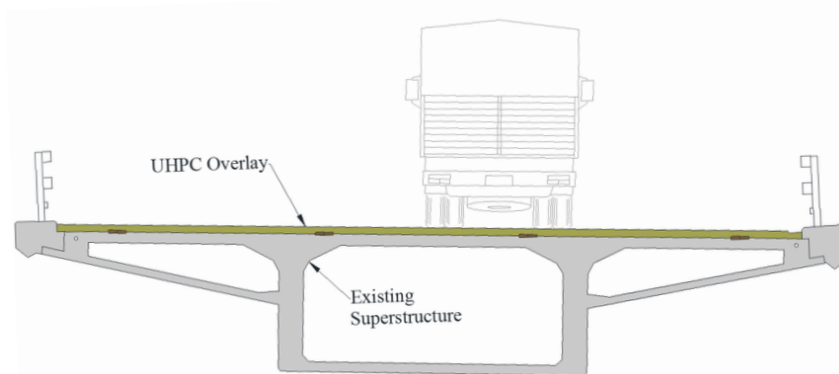


Figure 10 Overlay on a bridge deck

Historically, conventional concrete overlays, latex-modified concrete, and specialized asphalt mixes containing polymer-based substances were employed.

Presently, UHPC overlays are being effectively utilized.

UHPC overlays have the advantage of being able to

use thin overlays, ranging from 2.5 cm to 5.0 cm in thickness, that have a superior bond to the existing concrete. The extremely low permeability and exceptional strength properties of UHPC are sufficient to meet the necessary strengthening requirements, as well as provide protection against the penetration of contaminants such as chemical assaults and de-icing salts (Aitcin, 2000).

Bridge piles: Utilizing piles as a means of supporting bridge weight has long been a prevalent method for constructing high-performance infrastructure. Historically, piles have been constructed utilizing steel sections, precast concrete, or cast-in-place concrete.

The challenges associated with concrete piles include restricted load-bearing capability, potential failure of piles during installation, and degradation of piles caused by environmental factors.

The utilization of Ultra-High Performance Concrete (UHPC) blends in the construction of piles has significantly enhanced their load-bearing capability and long-term durability. Ultra-

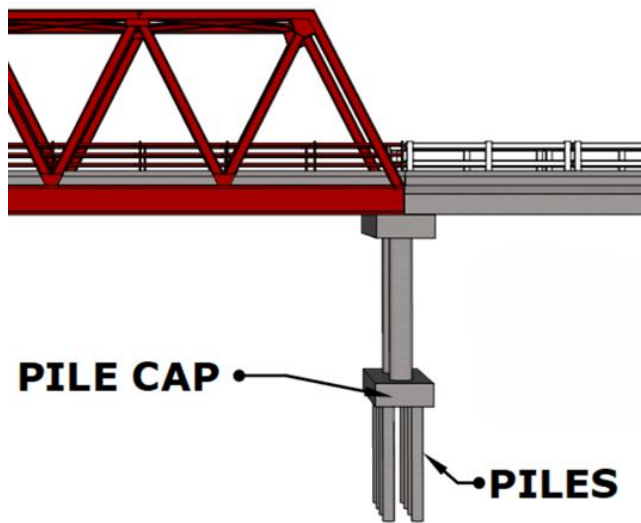


Figure 11 UHPFRC Bridge Piles

high performance concrete (UHPC) mixtures, characterized by their exceptional strength, may be effortlessly installed with minimal to no harm. The extremely low permeability of UHPC mixtures leads to enhanced resistance against environmental degradation. The elevated expense of UHPC mixes is balanced by the decreased material necessity resulting from smaller pile sizes, as well as the reduced need for maintenance throughout the construction project's lifespan.

Accelerated Bridge building (ABC) Applications involve the utilization of the Prefabricated Bridge Elements and Systems (PBES) technique, which entails the use of Ultra-High Performance

Concrete (UHPC) mixes for pouring various bridge elements. This approach enables the rapid building of bridges. The utilization of Ultra-High Performance Concrete (UHPC) in the Accelerated Bridge Construction (ABC) technique has empowered bridge design engineers to create inventive bridge sections with geometric dimensions that lead to substantial material cost reductions and simplified construction processes (Aitcin, 2000).

1.5 LIMITATIONS AND FUTURE OBJECTIVES OF UHPFRC

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is an advanced material with exceptional properties, but it also faces challenges that limit its widespread adoption. So far, these limitations bound them in a finite space, and addressing them through future objectives is crucial for the continued development and application of UHPFRC in the construction industry.

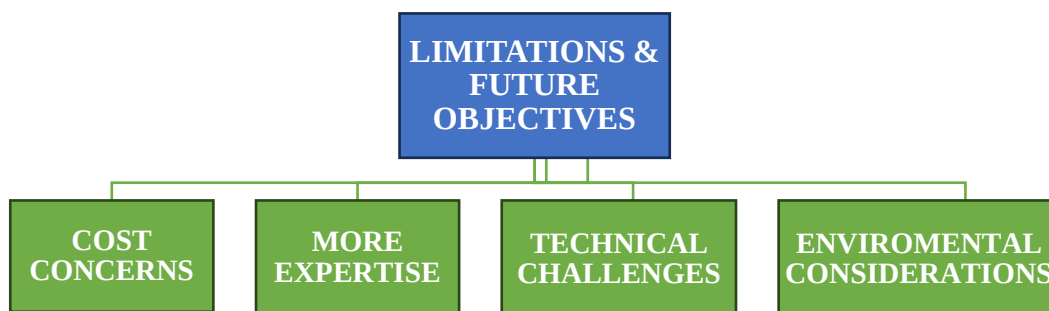


Figure 12 Limitations persisting in UHPFRC today

Cost and Material Considerations:

UHPFRC is often more expensive than traditional concrete due to its high-quality components and specialized fibers. This cost factor limits its use, especially in budget-constrained projects. Additionally, the availability of certain UHPFRC components may be limited in some regions. To address these issues, steps include:

- Developing cost reduction strategies without compromising performance
- Optimizing mix designs and exploring alternative materials
- Researching locally available materials or waste by-products as viable substitutes

Expertise and Standardization:

Working with UHPFRC requires specialized knowledge, and the lack of expertise is a limitation in certain regions. Moreover, as a relatively recent development, UHPFRC lacks standardized guidelines and building codes in some areas. Future objectives in this area include:

- Providing comprehensive education and training programs for construction professionals
- Developing clear guidelines and best practices for working with UHPFRC
- Collaborating with standards organizations to develop comprehensive codes for UHPFRC

Technical Challenges

UHPFRC is sensitive to mix design variations, and achieving optimal performance requires precise proportions and curing conditions. It may also exhibit brittleness under high-stress conditions and experience some degree of shrinkage. Future research aims to:

- Improve mix design consistency and performance
- Enhance ductility for broader structural applications
- Develop advanced shrinkage control methods

Environmental and Application Considerations

The production of UHPFRC does have a significant environmental footprint due to energy-intensive processes. Additionally, its exceptional properties may be unnecessary for less demanding applications. Future objectives include:

- Investigating more sustainable production methods
- Exploring broader applications where UHPFRC's benefits can be fully utilized
- Balancing performance requirements with environmental considerations

By addressing these limitations through focused research and development, the construction industry can unlock the full potential of UHPFRC.

With time, as the technology matures and becomes more widely accepted, solutions to current limitations will definitely emerge, making UHPFRC a more viable option for a broader range of construction projects.

Now,

As we conclude our discussion of the theoretical framework and the history of UHPFRC till date, we now turn our attention to the practical applications of this material.

The next chapter will present detailed case studies of bridges built using UHPFRC around the globe, that exemplify the principles explored thus far. Think of these case studies as a bridge between theory and reality. They'll help us see how theoretical knowledge translates into concrete situations, making it easier to grasp the practical value of what we've learned so far.

Each case study will serve as a vivid illustration, demonstrating how organizations and individuals apply these concepts to solve problems and drive success.

Additionally,

In the third section of our discussion, we'll take a step back and look at the bigger picture. We'll compare and contrast these case studies of the UHPFRC bridges, analyzing their similarities, differences, and unique insights. This comparative analysis will help us uncover patterns, best practices, and potential challenges in applying our theoretical framework about this ultimate material.

By examining these real-world applications and then stepping back for a broader analysis, this comprehensive exploration will serve as a solid foundation for drawing meaningful conclusions. The interplay between theory, practical examples, and comparative analysis will enable us to synthesize our findings, identify overarching themes, and formulate well-supported conclusions that bridge the gap between theoretical understanding and real-world applications, where we can see if this ultimate material known as UHPFRC is actually the go to material for future of construction or not. This holistic approach will ultimately lead to more robust and actionable insights, enhancing the overall value of our study.

2. DETAILED CASE STUDIES OF UHPFRC BRIDGES

2.1 SHERBROOKE PEDESTRIAN BRIDGE, CANADA



Figure 13 Sherbrooke Pedestrian Bridge

Location and Purpose:

- Located in Sherbrooke, Quebec, Canada, spanning the Magog River
- Connects the residential area to the city's sports complex
- Total length: 60 meters
- Width: 3.3 meters (Blais & Couture, 1999)

Construction Details:

- Constructed in 1997
- Design: Open-web space truss structure
- First major structure worldwide using UHPFRC (Reactive Powder Concrete at the time)
- Built using precast segments that were post-tensioned together
- The truss consists of a top and bottom chord connected by diagonal web members (Rebentrost & Wight, 2008)

Material Properties of UHPFRC used:

- Compressive strength: 200 MPa
- Flexural strength: 30-35 MPa
- Steel fiber content: 2% by volume
- Fiber length: 13mm
- Deck depth: 3.5m
- Maximum aggregate size: 0.5mm (Aïtcin et al., 1998)

Construction Process:

- Six precast segments were manufactured in a local precast plant
- Each segment was approximately 10 meters long
- Post-tensioning was applied both longitudinally and transversely
- The bridge was assembled on site in approximately 3 days (Blais & Couture, 1999)

Cost and Economic Aspects:

- Total construction cost: approximately 425,000 CAD (1997)
- Material cost of UHPFRC: about 1000 CAD/m³
- Despite higher material costs, reduced material volume and faster construction provided overall economy (Rossi, 2005)

Performance and Monitoring:

- Regular monitoring showed excellent durability
- No significant deterioration after more than 20 years in service
- Performed well under severe freeze-thaw conditions
- Minimal maintenance required compared to conventional concrete bridges (Charron et al., 2018)

Design Innovation:

- First use of UHPFRC in combination with post-tensioning for a bridge
- Demonstrated the possibility of creating very thin structural elements (only 30mm thick)
- Achieved significant weight reduction compared to conventional concrete design (Resplendino & Toulemonde, 2011)

2.2 WILD BRIDGE, SWITZERLAND

Material Properties

- Utilizes ultra-high-performance fiber-reinforced concrete (UHPFRC) with high tensile and compressive strength.
- UHPFRC enhances durability and minimizes maintenance needs due to its resistance to environmental damage (Sparowitz et al., 2011).

Construction Techniques

- Built using a segmental construction method with a “swivel-in” technique.

- Built in 2006 as part of a rehabilitation and widening project (Denarié and Brühwiler, 2006)
- Total length: 47.5 meters (155.8 feet) (Denarié and Brühwiler, 2006)
- Width: 3.5 meters (11.5 feet)
- UHPFRC deck thickness: 40-60 mm (1.57-2.36 inches) (Brühwiler and Denarié, 2013)
- Prefabricated UHPFRC segments were assembled with external tendons for stabilization (Reichel et al., 2010).

Cost Considerations

- Higher initial material costs for UHPFRC, offset by lower long-term maintenance.
- Rapid assembly and durability contribute to long-term cost savings (Freytag et al., 2012).

