JOURNAL OF ENGINEERING RESEARCH AND TECHNOLOGY, VOLUME 10, ISSUE 1, MARCH 2023

Received on (12-06-2022) Accepted on (11-11-2022)

Ultra-High-Performance Concrete (UHPC) - Applications Worldwide: A State-of-the-Art Review

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https://doi.org/10.33976/JERT.10.1/2023/2

Abstract. Research is in progress on the applications of ultra-high performance concrete (UHPC) as a new additive material in construction technology. Over the last twenty years' significant improvements have been achieved in mechanical properties of UHPC, such as its strength, workability, and ductility, with further improvements made in self-placing properties, higher density, and durability compared with normal concrete. One of the biggest advantages offered by ultra-high performance concrete over normal concrete is the possibility to minimize the cross-sectional dimensions of the structural elements. UHPC can be used to provide significant long-span members, whilst also showing less variation, creep, and drying shrinkage compared to conventional concrete. After many years of development and research into UHPC's properties, it is being used in commercial applications to meet the rising demand for quality constructions. Many projects in the world started using UHPC for different construction objectives such as long spans, columns, jacketing, rain-screen cladding systems, panel systems, façades, etc. Furthermore, there are not enough sources in the literature describing mixture design, preparation, and curing. This research gives an overview of the uses of UHPC in structural and architectural applications.

Keywords: UHPC, Structural Application, Architectural Application.

1. Introduction

UHPFC provides significantly improved mechanical properties compared with normal concrete through the use of a concrete mix without coarse aggregates, minimizing the quantity of water required, and the addition of materials such as silica fume and steel fiber [1-5]. Said, et al. [6] and Elsayed, et al. [7] suggested that the high compressive strength of ultra-high-performance fiber-reinforced concrete (UHPFC) can be used as a conventional jacketing material to ensure a strong mechanical bond between the normal concrete (NC) and UHPFC. Various researchers [8-10] have conducted studies focused on the mechanical properties of UHPFC as new concrete material. Meanwhile, other researchers [11, 12] have studied UHPFC as a composite material. There is, however, the limited information available in relation to UHPFC's behavior as a repair material in specific bonding behavior. Ultra-High Performance Fiber Concrete (UHPFC) is a new class of concrete. Because of its distinguished mechanical properties, UHPFC is considered as an ideal alternative material for use in developing new structural solutions.

Concrete is the second most consumed substance in the world after water, which is the most commonly used building material. Concrete is a construction material having a compression strength that is significantly higher than tensile strength. As a result, concrete is thought of as a substance that is brittle [13].

Advances in the science of concrete materials have led to the development of a new class of cementation composites, namely UHPFC. The mechanical properties of UHPFC make it an ideal alternative material for use in developing new solutions to pressing concerns about highway infrastructure deterioration, repair, and replacement, UHPFC is considered an ideal alternative material for use in developing new structural solutions [14]. This research gives an overview of the uses of UHPC in structural and architectural applications.

1.1 *Ultra-high performance fiber concrete (definitions, contents, properties and applications)*

During the last two decades, the demand for ultra-high performance concrete has increased in relation to mega projects and high-rise buildings [15]. Ultra-High-Performance-Fiber-Reinforced-Cement production is the result of the development over many years of High-Performance-Concrete to obtain a grain-binder matrix appropriate for the granular structure and cementitious-binder composition. UHPFC displays better mechanical properties compared to conventional concrete regarding compressive strength, modulus of elasticity, tensile strength, and elastic post cracking. It also has a high density, which results in better structure life as porosity and permeability are reduced [16-18]. Habel, et al. [19] classified fiber reinforced concrete as shown below in Fig. 1:

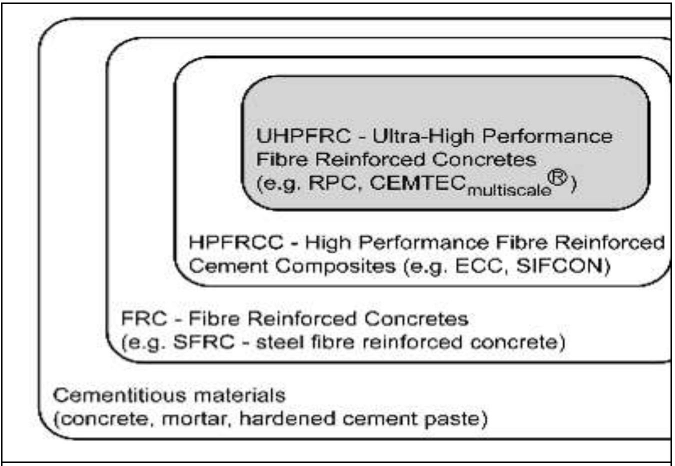


Fig. 1: Classification of FRC [36]