Purpose and Design Goals

- Demonstrates sustainable bridge engineering for Swiss infrastructure.
- Designed for longevity, structural resilience, and minimal upkeep (Sparowitz et al., 2011; Reichel, 2009).
- Serves as a pedestrian and cycling bridge over the Steinach River in St. Gallen, Switzerland (Denarié and Brühwiler, 2006)
- Connects the city center with recreational areas and improves urban mobility (Brühwiler and Denarié, 2013)
- Demonstrates the potential of UHPFRC in bridge engineering and rehabilitation



Figure 14 Sakata-Mirai Footbridge

2.3 SAKATA-MIRAI FOOTBRIDGE, JAPAN

Material Properties:

- Constructed in 2002, using ultra-high performance fiber-reinforced concrete (UHPFRC) (Tanaka et al., 2009)
- UHPFRC provides high compressive strength, reaching upto 238 MPa, and flexural strength upto 40 MPa (Abbas et al., 2016).

- Allows for a lightweight, slender, and aesthetically pleasing design

Purpose:

- Serves as a pedestrian bridge in Sakata City, Yamagata Prefecture, Japan (Tanaka et al., 2009)
- Connects the city center with the waterfront area, improving urban mobility
- Demonstrates the potential of UHPFRC in bridge engineering in Japan (Dingqiang et al., 2018)

Precast Segmental Construction:

The bridge's design used precast UHPFRC segments, facilitating rapid construction and quality control by minimizing onsite work. This method also reduces project duration and is cost-effective for challenging locations (Kono et al., 2013; Eriguchi et al., 2008).

Environmental Considerations:

Constructed in a coastal area, the bridge design capitalizes on UHPFRC's resistance to chloride and harsh weather, ensuring durability despite exposure to seawater and seasonal temperature fluctuations (Tanaka & Kono, 2013; RILEM, 2004).

Construction process:

- Assembly and post-tensioning of segments on-site (Tanaka et al., 2009)
- Total length: 50.7 meters (166.3 feet)
- Main span: 49.2 meters (161.4 feet) (Dingqiang et al., 2018)
- Width: 2.4 meters (7.9 feet)
- UHPFRC deck thickness: varies from 125 mm (4.9 inches) at mid-span to 225 mm (8.9 inches) at supports (Tanaka et al., 2009)
- Beam Depth ranging from 0.55 m – 1.65 m

Key Features:

- Pi-shaped cross-section for improved structural efficiency (Tanaka et al., 2009)
- Longitudinal and transverse post-tensioning to enhance structural performance
- Minimalist design showcasing the material's capabilities (Dingqiang et al., 2018)
- Enhanced durability and reduced maintenance requirements
- Improved load-bearing capacity with minimal self-weight

Cost Implications and Lifecycle Benefits

- **Higher Initial Investment:**

While UHPFRC is more costly than traditional concrete, its exceptional durability reduces the frequency and costs of maintenance, providing an overall cost advantage over the bridge's lifecycle (Kawabata & Fujimoto, 2016; Eriguchi et al., 2008).

- **Sustainability and Cost-Efficiency:**

The bridge's low maintenance requirements make UHPFRC a sustainable choice, especially in regions where access for repairs is limited or expensive (Kono et al., 2013; Fracture Mechanics of Concrete Structures, 2010).

Design and Engineering:

- Designed to withstand severe environmental conditions, including sea salt exposure (Tanaka et al., 2009)
- Utilizes external post-tensioning system for easy inspection and maintenance
- Incorporates stainless steel reinforcement for additional corrosion resistance (Dingqiang et al., 2018)
- Design life expectancy of 100 years with minimal maintenance.

2.4 SEONYU FOOTBRIDGE, SOUTH KOREA

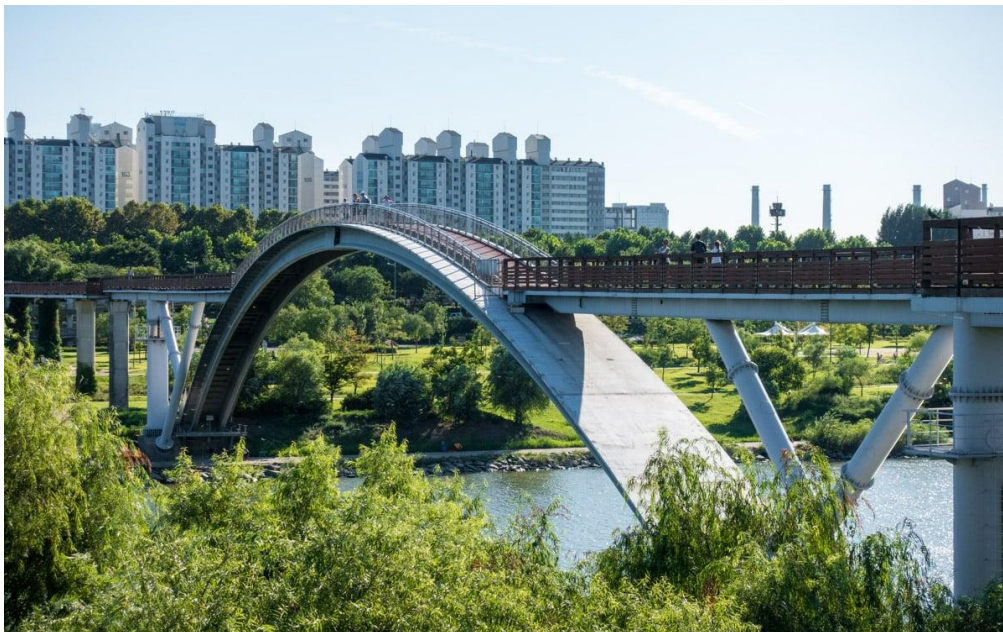


Figure 15 Seonyu Footbridge

Location and Purpose:

- Located in Seoul, South Korea
- Spans the Han River
- Connects Seonyu Island to mainland
- Total length: 120 meters

- Width: 4.3 meters
- Arch rise: 15 meters (Behloul & Lee, 2003)

Construction Details:

- Constructed in 2002
- Design: Single arch structure
- World's first arch bridge made entirely of UHPFRC (Ductal®)
- Deck supported by steel hangers attached to the arch

- Arch cross-section: π -shaped (Park et al., 2003)

Material Properties (Ductal®):

- Compressive strength: 180 MPa
- Steel fiber content: 2% by volume
- Depth: 1.3m

Construction Process:

- Designed by French architect Rudy Ricciotti.
- Arch constructed using 6 precast segments
- Each segment approximately 20 meters long
- Segments connected using post-tensioning
- Deck installed using precast UHPFRC panels
- Total construction time: 4 months (Park et al., 2003)

Structural Innovation:

- First large-scale application of UHPFRC in bridge arch
- Total structure weight reduction of 70% compared to conventional concrete
- No passive reinforcement in arch structure (Behloul & Lee, 2003)

Performance Monitoring:

- Regular monitoring since construction
- Excellent durability in severe weather conditions
- No significant cracking or deterioration observed
- Performed well under thermal variations (Bonneau et al., 2013)

Construction Cost:

- Approximately 2.5 billion South Korean Won (around USD 2.1 million), reflecting the specialized materials and early-stage technology of UHPFRC (Bonneau et al., 2013; Behloul et al., 2002).

Design Features:

- Arch thickness varies from 30cm at springing to 3cm at crown
- Total structure weight: 260 tons
- Design life: 100 years (Behloul et al., 2002)

2.5 MARS HILL BRIDGE, IOWA, USA



Figure 16 Mars Hill Bridge

Location and Purpose:

- Located in Wapello County, Iowa
- Single-span bridge on low-volume road
- Length: 113 ft (34.5 m)
- Width: 24.5 ft (7.5 m)
- First UHPC bridge

in North America (Bierwagen & Abu-Hawash, 2005)

Material Properties of UHPFRC used:

- Compressive strength: 21.7 ksi (150 MPa)
- Steel fiber content: 2% by volume
- Length of steel fibers: 0.5 inch (13 mm)
- Depth: 1.07m

Construction Details:

- Built in 2006
- Three 113-ft long precast, prestressed concrete beams
- No mild steel reinforcement in beam web
- Used modified bulb-tee beam shape (Wipf et al., 2009)

Construction Process:

- Beams cast at Lafarge's Winnipeg plant
- Steam cured at 190°F (88°C) for 48 hours
- Cast-in-place UHPC deck joints between beams
- Total construction time significantly reduced compared to conventional concrete (Phares et al., 2006)

Cost Information:

- Total project cost: \$432,000 (Endicott, 2006)

Performance:

- Regular monitoring showed excellent durability
- No significant cracking or deterioration observed
- Performed well under local traffic and environmental conditions (Russell & Graybeal, 2013)

2.6 PONT DU DIABLE FOOTBRIDGE, FRANCE



Figure 17 Pont Du Diable Footbridge

Material Properties:

- Constructed using ultra-high performance fiber-reinforced concrete (UHPFRC) (Resplendino, 2012)
- UHPFRC provides high compressive strength (>150 MPa), high tensile strength, and excellent durability (Toutlemonde et al., 2009)
- Allows for a lightweight, slender,

and innovative design.

Purpose:

- **Location and Significance:** Part of a "Grand Site de France" and UNESCO World Heritage site in the Hérault gorges, Languedoc-Roussillon, including Saint-Guilhem-le-Désert. (ECCE, et al, 2014)
- **Purpose of Footbridge:** Provides safe pedestrian access to the historic Pont du Diable (Devil's Bridge), an 11th-century monument. (ECCE, et al, 2014)
- Demonstrates the potential of UHPFRC in creating aesthetically pleasing structures in sensitive historical contexts (Toutlemonde et al., 2009)

Construction:

- Completed in 2008
- One of the early applications of UHPFRC for footbridges in France (Resplendino, 2012)
- Construction process:
 - Prefabrication of UHPFRC elements off-site
 - Transportation of elements to the construction site
 - Two parallel isostatic T-beams serve as the bridge's structure and railings. (ECCE, et al, 2014)
 - Length: 72 meters; Width and Depth: 1.80 meters each. (ECCE, et al, 2014)
 - Constructed from 15 segments, each 4.6 meters long and 10 tonnes. (ECCE, et al, 2014)
 - Prefabrication: 3 months; Site Preparation: 1 month; Installation: 1 week; Dismantling: 1 week. (ECCE, et al, 2014)
 - Total on-site work time: Less than 2 months. (ECCE, et al, 2014)

Key Features:

- Single-span structure without intermediate supports
- Minimalist design showcasing the material's capabilities
- Enhanced durability and reduced maintenance requirements
- Designed to harmonize with the surrounding landscape and historical bridge (Toutlemonde et al., 2009)

Design and Engineering:

- Designed to meet French bridge design standards and UNESCO site requirements (Resplendino, 2012)
- Utilizes post-tensioning for improved structural performance
- Incorporates stainless steel reinforcement for additional corrosion resistance (Toutlemonde et al., 2009)
- Design life expectancy of over 100 years with minimal maintenance

Construction Challenges:

- Limited access to the site required careful planning and execution (Toutlemonde et al., 2009)
- Precise geometry control was necessary to achieve the desired aesthetic and structural performance (Resplendino, 2012)

Awards and Recognition:

- Received the 2009 FIB Award for Outstanding Concrete Structures in the "Buildings" category (Toutlemonde et al., 2009)

Cost:

- Total cost: approximately 720,000 euros (2008 value) (Resplendino, 2012)

2.7 GÄRTNERPLATZ BRIDGE, GERMANY



Figure 18 Gärtnerplatz Bridge

Material Properties:

- Constructed using ultra-high performance fiber-reinforced concrete (UHPFRC) (Fehling et al., 2014)
- UHPFRC provides high compressive strength (>150 MPa), high tensile strength, and excellent

durability (Schmidt et al., 2012)

- Allows for a lightweight, slender, and innovative design

Purpose:

- Serves as a pedestrian and cyclist bridge over the Fulda River in Kassel, Germany (Fehling et al., 2014)
- Connects the Karlsaue park with the city center, improving urban mobility
- Demonstrates the potential of UHPFRC in bridge engineering in Germany (Schmidt et al., 2012)

Construction:

- Completed in 2007
- One of the early applications of UHPFRC for bridge construction in Germany
- Construction process:

- Prefabrication of UHPFRC segments off-site
- Transportation of segments to the construction site
- Assembly and post-tensioning of segments on-site (Fehling et al., 2014)
- Total length: 133.2 meters (437 feet)
- Width: 5 meters (16.4 feet)
- Deck thickness: varies from 0.65 meters (2.13 feet) at supports to 0.25 meters (0.82 feet) at midspan (Schmidt et al., 2012)

Cost:

- Total cost: approximately 1.4 million euros (2007 value) (Schmidt et al., 2012)

Key Features:

- Innovative Six-span continuous beam design (Fehling et al., 2014)
- Slender and aesthetically pleasing structure
- Minimalist design showcasing the material's capabilities
- Enhanced durability and reduced maintenance requirements

Design and Engineering:

- Utilizes post-tensioning for improved structural performance
- Incorporates passive reinforcement for local force transfer and crack control (Fehling et al., 2014)
- Design life expectancy of over 100 years with minimal maintenance

Construction Challenges:

- Precise geometry control was necessary to achieve the desired aesthetic and structural performance
- Special attention was required for the UHPFRC mixing and casting process to ensure uniform fiber distribution (Fehling et al., 2014)

2.8 MUCEM FOOTBRIDGE, FRANCE



Figure 19 Mucem Footbridge

Material Properties

- Constructed in 2013, using Ultra High-Performance Fiber-Reinforced Concrete (UHPFRC), specifically Lafarge's Ductal brand.
- Exhibits high compressive strength (up to 200 MPa), suitable for load-bearing applications in slender structures.
- Features low porosity, enhancing

resistance to corrosion, crucial for the coastal environment (Kaltenbach, 2013; EUMiesAward, 2015).

- Designed to sustain minimal maintenance and extended lifespan due to material durability (Freyssinet, 2013).

Cost

- Total project construction cost estimated at 3,200 EUR/m², reflecting the high-performance material and sustainable approach.
- The estimated construction cost for the MuCEM Footbridge would be around €800,000 based on these dimensions and per square meter cost.
- The UHPFRC's durability reduces long-term maintenance costs, balancing the initial investment (EUMiesAward, 2015).

Purpose

- Serves as a pedestrian link between the MuCEM museum and the historic Fort Saint-Jean.
- Enhances public access while visually integrating the historic and modern sections of Marseille's waterfront.
- Aligns with MuCEM's sustainable design goals by utilizing durable, long-lasting materials in public infrastructure (Freyssinet, 2013; Kaltenbach, 2013).

Construction

- Total length: 135 meters (443 feet), main span 76.5 meters.

- Width: 1.8 meters (5.9 feet), depth: 1.5 meters.
- Built from 15 prefabricated UHPFRC segments, each weighing around 10 tons, for controlled production and quality.
- Post-tensioned on-site assembly provided structural integrity while accommodating the bridge's slender profile.
- Advanced vibration control through mass dampers was integrated to ensure comfort for pedestrians despite the bridge's span-to-rise ratio (DETAIL, 2013; RILEM, 2013).
- No visible supports, creating an illusion of a floating walkway

2.9 BOURG-LÈS-VALENCE BRIDGE, FRANCE



Figure 20 Bourg-Lès-Valence Footbridge

The UHPFRC road bridge at Bourg-lès-Valence, constructed in 2001, was a pioneering project that showcased the potential of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) in bridge construction.

Material Properties

The UHPFRC used in the Bourg-lès-Valence bridge exhibited exceptional mechanical

properties:

- Compressive strength: Approximately 180-200 MPa (El-Tawil et al., 2022)
- Tensile strength: Up to 8.8 MPa (Puri, 2023)
- Flexural strength: Around 30 MPa (Puri, 2023)
- Elastic modulus: 45-50 GPa (Brühwiler, 2021)

The material's high strength and durability were achieved through a combination of:

- Low water-to-binder ratio (0.15-0.25)
- High particle packing density (0.825-0.855)
- Inclusion of steel fibers ($\geq 2\%$ by volume)
- Use of silica fume and superplasticizers (El-Tawil et al., 2022)

Purpose and Construction

The Bourg-lès-Valence bridge was the first UHPC road bridge in the world, designed to demonstrate the material's potential in vehicular bridge applications (Toutlemonde et al., 2013). Its construction served as a proof of concept for using UHPFRC in load-bearing structures exposed to traffic and environmental conditions.

Construction Process

1. Prefabrication: Five π -shaped precast UHPFRC beams were manufactured off-site (Puri, 2023).
2. Assembly: The precast beams were transported to the site and assembled.
3. In-situ joints: The connections between the precast elements were made using cast-in-place UHPFRC with internal reinforcements (Puri, 2023).
4. Prestressing: All π -shaped beams were prestressed without transverse passive reinforcement (Puri, 2023).

Bridge Specifications

- Total length: 42 m. The bridge consists of two isolated spans, each approximately 20 meters long (Puri, 2023).
- Cross-section: Composed of five spliced pretensioned beams resembling a double-tee with additional bottom flanges, similar to a pi-shaped section (Toutlemonde et al., 2013).

Construction Cost

The construction cost of the bridge was approximately \$1.7 million.

However, the use of UHPFRC can lead to long-term cost savings through:

- Reduced material volume and structural self-weight (Brühwiler, 2021).
- Improved durability, resulting in lower maintenance costs over the structure's lifetime (Brühwiler, 2021).
- Faster construction times due to prefabrication and simplified on-site assembly (El-Tawil et al., 2022).

The Bourg-lès-Valence bridge has served as an important case study for the long-term performance of UHPFRC in bridge applications, providing valuable data on durability and structural behavior over time (Toutlemonde et al., 2013).

2.10 GLENMORE/LEGSBY BRIDGE, CALGARY, ALBERTA, CANADA



Figure 21 Glenmore/Legsby Bridge

- Completed in 2006, is a notable example of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) application in bridge construction.

Bridge Specifications

- Location: Spans Glenmore Trail at Legsby Road in southwest Calgary
- Total Length: 53

meters (174 feet)

- Clear Span: 52.9 meters
- Traffic: Crosses 8 lanes of traffic (Ghoneim & Brown, 2012)

Structural Design

The bridge employs a unique cantilever-type design with three main components:

1. UHPC Precast Drop-in Girder:
 - Length: 33.6 meters (110 feet)
 - Shape: T-section with an arch
 - Depth: 1.1 meters (3.6 feet) at mid-span, 1.45 meters at ends
 - Deck width: 3.6 meters (12 feet)
2. Cast-in-Place High Performance Concrete (HPC) Cantilever Girders:
 - Two cantilever girders, each 9.65 meters long
 - Post-tensioned design
3. Main Piers: Two piers supporting the cantilever girders (Ghoneim & Brown, 2012)

Material Properties and Construction

The UHPC used in the precast girder exhibits exceptional characteristics:

- Compressive strength: Over 150 MPa
- Reinforcement: 13 mm (0.5") steel fibers

- Post-tensioning: 42 – 15 mm (0.6") strands
- Volume: Required 40 m³ (52 yd³) of UHPC material (Ghoneim & Brown, 2012)
- Total project cost: approximately CAD 1.2 million (USD 900,000)

Construction Process

1. Precast Girder Fabrication:
 - Cast in a steel mould
 - UHPC mixed in a high-shear plant mixer
 - 16-hour batch cycle using low heat/slow setting cement and admixtures
 - Temperature-controlled setting and curing process
2. On-Site Assembly:
 - Precast UHPC girder installed as a drop-in span
 - Cast-in-place HPC cantilever girders constructed on-site
 - Post-tensioning applied to both cantilever and drop-in girders (Ghoneim & Brown, 2012)

Design Challenges and Solutions

1. Limited Construction Space: The cantilever design minimized the need for extensive on-site work.
2. Traffic Disruption: The design allowed for minimal closure of the busy roadway.
3. Structural Stability: The T-section's instability was addressed using UHPC strength and additional glass fiber reinforcement.
4. Span-to-Depth Ratio: Achieved an aggressive ratio of 48.1, showcasing UHPC's structural efficiency (Ghoneim & Brown, 2012)

Unique Features

1. Educational Art Components: Incorporated structural-themed words by artist Adam Kuby, offering an educational aspect to the bridge (DIALOG, 2019).
2. Largest Monolithic UHPC Pour: At the time of construction, it was the world's largest single UHPC pour.
3. Minimal Maintenance: The use of UHPC aims to reduce long-term maintenance requirements.
4. Aesthetic Design: The bridge's unique shape and material use contribute to its visual appeal (DIALOG, 2019).

2.11 SOLE RIVER BRIDGE, INDIA



Figure 22 Sole River Bridge

Purpose and Location

- India's first major bridge constructed using UHPFRC technology, was completed in 2021.
- The bridge is part of a larger project for the "Rehabilitation and Up-gradation to two/four lane with paved shoulder configuration of NH 65-Jahirabad – Virur – (NH50) – Bhalki

(NH52) Nilanga – Nitur – Latur in the state of Maharashtra" (Unique UHPC Infra, 2022).

It serves as a major bridge on the NH-752K (Latur-Nilanga-Aurad Section).

Material Properties

- Compressive strength: 155 MPa.
- Tensile strength: 10 MPa, whereas Flexural strength: 30 MPa.
- Durability: 100 times more durable in terms of impermeability, water and carbon resistance (Singh, n.d.)
- Fracture energy: 100 times higher, providing improved impact resistance and ductility (Singh, n.d.)
- Weight: 30 to 35% lighter than conventional structures (Singh, n.d.)

Construction

- Total length: 112 m
- Overall width: 16 m
- Design life: 150 years
- The construction process likely involved fewer spans than a conventional bridge. The original proposal was for 5 spans, but the UHPFRC design allowed for only 2 spans, reducing construction time and minimizing obstruction to river flow (Singh, n.d.).

Project Cost

359.00 lacs (approximately 3.59 crore Indian Rupees), corresponding to \$425,000. (Unique UHPC Infra, 2022).

2.12 SHEPHERD CREEK BRIDGE, AUSTRALIA



Figure 23 Shepherd Creek Bridge

Purpose and Location:

Constructed in New South Wales, Australia in 2004-2005.

- One of the world's first road bridges using Ultra-High Performance Fiber Reinforced Concrete (UHPFRC).
- The bridge was built to replace an existing obsolete timber bridge. It was designed and constructed to provide improved durability, strength, and reduced maintenance costs

compared to conventional bridges (Perry, 2005).

Bridge Specifications

- Span: 15m (49 feet, 2 inches) single span with a 16° skew (Russell & Graybeal, 2013)
- Width: 21m (69 feet) wide, accommodating four traffic lanes and a footway, Depth: 0.65 meters (Perry, 2005)

Material Properties

- Compressive strength: Up to 206 MPa (30,000 psi) (Perry, 2005)
- Flexural strength: Up to 41 MPa (6,000 psi) (Perry, 2005)
- No passive reinforcing steel in the girders (Perry, 2005)

Structural Components

- Superstructure: 16 precast pre-tensioned UHPFRC I-beams
- Deck: 170mm thick in-situ reinforced concrete deck slab
- Thin permanent precast UHPFRC formwork panels (25mm thick, 1.1m wide, 2.4m long) spanning between beams (Russell & Graybeal, 2013)

Construction Process

- Precast UHPFRC I-beams were manufactured off-site.
- Beams were installed on-site. Precast UHPFRC formwork panels were placed between beams.
- In-situ reinforced concrete deck was cast on top of the formwork panels. (Russell & Graybeal, 2013)

- Estimated at approximately AUD 1.2 million, around 1 million USD.

Advantages

Lightweight design: UHPFRC beams weighed 4.2 tonnes over 15.1m length, compared to about 9 tonnes for conventional prestressed beams (Russell & Graybeal, 2013).

Improved durability: UHPFRC offers superior resistance to chloride ingress and other environmental factors (Perry, 2005).

Reduced maintenance: The use of UHPFRC is expected to result in lower long-term maintenance costs (Perry, 2005).

Performance Evaluation

The bridge was load-tested upon completion of the first stage (comprising the first two lanes) and again one year later. The tests confirmed that the bridge's behavior conformed to the design, with the deflection of the most highly loaded girder being only 5mm compared to the theoretical estimate of 6mm (Russell & Graybeal, 2013).

2.13 AIGUILLON RAILWAY BRIDGE, SWITZERLAND



Figure 24 Aiguillon Railway Bridge

One of the first railway bridges constructed entirely using Ultra-High Performance Fiber-Reinforced Cementitious Composite (UHPFRC).

Purpose and Location

- The bridge was built in 2021 in a remote mountainous area of Switzerland, designed for a narrow-gauge railway track and two pedestrian walkways (Trinh et al., 2022a).

- It serves as a demonstration of

UHPFRC's potential in infrastructure projects, particularly for railway applications (Gruner AG, 2022).

Bridge Specifications

- Span: 6.6 meters single span
- Width: 5.4 - 5.7 meters

- Cross-section: U-shaped trough for ballast
- Deck thickness: 60 mm
- Transverse beams: 180 mm deep, spaced every 650 mm
(Trinh et al., 2022a; Trinh et al., 2022b)

Material Properties

- High resistance in both tension and compression
- Waterproof and crack-free under service conditions
- Improved durability compared to conventional reinforced concrete
(Trinh et al., 2022a)

Construction Process

1. Two prefabricated UHPFRC elements with steel reinforcement bars were manufactured off-site.
2. The prefabricated elements were transported to the construction site.
3. On-site assembly was performed using a longitudinal cast-in-place UHPFRC keying joint.
(Trinh et al., 2022a; Gruner AG, 2022)

Experimental Validation

- Static testing of a transverse beam composed of two precast elements and the keying joint
- Digital-Image-Correlation measurements to analyze cracking patterns
Results showed post-peak ductile behavior and elastic behavior under service loads, validating the keying joint concept.
(Trinh et al., 2022a)

Advantages

1. Improved durability: UHPFRC structures show better durability performance than traditional reinforced concrete structures.
2. Reduced maintenance: Due to its mechanical properties, UHPFRC structures require less maintenance.
3. Slender design: UHPFRC allows for relatively slender structural elements.
(Trinh et al., 2022a)

2.14 BATU 6 BRIDGE, GERIK-PERAK, MALAYSIA



Figure 25 Batu 6 Bridge

Purpose and Location

- The bridge was constructed over the Perak River to provide the city of Gerik with its first road access across the river, improving transportation infrastructure and connecting isolated communities (PCI, 2016).

- The Batu 6 Bridge in Gerik, Perak, Malaysia was completed in February 2015 (PCI, 2016).

Bridge Specifications

- Span: Single span of 100 meters (328 feet)
- Structure: Concrete box-girder bridge
- Total weight: 850 tons
- Components: 40 UHPC pieces, ranging from 18 to 22 tons each (PCI, 2016)

Material Properties

- Compressive strength: 190 MPa
- Tensile strength: 10 MPa
- High durability under extreme weather conditions
- Abrasion resistance nearly twice as high as normal concrete (Pinatih, n.d.)

Construction Process

1. Prefabrication: UHPC segments were precast off-site.
2. Assembly: A 600-ton crawler crane with a 354-ft boom length was used for positioning most segments.

3. Rapid assembly: All 40 segments were assembled in just 18 days, including 2 rest days.
(PCI, 2016)

Construction Cost

The project cost was \$1,575,000 (PCI, 2016).

Advantages

1. Lightweight design: Eliminated the need for major floating structures or temporary post-tensioning during assembly.
2. Accelerated construction: The use of precast UHPC elements significantly reduced construction time.
3. Improved durability: UHPC provides superior durability, crucial for the longevity of the infrastructure.
4. Low maintenance: The bridge requires negligible maintenance compared to conventional concrete designs.
(PCI, 2016; Pinatih, n.d.)

2.15 KAMPUNG BAHARU-KAMPUNG TELUK BRIDGE, MALAYSIA



Figure 26 Kampung Baharu-Kampung Teluk Bridge

Purpose and Specifications

- The bridge was constructed in 2016, to improve transportation infrastructure, connecting isolated communities (Pinatih, n.d.).
- It currently holds the record as the world's longest multiple-

span road bridge superstructure constructed using UHPC precast girders (Pinatih, n.d.).

- Total length: 420 meters
- Span configuration: Ten equal spans
- Superstructure: Consists of 20 UHPC precast U-beams

Material Properties

- Compressive strength: about 200 MPa
- Tensile strength: 1,400 psi or 10 MPa
- High durability under extreme weather conditions
- Abrasion resistance nearly twice as high as normal concrete (Pinatih, n.d.)

Construction Process

1. Project costed RM 52 million, around 12.5 million USD (The Sun, et al., 2015)
2. No vertical shear reinforcement in the U-beams
3. Only conventional reinforcement used is:
 - Anti-bursting reinforcement at the anchorage zones
 - Reinforcement for transferring longitudinal shear at the connection of flanges and in-situ deck slab (Pinatih, n.d.)

Advantages

1. Cost-effective: Immediate cost saving of more than 10% compared to conventional methods
2. Low maintenance, Improved durability
3. Accelerated construction: Use of precast elements speeds up the process (Pinatih, n.d.; Voo & Foster, 2017)

2.16 LANGAT RIVER BRIDGE, MALAYSIA



Figure 27 Langat River Bridge

Purpose and Specifications

- The bridge was constructed in 2023, to serve a 1000-acre industrial park and the surrounding community (PCI, 2024).
- It spans more than 1600 ft (approximately

488 meters) and consists of 15 spans, including 2 abutments and 14 piers, with 1 span crossing the Langat River (PCI, 2024).

Material Properties

The UHPC used in this project exhibits the following characteristics:

- Compressive strength: 190 - 210 MPa
- Tensile strength: 10 - 15 MPa
- High durability under extreme weather conditions
- Extended service life (expected to be in service for several hundred years)
- Minimized maintenance requirements (CPI Worldwide, 2024)

Construction Process

1. Precast-prestressed UHPC U-girders were manufactured off-site.
2. Each U-girder required 220 yd³ of concrete.
3. The U-girders consist of two 6-inch thick webs and a 9-inch thick bottom flange.
4. Post-tensioning was used with seven bonded tendons in the bottom flange (37-inch-diameter strands) and one 13-strand tendon in each top bulb.
5. Nine record-setting U-girders measuring 344.5 ft in length and weighing 440 tons were installed.
6. Despite the 44-degree skew of the bridge, the team was able to erect one precast UHPC girder in less than two hours using a single launching operation.
7. A conventional concrete deck was cast in place.
(PCI, 2024; CPI Worldwide, 2024)

Construction Cost

The total project cost was \$20 million, with \$5 million (25%) dedicated to the precast UHPC components (PCI, 2024).

Advantages

1. Cost-effective: The precast solution was 30% less expensive than the originally planned steel design.
2. Accelerated construction: Faster installation compared to traditional methods.
3. Improved durability: UHPC offers superior resistance to environmental factors.
4. Sustainability: The UHPC composite bridge exhibits significantly better sustainability metrics, with less than 60% of the embodied carbon compared to an alternative steel design.
5. Local sourcing: Avoided supply-chain issues by using locally produced raw materials.
(PCI, 2024; CPI Worldwide, 2024)

2.17 MARTINET FOOTBRIDGE, SWITZERLAND



Figure 28 Martinet Footbridge

Material Properties

- Completed in 2015
- Compressive strength reaching 180 MPa and tensile strength up to 16 MPa (Brühwiler, 2020)
- Young's modulus between 45-50 GPa with strain-hardening behavior
- Extremely low permeability,

approximately 30 times lower than traditional concrete (Denarié et al., 2005)

Structural Design

- Total span length of 15.3m with an asymmetric U-shaped cross-section
- Two main girders: one "organic" and one with a full web, depth: 1.1 meters.
- Nine precast segments connected using post-tensioned cables
- Support system consisting of two reinforced-concrete abutment walls

Construction Process

- Precast segmental construction methodology
- Post-tensioning technique for segment connection
- The construction of the Martinet Footbridge likely cost around \$125,000.
- Integration with existing urban infrastructure in Lausanne (Emch+Berger SA Lausanne, 2015)
- Its construction cost was approximately \$3,200 per square meter of walkway surface. This figure was about 10% higher than traditional reinforced concrete (RC) alternatives. However, the UHPFRC design offered significantly reduced maintenance costs over the bridge's lifecycle due to its crack-free performance and superior durability under Swiss standards.

Project Purpose

The Martinet Footbridge serves as a crucial component of Lausanne's soft mobility infrastructure, representing Switzerland's first UHPFRC footbridge. The material choice was specifically made to achieve:

- Discrete integration into the urban environment
- Creation of an aesthetically pleasing structure
- Demonstration of UHPFRC's potential in slender structural design

Performance Benefits

- Crack-free performance under service conditions due to strain-hardening behavior
- Enhanced durability through waterproof properties
- Significant structural efficiency compared to traditional materials (Denarié and Brühwiler, 2015)

THE LEGACY AND FORESEEABLE FUTURE OF UHPFRC IN BRIDGE ENGINEERING

The 17 bridges discussed in this section represent more than just individual structures; they embody a paradigm shift in bridge engineering. These projects, spanning various years, locations, and design philosophies, collectively demonstrate the versatility and potential of UHPFRC in the construction world. From the pioneering early applications to the more recent, sophisticated designs, each bridge has contributed to the evolving narrative of UHPFRC in construction.

Lessons and Best Practices Learned: Through these projects, the industry has gained invaluable insights into the optimal use of UHPFRC. Engineers and designers have refined their approaches, learning to harness the material's exceptional strength, durability, and aesthetic possibilities. The successes and challenges encountered in these projects have paved the way for more efficient, cost-effective, and innovative applications of UHPFRC in future bridge constructions.

In essence, these UHPFRC bridges represent a new chapter in bridge construction, blending functionality with aesthetics and sustainability. They stand as enduring symbols of progress in civil engineering, inspiring future innovations and setting the stage for even more ambitious applications of UHPFRC in the years to come.

3. COMPARATIVE ANALYSIS: FUTURE PERSPECTIVES OF UHPC

Now, as we delve into the comparative analysis of the UHPFRC bridges discussed in the previous section, it becomes evident that these structures not only represent technological marvels but also offer valuable insights into the evolution of ultra-high-performance fiber-reinforced concrete in bridge engineering. By examining various parameters such as project costs, cost per square meter, material strength, and their changes over time, we can uncover trends and patterns that illuminate the progress and challenges in UHPFRC bridge construction. This analysis will provide a deeper understanding of the economic feasibility, technological advancements, and practical applications of UHPFRC in the bridge industry, offering a comprehensive view of its impact and potential for future developments.

3.1 ANALYSIS FROM ECONOMIC PERSPECTIVE

Let's start this section with the economic analysis of the case studies in section 2. One of the main concerning points of adaptation of UHPFRC always revolves around the cost of the project, which largely is influenced by the UHPFRC components. Following is a detailed comparison of cost per metre sq of the various bridges over the years:

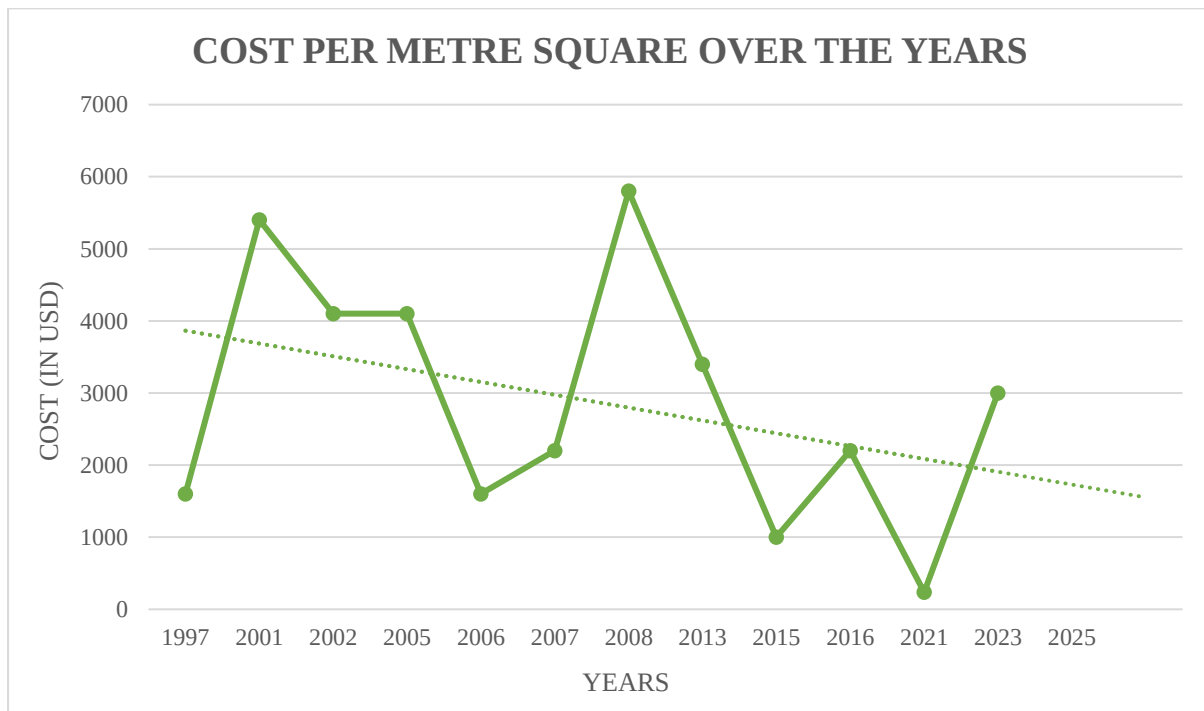


Figure 29 Trend chart for cost per m2

Cost Per Square Meter Analysis in fig 29 suggests:

- Started at around \$1,700 in 1997
- Sharp increase to \$5,400 in 2001
- Major peak in 2008 reaching \$5,800
- Significant decline post-2008
- Lowest point in 2021 at approximately \$300
- Recent increase to \$3,000 in 2023

Below, is a detailed comparison of cost per metre cube of the various bridges over the years:

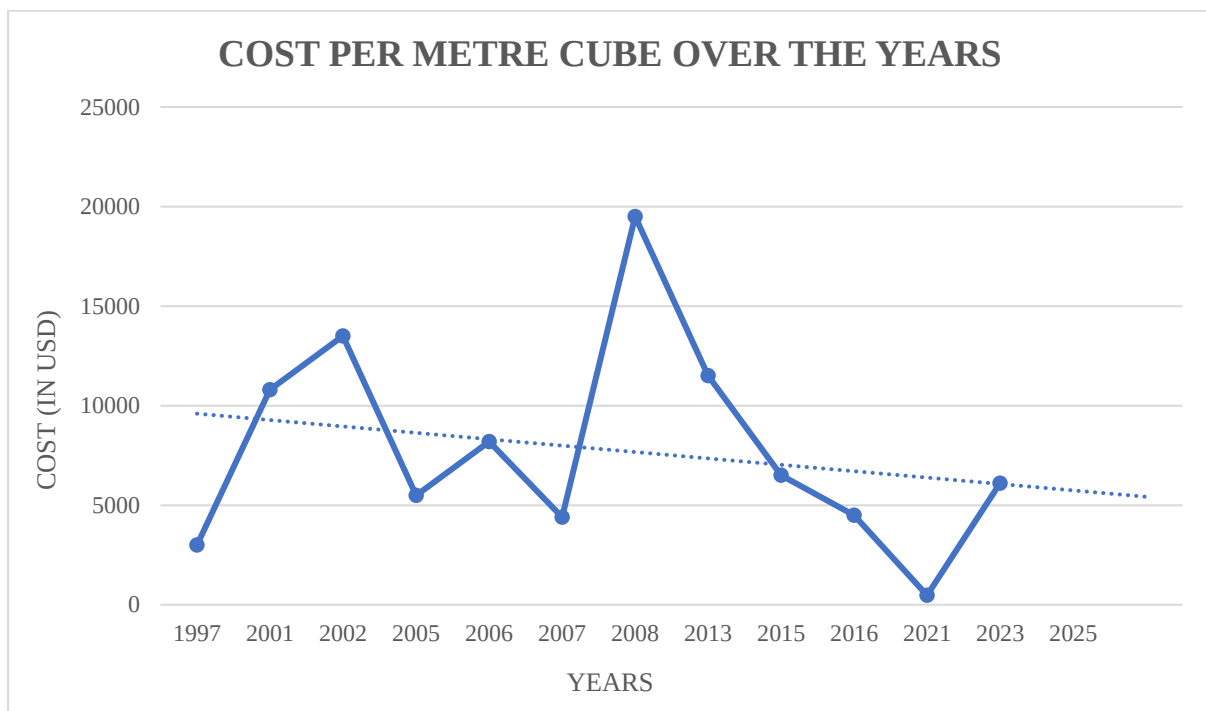


Figure 30 Trend chart for cost per m3

Cost Per Cubic Meter Analysis in fig 30 suggests:

- Started at \$3,000 in 1997
- Increased to \$11,000 in 2001
- Dramatic peak in 2008 at \$19,500
- Sharp decline post-2008
- Lowest point in 2021 at around \$500
- Recent increase to \$6,000 in 2023

From these explanatory trend charts, we can deduce some important points:

Pattern Correlation

- Both metrics show similar patterns, indicating consistent relationship between volume and area costs
- Major cost spikes coincide with global economic events, particularly the 2008 financial crisis
- Recent years show increased cost stability

Technology Impact

- Overall downward trend suggests improving technology and manufacturing processes
- Cost fluctuations reflect industry maturation and adoption rates
- Lower costs in recent years indicate more efficient production methods

The "cost of a linear meter" of a bridge refers to the total construction cost of the bridge divided by its length in meters. This provides a standardized way to compare the cost-effectiveness of different bridge designs and lengths. Below, is a detailed comparison of total length of the bridges to total cost over the years:

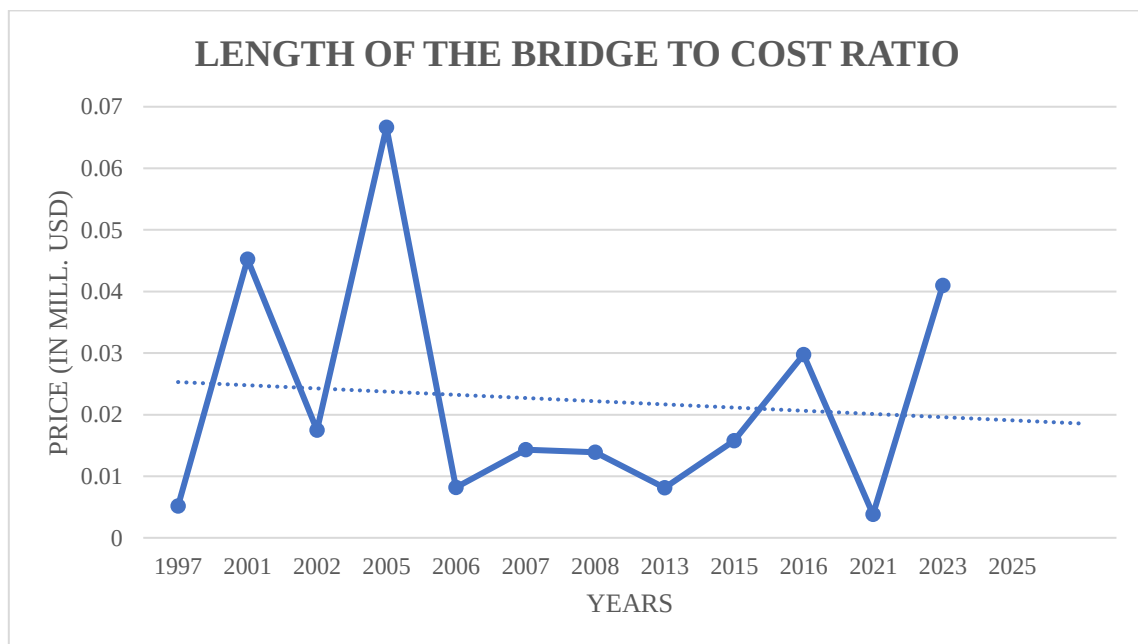


Figure 31 Trend chart for total Length to Cost ratio

Total Length to Cost Analysis in fig 31 suggests:

Peak Values

- The highest length-to-cost ratio occurred in 2005 at approximately 0.065 million USD per linear meter
- The second highest peak was in 2001 at about 0.045 million USD per linear meter

- A recent peak appears in 2023 at roughly 0.04 million USD per linear meter

Pattern Analysis

- There's a dotted trend line showing a slight downward trend over the years, suggesting gradual improvement in cost efficiency
- The cost ratio shows cyclical behavior with peaks followed by sharp declines
- After 2005's peak, the values stabilized between 2006-2015 at around 0.01-0.015 million USD
- Recent years (2015-2023) show increased volatility in the cost ratio, but it may have been because of other factors affecting the total cost of the project.
- Despite fluctuations, the average cost ratio remains relatively stable around 0.02-0.03 million USD per linear meter

3.2 ANALYSIS FROM STRENGTH PERSPECTIVE

The progression in compressive strength is a key indicator of UHPFRC's advancing capabilities and its potential for revolutionizing structural design. Below is a detailed examination of how the compressive strength of UHPFRC has developed and maintained over time, reflecting the continuous innovation in concrete technology:

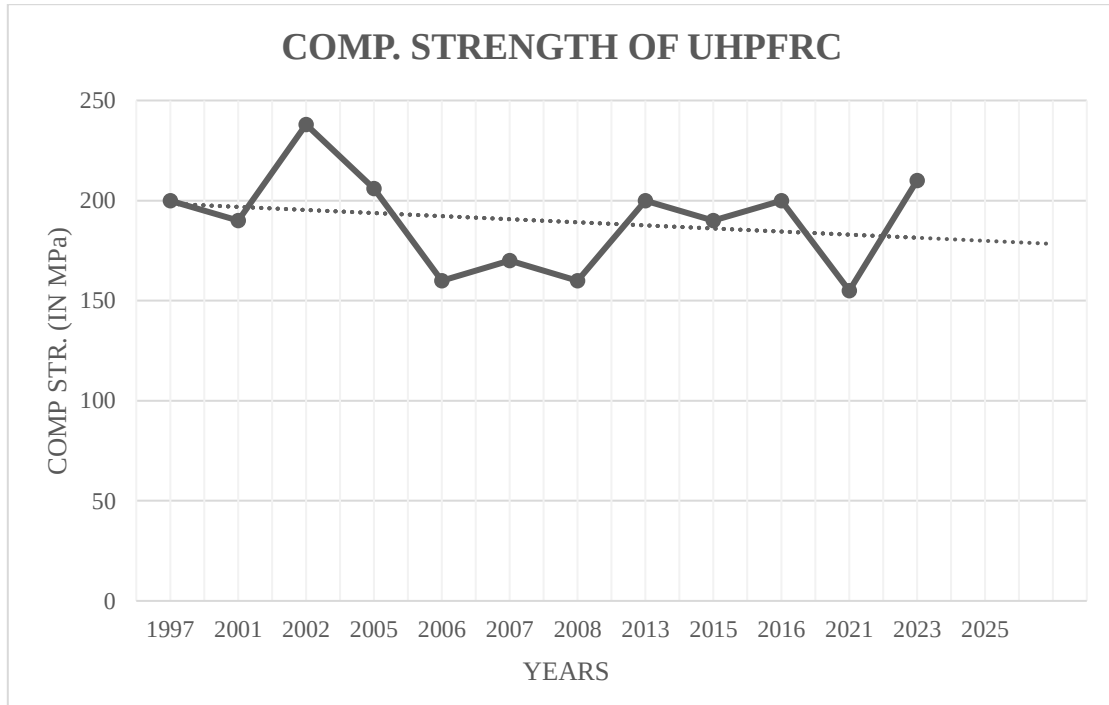


Figure 32 Trend chart for overall strength of UHPFRC

The chart depicting the compressive strength of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) over the years provides valuable insights into the material's performance in bridge applications:

Historical Performance

- The compressive strength of UHPFRC has indeed remained consistently high, ranging between 150-230 MPa from 1997 to 2023.
- The average compressive strength over this period is approximately 185.83 MPa, which is significantly higher than conventional concrete.
- This suggests that UHPFRC has maintained its ultra-high performance characteristics consistently over more than two decades.

Key Observations from the chart in fig 32

1. **Consistency:** The material has consistently delivered ultra-high strength, living up to its name throughout the observed period.
2. **Variability:** There are noticeable fluctuations in strength from year to year, which could be attributed to various factors such as mix design improvements, application-specific requirements, or advancements in testing methods.
3. **Recent Uptick:** After a dip to 160 MPa in 2021, there's a significant increase to 210 MPa in 2023, indicating potential improvements in UHPFRC formulation or production techniques.

3.3 ANALYSIS FROM LENGTH & SPAN PERSPECTIVE

To gain a comprehensive understanding of the evolution of UHPFRC bridges, it's crucial to examine not only their costs but also their lengths over time. Through this, we can discern trends in engineering capabilities, project scopes, and the growing confidence in this innovative material. Below is a detailed comparison of UHPFRC bridge lengths over the years:

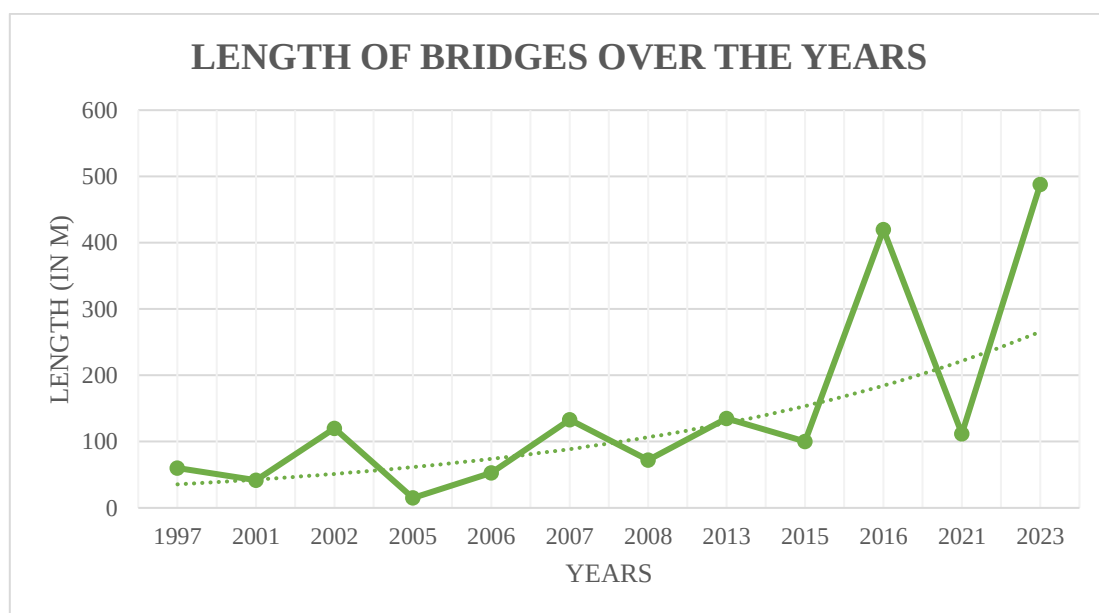


Figure 33 Trend chart for length of UHPFRC bridges over the years

Trend Analysis for the chart in fig 33:

- There is an overall upward trend in span lengths as shown by the dotted trend line
- The trend line increases from approximately 50m in 1997 to 250m in 2023

Pattern Observations

- Three distinct periods are visible:
 - 1997-2005: Relatively stable spans (50-120m)
 - 2006-2015: Moderate increase in spans (100-150m)
 - 2016-2023: Dramatic increases and variations (100-480m)
- Initial spans in 1997 were modest (approximately 60m)
- Technology advancement is evident from the increasing span capabilities

Having explored the fundamental properties and advantages of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC), we now turn our attention to a critical aspect of bridge design: the span-to-depth ratio. This parameter is particularly significant for UHPFRC bridges, as it showcases the material's exceptional capabilities in creating more efficient and aesthetically pleasing structures. The following chart is a detailed analysis of how it varied over the years:

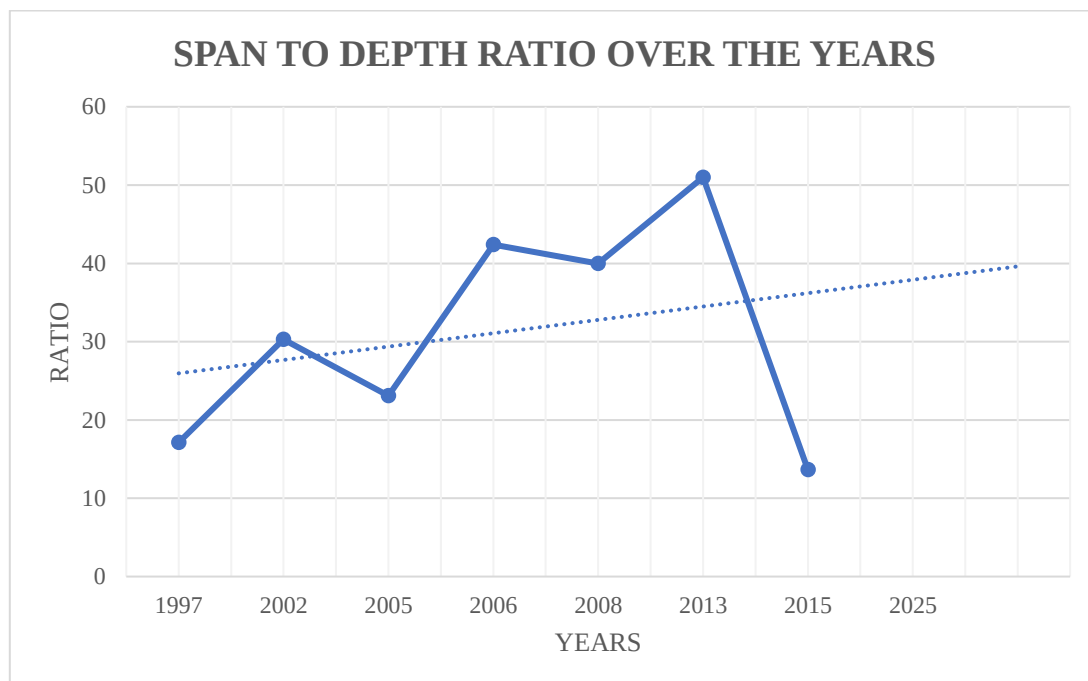


Figure 34 Trend chart for span to depth ratio for UHPFRC bridges

Key Observations that can be taken from fig34:

1. Overall upward trend from 1997 (17.5) to 2013 (51), shown by dotted trendline
2. Sharp decline after 2013, dropping to approximately 14 in 2015, because of short span bridge construction
3. Notable peak in 2013 with ratio reaching 51
4. Secondary peak in 2006 at ratio ~42

Technical Implications:

- Higher ratios (40-50) indicate more efficient material use and slender designs
- 2006-2013 period shows mature UHPFRC technology with optimal structural efficiency
- Initial low ratios (1997) reflect conservative early designs
- Projected trend (dotted line) suggests future ratios around 40

Therefore, if we sum up the length and span analysis, we can conclude the following:

1. Technical Evolution

- Span-to-depth ratio increased from 17 (1997) to peak of 51 (2013)
- Bridge lengths grew from 50m to 480m (1997-2023)
- Material efficiency improved by 200% over 26 years

2. Design Patterns

- Post-2013: Trade-off between length and depth ratio
- 2015-2023: More experimental designs emerge
- Recent focus on achieving longer spans

3. Construction Capabilities

- Consistent progress in maximum bridge lengths
- Greater design flexibility (varying ratios from 14-51)
- Improved structural efficiency
- Better material optimization

The overall trends suggest that UHPFRC bridge construction is moving from experimental phases to mainstream implementation, particularly in terms of bridge length capabilities.

4. CONCLUSIONS

The analysis of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) bridges over the past two decades reveals a remarkable evolution in terms of economic viability, strength performance, and structural efficiency. This material has transitioned from an experimental technology to a mature solution for modern bridge construction, demonstrating significant advancements across all key metrics.

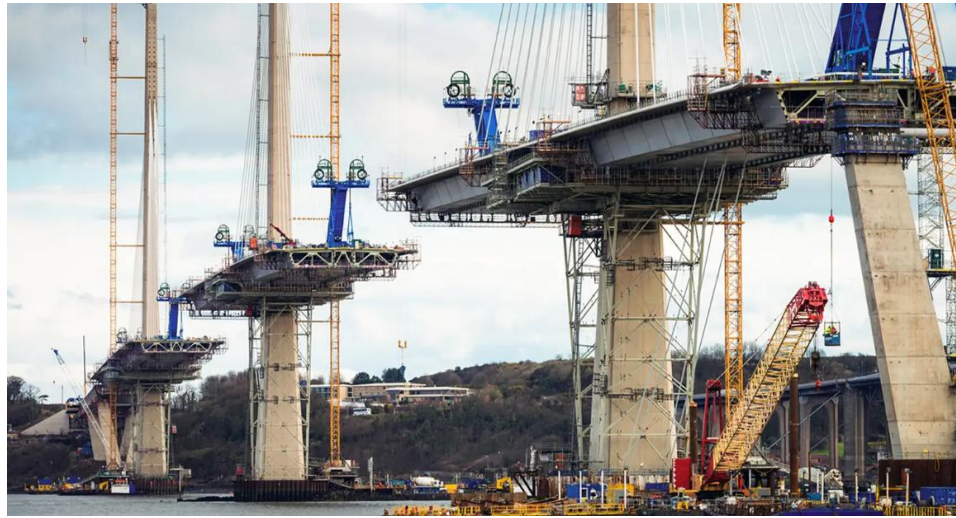


Figure 35 UHPFRC Bridge Construction

A. Economic Viability and Cost Trends, suggests:

- Increasing cost-effectiveness of UHPFRC
- Greater potential for widespread adoption
- More competitive pricing compared to traditional materials
- Potential for increased use in infrastructure projects

From an economic standpoint, UHPFRC has shown a clear trajectory of cost optimization. Initial high costs, peaking during the 2008 financial crisis at \$5,800 per square meter and \$19,500 per cubic meter, have since stabilized and reduced significantly. By 2023, costs settled at \$3,000 per square meter and \$6,000 per cubic meter, indicating improved production efficiency and broader industry adoption.

This trend suggests that UHPFRC has become increasingly cost-effective for large-scale infrastructure projects. The forecasts indicate that UHPFRC is becoming more economically viable for bridge construction, which could lead to its increased adoption in future infrastructure projects.

B. Strength Consistency and Technological Advancements:

1. **Reliability:** The consistent ultra-high strength over the years demonstrates UHPFRC's reliability for long-term bridge applications.
2. **Design Flexibility:** With compressive strengths consistently above 150 MPa, engineers can design more efficient and durable bridge structures.

3. **Innovation Potential:** The recent uptick in strength (2023) suggests there's still room for improvement and innovation in UHPFRC technology.

Here, UHPFRC has proven to be a remarkably consistent and high-performing material for bridge applications over the past two decades. While the overall trend shows a slight decline, demonstrates ongoing innovations in material formulation and mix design, still the material continues to deliver exceptional strength, and recent data points suggest potential for further improvements.

As bridge engineers and materials scientists continue to refine UHPFRC formulations and applications, we may see even higher strengths and more efficient use of this advanced material in future bridge designs.

C. Structural Efficiency: Span Lengths and Ratios:

Perhaps most impressively, UHPFRC bridges have shown remarkable advancements in structural efficiency.

Span lengths have increased dramatically from around 60m in 1997 to approximately 480m in 2023, showcasing the material's growing capabilities to support longer spans without compromising structural integrity.

The span-to-depth ratios of UHPFRC bridges have also demonstrated superior efficiency compared to conventional concrete designs. While traditional concrete bridges typically achieve ratios of 20:1 to 25:1, UHPFRC bridges have achieved ratios more than double these values, in initial experimentation days from ratios around 20:1 to staggering 50:1, showcasing superior material performance and design optimization. This exceptional efficiency translates to material savings, lighter structures, and reduced environmental impact.

This analysis demonstrates the significant advancement in UHPFRC bridge technology, enabling increasingly longer spans over time, particularly in recent years.

INTEGRATED OBSERVATIONS

1. Technological Maturity:

- The trends across all metrics—costs, strength, spans—indicate that UHPFRC has transitioned from an experimental material to a mature technology with standardized practices.
- The stabilization of span-to-depth ratios and compressive strength highlights a deep understanding of the material's capabilities.

2. Economic Feasibility:

- While initial costs were prohibitive, recent reductions make UHPFRC increasingly accessible for large-scale projects.
- Continued innovation in production methods (e.g., automation) will likely drive further cost reductions.

3. Sustainability Potential:

- Lighter structures enabled by superior span-to-depth ratios reduce material usage and environmental impact.
- Future research into hybrid systems or recycled components could enhance sustainability further.

4. Global Applicability:

- The increasing economic viability and proven performance make UHPFRC suitable for both developed and developing regions.
- Its ability to support long spans with minimal maintenance requirements makes it ideal for critical infrastructure projects like highways and railways.

Future Perspective

UHPFRC bridges represent a paradigm shift in bridge engineering by combining ultra-high strength with exceptional structural efficiency. Moving forward:

- **Research Focus:** Ongoing R&D should explore enhancing ductility and sustainability while maintaining cost-effectiveness. There are evidences that various countries are trying their best to formulate standard codes for themselves. Swiss guidelines, Canadian guidelines are in progress, whereas countries like India is evolving too by testing UHPFRC capabilities and its adaptability for standardization.
- **Broader Adoption:** Wider implementation across diverse geographies will help normalize costs through economies of scale.
- **Innovative Applications:** The material's unique properties open up possibilities for futuristic designs such as modular or prefabricated bridge systems.

In conclusion, UHPFRC bridges exemplify the future of resilient, efficient, and sustainable infrastructure development. With continued innovation and strategic adoption, they are poised to address the growing demands of modern transportation networks while minimizing environmental impact.

5. REFERENCES

- 1) Mahmoud H. Akeed, Shaker Qaidi, Hemn U. Ahmed, "Ultra-high-performance fiber-reinforced concrete. Part II: Hydration and microstructure," *Case Studies in Construction Materials*, 2022.
- 2) Junquan Li, Zemei Wu, Qiang Yuan, Zuhua Zhang, "Durability of ultra-high performance concrete – A review," *Construction and Building Materials*, vol. 255, 2020.
- 3) Pierre Richard, Marcel Cheyrezy, "Composition of reactive powder concretes," *Cem. Concr. Res.*, vol. 25(7), pp. 1501-1511, 1995.
- 4) N. Shafiq, N.M. Azmee, "Ultra-high performance concrete: From fundamental to applications," *Case Studies in Construction Materials*, vol. 9, pp. 10-11, 2018.
- 5) A. Karmacharya, Shih-Ho Chao, "Precast Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC) for Fast and Sustainable Pavement Repair," *MATEC Web of Conferences* 271(5):01004, vol. 5, 2019.
- 6) Bassam A. Tayeh, Ayad S. Aadi, Nahla Hilal, B.H. Abu Bakar, "Properties of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) -A Review Paper," *Conference: International Symposium on Green and Sustainable Technology*, vol. 2157, 2019.
- 7) Yen Lei Voo, Stephen Foster, Chen Cheong Voo, "Ultrahigh-Performance Concrete Segmental Bridge Technology: Toward Sustainable Bridge Construction," *J. Bridg. Eng.*, vol. 20, no. 8, 2014.
- 8) S. Abdal, Walid Mansour, Ibrahim Saad Agwa, Mohammed Salah Nasr , "Application of Ultra-High-Performance Concrete in Bridge," pp. 15-17, 2023.
- 9) P.-C. Aïtcin, "Cements of yesterday and today: Concrete of tomorrow," *Cement and Concrete Research*, vol. 30, no. 9, pp. 1349-1359, 2000.
- 10) B. Middendorf, A. Wetzel, "Influence of silica fume on properties of fresh and hardened ultra-high performance concrete based on alkali-activated slag," *Cem. Concr. Compos.*, vol. 100, pp. 53-59, 2019.
- 11) Vadim Soloviev, Evgenii Matiushin (2023). The Effects of Corrugated Steel Fiber on the Properties of Ultra-High Performance Concretes. *Buildings*, 13(10), 2591.
- 12) Shehab El-Din, Heba A. Mohamed, Mahmoud Abd El Hak Khater and Sayed Ahmed (2016). The effects of steel fibers on the properties of ultra-high performance concrete (UHPC). *International Journal of Engineering Research and Technology*, 5(11), 329-339.
- 13) Yingying Huang, Dewen Kong, Yi Li, Shenghui Zhou (2024). Effect of different shapes of steel fibers and palygorskite-nanofibers on the properties of ultra-high performance concrete. *Scientific Reports*, 14(1), 1-14.
- 14) Jian-Guo Dai, Bo-Tao Huang, Surendra P. Shah (2021). Recent advances in strain-hardening UHPC with synthetic fibers. *Materials*, 5(10), 283.
- 15) Xu Han, Peng Zhang, Yuanxun Zheng, Jinyi Wan, (2021). Effect of PVA fiber on mechanical properties of fly ash-based geopolymer concrete. *De Gruyter*.
- 16) Lixin Tan, Jun Yang, Chuanxi Li, Gaozhan Zhang, Qingjun Ding, Daosheng Sun, Yongyuan Zhang (2023). Effect of Polyoxymethylene Fiber on the Mechanical Properties and Durability of Ultra-High-Performance Concrete. *Materials*, 16(3), 1699.

- 17) Ogi, K., Shinoda, T., & Mizui, M. (2016). Strength in concrete reinforced with recycled CFRP pieces. *Composites Part A: Applied Science and Manufacturing*, 78, 226-235.
- 18) Mastali, M., Dalvand, A., & Sattarifard, A. R. (2016). The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fibre reinforced polymers. *Journal of Cleaner Production*, 124, 312-324.
- 19) Xing Quan Wang, Cheuk Lun Chow & Denvind Lau (2024). Multiscale perspectives for advancing sustainability in fiber reinforced ultra-high performance concrete. *npj Urban Sustainability*, 4(1), 1-17.
- 20) Kromoser, B., Preinstorfer, P., & Kollegger, J. (2019). Building lightweight structures with carbon-fiber-reinforced polymer-reinforced ultra-high-performance concrete: Research approach, construction materials, and conceptual design of three building components. *Structural Concrete*, 20(2), 730-744.
- 21) Nguyen, H., Carvelli, V., Fujii, T., & Okubo, K. (2022). Cement-based mortars reinforced with reclaimed carbon fibres. *Construction and Building Materials*, 315, 125714.
- 22) Maya, L.F., De la Varga, I., & Graybeal, B. (2016). Fiber reinforcement influence on the tensile response of UHPFRC. *First International Interactive Symposium on UHPC*.
- 23) Puri, S.K. (2024). *Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)*. Intercontinental Consultants and Technocrats Private Limited.
- 24) Nikolai Ivanovich Vatin, Mohammad Hematibahar, Tesfaldet Gebre, (2023). Impact of basalt fiber reinforced concrete in protected buildings. *Frontiers in Built Environment*.
- 25) A. Arora, M. Aguayo, F. Kianmofrad, Y. Yao, B. Mobasher and N. Neithalath, (2016). First Principles-Based Design of Economical Ultra-High Performance Concrete. *International Conference on Durability of Concrete Structures*.
- 26) Aïtein, P.C., Lachemi, M., Adeline, R., & Richard, P. (1998). "The Sherbrooke reactive powder concrete footbridge." *Structural Engineering International*, 8(2), 140-144.
- 27) Blais, P.Y., & Couture, M. (1999). "Precast, prestressed pedestrian bridge - World's first reactive powder concrete structure." *PCI Journal*, 44(5), 60-71.
- 28) Charron, J.P., Denarié, E., & Brühwiler, E. (2018). "Twenty years of experience in the development of UHPFRC for structural applications." *Materials and Structures*, 51(3), 1-19.
- 29) Rebentrost, M., & Wight, G. (2008). "Experience and applications of ultra-high performance concrete in Asia." *Proceedings of the Second International Symposium on Ultra High Performance Concrete*, Kassel, Germany.
- 30) Resplendino, J., & Toulemonde, F. (2011). "Designing and Building with UHPFRC: State of the Art and Development." ISTE Ltd. and John Wiley & Sons, Inc.
- 31) Rossi, P. (2005). "Development of new cement composite materials for construction." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 219(1), 67-74.
- 32) Brühwiler, E., & Denarié, E. (2013). Rehabilitation and strengthening of concrete structures using Ultra-High Performance Fibre Reinforced Concrete. *Structural Engineering International*, 23(4), 450-457.

- 33) Denarié, E., & Brühwiler, E. (2006). Structural rehabilitations with Ultra-High Performance Fibre Reinforced Concretes (UHPFRC). *International Journal for Restoration of Buildings and Monuments*, 12(5), 453-467.
- 34) Sparowitz, L., Freytag, B., Reichel, M., & Zimmermann, W. (2011). WILD Bridge - A Sustainable Arch Made of UHPFRC. In *Proceedings of the 3rd Chinese-Croatian Joint Colloquium on Sustainable Arch Bridges* (pp. 45-70). SECON-HDGK.
- 35) Freytag, B., Zimmermann, W., & Reichel, M. (2010). Road Bridge "Wild" - Application of the UHPFRC Precast Segmental Construction Method. In *AFGC Symposium on Ultra High Performance Fibre Reinforced Concrete (UHPFRC)*, Marseille, France.
- 36) Reichel, M., Sparowitz, L., & Freytag, B. (2009). Designing and Building with UHPFRC: State of the Art and Development. In *Proceedings of the International Symposium on Ultra-High Performance Concrete (UHPC)*, Marseille, France.
- 37) Zimmermann, W., Freytag, B., & Reichel, M. (2012). Wild-Bridge Scientific Preparation for Smooth Realisation. In *Proceedings of the IABSE Conference, Innovative Infrastructures*, Cairo, Egypt.
- 38) Reichel, M., Freytag, B., & Zimmermann, W. (2011). Advanced Bridge Monitoring for Structural Analysis of UHPFRC Structures. In *Proceedings of the International Association for Bridge Maintenance and Safety (IABMAS)*, Philadelphia, USA.
- 39) Tanaka, Y., Maekawa, K., Kameyama, Y., Ohtake, A., Musha, H., & Watanabe, N. (2009). The innovation and application of UHPFRC bridges in Japan. *Proceedings of the International Workshop on Ultra High Performance Fibre Reinforced Concrete - Designing and Building with UHPFRC: State of the Art Development*, Marseille, France.
- 40) Dingqiang, Fan & Tian, Wenjing & Dandian, Feng & Jiahao, Cheng & Rui, Yang & Kaiquan, Zhang. (2018). Development and application of ultra-high performance concrete for bridges in Japan. *Proceedings of the 2nd International Symposium on Ultra High Performance Concrete*, Kassel, Germany.
- 41) Resplendino, J., & Toulemonde, F. (2011). *Designing and Building with UHPFRC: State of the Art and Development*. John Wiley & Sons.
- 42) Uchida, Y., Niwa, J., & Tanaka, Y. (2006). Recommendations for design and construction of ultra high strength fiber reinforced concrete structures. *Concrete Journal*, 44(3), 141-151. (in Japanese)
- 43) Kono, K., Musha, H., Kawaguchi, T., Eriguchi, A., Tanaka, S., Kobayashi, T., & Ikeda, M. (2013). "Durability study of the first PC bridge constructed with ultra high strength fiber reinforced concrete in Japan." *RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete*, 239-248.
- 44) Tanaka, S., & Kono, K. (2013). "Applications and Durability of Ultra-High Performance Concrete for Bridges in Japan." *Proceedings of the UHPFRC Symposium*.
- 45) Kawabata, Y., & Fujimoto, T. (2016). "Ultra High Strength Concrete in Public Infrastructure Projects: Case Study of Sakata-Mirai Footbridge." *Japan Concrete Institute Journal*, Vol. 42, Issue 2.
- 46) Eriguchi, A., Kono, K., & Musha, H. (2008). "Design and Performance Evaluation of Sakata-Mirai Footbridge." *Fracture Mechanics of Concrete Structures*, 13-17. PDF Document.

- 47) Behloul, M., & Lee, K. C. (2003). "Ductal® Seonyu footbridge." *Structural concrete*, 4(4), 195-201.
- 48) Behloul, M., Causse, G., & Etienne, D. (2002). "Passerelle en Ductal de Séoul/Ductal footbridge in Seoul." *Proceedings of the 1st fib Congress*, 215-224.
- 49) Bonneau, O., et al. (2013). "Twenty years-long French experience in UHPFRC application and paths opened from the completion of the standards for UHPFRC." *AFGC-International Symposium on Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC)*, 1-10.
- 50) Park, J. S., Kim, Y. J., Cho, J. R., & Pasquier, P. (2003). "Construction of a new Korean footbridge: The Seonyu footbridge." *Structural Engineering International*, 13(2), 108-111.
- 51) Park, V. (2013). "Seonyu Footbridge: Design and Implementation of a UHPFRC Pedestrian Bridge in South Korea." *Proceedings of the International Symposium on Ultra-High Performance Fibre-Reinforced Concrete, RILEM-fib-AFGC*.
- 52) Bierwagen, D., & Abu-Hawash, A. (2005). "Ultra High Performance Concrete Highway Bridge." *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*, Ames, Iowa.
- 53) Phares, B. M., Wipf, T. J., Klaiber, F. W., & Arneson, D. (2006). "Ultra-High Performance Concrete Bridge Demonstration Project." Iowa Department of Transportation, Research Report No. FHWA-IA-06-08.
- 54) Russell, H. G., & Graybeal, B. A. (2013). "Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community." FHWA-HRT-13-060, Federal Highway Administration.
- 55) Wipf, T. J., Phares, B. M., Klaiber, F. W., & Russo, B. (2009). "Construction and Design of a UHPC Bridge." *HPC Bridge Views*, Issue 54, Federal Highway Administration.
- 56) Iowa Department of Transportation. (2008). "Mars Hill Bridge: UHPC Implementation." Technical Brief, Office of Bridges and Structures.
- 57) Resplendino, J. (2012). State of the art of design and construction of UHPFRC structures in France. In *Designing and Building with UHPFRC: State of the Art and Development* (pp. 27-41). John Wiley & Sons.
- 58) Toutlemonde, F., Renaud, J. C., Lauvin, L., Brisard, S., & Resplendino, J. (2009). Local bending tests and punching failure of a ribbed UHPFRC bridge deck. In *Proceedings of the BFUP 2009 International Symposium on Ultra High Performance Fibre-Reinforced Concrete*, Marseille.
- 59) Hajar, Z., Lecoindre, D., Simon, A., & Petitjean, J. (2013). Design and construction of the world first ultra-high performance concrete road bridges. In *Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete*, Marseille, France (pp. 443-452).
- 60) Graybeal, B. A. (2011). Ultra-high performance concrete. (No. FHWA-HRT-11-038). United States. Federal Highway Administration. Office of Infrastructure Research and Development.
- 61) Russell, H. G., & Graybeal, B. A. (2013). Ultra-high performance concrete: A state-of-the-art report for the bridge community. (No. FHWA-HRT-13-060). United States. Federal Highway Administration. Office of Infrastructure Research and Development.
- 62) Gorazd Humar. (2014). *ECCE_Footbridges_book.pdf*

- 63) Fehling, E., Schmidt, M., Walraven, J., Leutbecher, T., & Fröhlich, S. (2014). Ultra-High Performance Concrete UHPC: Fundamentals, Design, Examples. John Wiley & Sons.
- 64) Schmidt, M., Fehling, E., Fröhlich, S., & Thiemicke, J. (2012). Sustainable building with ultra-high performance concrete: Results of the German priority programme 1182 funded by Deutsche Forschungsgemeinschaft (DFG). In Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials (pp. 13-26).
- 65) Grünberg, J., & Ertel, C. (2012). A triaxial fatigue model of ultra-high performance concrete (UHPC). In Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials (pp. 603-610).
- 66) Scheydt, J. C., & Müller, H. S. (2012). Microstructure of ultra high performance concrete (UHPC) and its impact on durability. In Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials (pp. 349-356).
- 67) Stengel, T., & Schießl, P. (2014). Sustainable construction with UHPC - from life cycle inventory data collection to environmental impact assessment. In Proceedings of Hipermat 2014, 4th International Symposium on Ultra-High Performance Concrete and High Performance Construction Materials.
- 68) Kaltenbach, F. (2013). MuCEM in Marseille – Diaphanous and Structural Applications of UHPC. DETAIL Magazine.
- 69) EUMiesAward. (2015). Museum of European and Mediterranean Civilizations - MUCEM. Fundació Mies van der Rohe.
- 70) Freyssinet. (2013). MuCEM Footbridge Construction Overview. Freyssinet Official Website.
- 71) RILEM Proceedings. (2013). UHPFRC Applications in Bridges and Structures: MuCEM Case Study. RILEM Conference.
- 72) Toutlemonde, F., Spasojevic, A., & Torrenti, J. M. (2005). Footbridges in UHPFRC: First lessons and recommendations. In International Symposium on Ultra High Performance Concrete (pp. 697-706).
- 73) Chanvillard, G., & Rigaud, S. (2003). Complete characterization of tensile properties of Ductal® UHPFRC according to the French recommendations. In Proceedings of the 4th International RILEM Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC4) (pp. 21-34).
- 74) Resplendino, J., & Toulemonde, F. (2011). Designing and Building with UHPFRC: State of the Art and Development. John Wiley & Sons.
- 75) Graybeal, B. A. (2006). Material property characterization of ultra-high performance concrete. FHWA-HRT-06-103, Federal Highway Administration, Washington, DC.
- 76) Acker, P., & Behloul, M. (2004). Ductal® technology: A large spectrum of properties, a wide range of applications. In Proceedings of the International Symposium on Ultra High Performance Concrete (pp. 11-23).
- 77) Fehling, E., Schmidt, M., Walraven, J., Leutbecher, T., & Fröhlich, S. (2014). Ultra-High Performance Concrete UHPC: Fundamentals, Design, Examples. John Wiley & Sons.

- 78) Hajar, Z., Lecoindre, D., Simon, A., & Petitjean, J. (2004). Design and construction of the world first ultra-high performance concrete road bridges. In *Proceedings of the International Symposium on Ultra High Performance Concrete* (pp. 39-48).
- 79) Perry, V.H., et al. (2013). Fifteen Years of UHPC Construction for Precast Bridges. *Journal of Bridge Engineering*.
- 80) Perry, V.H., & Seibert, P.J. (2013). Performance Evaluation of Field Cast UHPC Connections for Precast Bridge Elements. *ASCE Journal of Bridge Engineering*.
- 81) Graybeal, B. (2014). *Ultra-High Performance Concrete: A State-of-the-Art Report*. FHWA.
- 82) Seibert, P.J., et al. (2013). Accelerated Bridge Construction using UHPFRC. *Journal of Transportation Engineering*.
- 83) Singh, A. (n.d.). Ultra High-Performance Fibre Reinforcement Concrete (UHPFRC). LinkedIn.
- 84) Unique UHPC Infra. (2022, December 30). India's First Major Bridge Using UHPFRC Technology.
- 85) Russell, H.G., & Graybeal, B.A. (2013). *Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community*. Federal Highway Administration, U.S. Department of Transportation.
- 86) Perry, V. (2005). *The Use of UHPC for Precast Bridges - The Technology, Applications & Challenges Facing Commercialization*. PCI National Bridge Conference.
- 87) Gruner AG. (2022). The Aiguillon railway bridge in Switzerland, one of the first railway bridges completely made of Ultra-High-Performance Fiber-Reinforced Cementitious Composite (UHPFRC).
- 88) Trinh, N.T., Bertola, N.J., Garcia, E., & Brühwiler, E. (2022). Short span UHPFRC railway bridge in Switzerland - from design to implementation. IABSE Symposium Prague 2022.
- 89) PCI. (2016). Construction of 100M Single Span BATU 6 UHPC Bridge. PCI.org.
- 90) Pinatih, A. (n.d.). Building Bridges with Ultra-High-Performance Concrete (UHPC). Construction Plus Asia.
- 91) Voo, Y.L., & Foster, S.J. (2017). Malaysia, taking ultra-high performance concrete bridges to new dimensions. In *UHPFRC 2017 Designing and Building with UHPFRC: New large-scale implementations, recent technical advances, experience and standards*. RILEM Publications SARL.
- 92) CPI Worldwide. (2024). Construction and Environmental Impact Assessment of Langat River 105 Metre Span UHPC Composite Bridge. CPI Worldwide.
- 93) PCI. (2024). Langat River Bridge - Project Profile Details. Precast/Prestressed Concrete Institute.
- 94) Brühwiler, E. (2020). "Structural UHPFRC: Welcome to the post-concrete era." ETH Zurich, Switzerland.
- 95) The Sun, et al. (2015). Article Title. Retrieved from <https://thesun.my/archive/1910492-GSARCH382398>
- 96) Denarié, E., Brühwiler, E. (2015). "Cast-on site UHPFRC for improvement of existing structures - Achievements over the last 10 years in practice and research." *Construction and Building Materials*.

- 97) Denarié, E., Habel, K., Brühwiler, E. (2005). "Structural behavior of hybrid elements with Advanced Cementitious Materials." HPFRCC-4, Ann Arbor, USA.
- 98) Emch+Berger SA Lausanne. (2015). "Martinet footbridge - SCIA Engineer." Technical Report, Lausanne, Switzerland.
- 99) Liu, M., Brühwiler, E., Cui, F., Xu, Y. (2018). "Study on Mechanical Performance of Prestressed UHPFRC U-Beam Bridges." Journal of Bridge Engineering.
- 100) Brühwiler, E. (2018). "A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland." Structural Engineering International.
- 101) Devènes, J., Brütting, J., Küpfer, C., Bastien-Masse, M., Fivet, C. (2021). "Re:Crete – Reuse of concrete blocks from cast-in-place building to arch footbridge." Structural Engineering International.
- 102) Brühwiler, E. (2021). UHPFRC technology to enhance the performance of existing concrete bridges. Structure and Infrastructure Engineering, 17(6), 838-852.
- 103) El-Tawil, S., Tai, Y. S., & Belcher II, J. A. (2022). Open-source dataset for ultra-high-performance concrete (UHPC) material models. Journal of Structural Engineering, 148(2), 04021252.
- 104) Puri, S. K. (2023). ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE: AE & IE Perspective. Ministry of Road Transport and Highways, India.
- 105) Toutlemonde, F., Resplendino, J., Sorelli, L., Bouteiller, V., & Boudot, S. (2013). Long-Term Material Performance Checked on World's Oldest UHPFRC Road Bridges at Bourg-Lès-Valence. In Proceedings of the Second International Symposium on Ultra-High Performance Concrete, Marseille, France.
- 106) DIALOG. (2019). Glenmore/Legsby Pedestrian Bridge. DIALOG. Retrieved from <https://dialogdesign.ca/projects/glenmore-trail-pedestrian-bridge-at-legsby-road-2/>
- 107) Ghoneim, G., & Brown, T. (2012). Ultra-High Performance Concrete in Bridges: The Glenmore Pedestrian Bridge. In Proceedings of the 3rd International Symposium on Ultra-High Performance Concrete and Nanotechnology for High Performance Construction Materials (pp. 787-794). Kassel University Press GmbH.