Morin, et al. [20] state that the material used in UHPFC has a high technology cement-based matrix and high fiber content that result in strong and durable concrete. Nevertheless, UHPFC applications are rare due to the cost compared with traditional concrete. Similarly, Rossi (2002) describes UHPFC as a dense concrete that contains a large number of evenly embedded steel fibers, resulting in high tensile strength, strain hardening, and low permeability. Based on [21], compressive strength can reach 150 MPa, with better ductility compared with normal strength concrete. Moreover, testing of compressive strength of HPC and UHPFC by other researchers [15, 22] indicated that UHPFC has better tensile strength and durability.

One of the significant features of UHPFC is the reduction of water content in the mixture, which enhances the concrete's mechanical properties. Another feature is the replacement of coarse aggregate with refined silica fume and steel fibers [23]. Ghafari, et al. [24] suggest that UHPFC's efficiency depends on its density, which can be increased by optimizing the particle packing to obtain ultra-high consolidation of the concrete matrix, with perfect grain size distribution achieved through the absorption of a homogeneous gradient of fine and coarse particles in the mixture.

1.2*Ultra-high performance fiber concrete components*

The homogeneity of a UHPC mix containing no coarse aggregate enhances its properties compared with normal concrete [15]. Optimization of the grain size distributions in UHPC materials means that UHPC has very low permeability due to its dense matrix [25]. The dimensions of the materials, ranging from the biggest to the smallest, are as follows: sand, very finely graded and ranging from one hundred fifty µm to six hundred µm, is the largest material in the UHPC materials. The second largest granular material is cement, with an average diameter size equal to fifteen µm. Finally, silica fume has the smallest particle size in the UHPC mix Table 1. Crushed quartz has an average diameter of ten µm. When steel fiber is added to the UHPC mix to improve the ductility it becomes the largest component in the UHPC [15].

Table 1: Range of UHPFC mix components [26]

Component	Typical range by weight (kg/m^3)
Sand	490 – 1390
Cement	610 – 1080
Silica Fume	50 – 334
Crushed Quartz	0 – 410
Fibers	40 – 250
Superplasticizer	9 – 71
Water	126 – 261

Using sand in the UHPC mix confines the cement matrix to add strength. In addition, a variety of quartz sand that is not chemically active in the cement hydration reaction at room temperature should be used [27]. Vernet [28] demonstrated that because of the low water content of the mix some cement grains in the UHPC cannot become. in fact, the anhydrate cement grain act as high elastic modulus reinforcements in the matrix. Silica fume with a diameter of 0.2 µm is used in the UHPFC matrix. It fills the voids between the cement grains as well as forming hydration products by pozzolanic activity and enhancing the rheological characteristics. With hydration of the OPC the silica fume reacts with Ca(OH)2, the latter being consumed to produce C-S-H hydrates [29-31].

In concrete mix, the workability is affected by functions of both the fiber size and the coarse aggregate size. In the case of UHPFC without coarse aggregate, the size of the steel fibers affects the concrete flow ability. The workability of UHPFC mixes clearly decreases with increasing fiber size [32]. Third-generation superplasticizers: polycarboxylate and polycarboxylate ethers are generally used in UHPFC mix for their high efficiency and lack of appropriate threshold for low water/cement ratios [33].

1.3*Mmechanical and durability properties of UHPC*

Ultra-High performance Fiber concrete is an extremely strong cementation matrix with a high fiber content makes up the advanced concrete material known as ultra-high performance fiber concrete. UHPFC is more durable than regular concrete because of its strong tensile and compressive strengths, which are made possible by the utilization of powder components [34, 35]. In comparison to regular concrete, UHPFC's strain hardening behavior in tension ensures that crack openings stay smaller and offers a material with greater ductility. Ultra-high-performance-fiber reinforced concretes are a type of cement composite formed from a distributed three-dimensional reinforcement of steel or synthetic fibers and a strong and compact powder-based matrix. Fibers have ductility among other qualities, and in sufficient quantities, they cause a strain hardening behavior in tension.

According to Aitcin, et al. [36], the UHPFC can achieve great strength by doing the following: On an industrial level, UHPFC has very high mechanical characteristics. It follows that a coarse aggregate is concrete's weakest component. To increase the compressive strength of concrete, only the coarse aggregate needs to be removed. This claim illustrates the UHPFC's potential strength.

UHPFC advantages are listed below:

1. Simple placement (good filling and passing ability).
2. High early strength.
3. Long-term mechanical properties.
4. Low Permeability.
5. Stability of volume.
6. Long life in harsh conditions.

Additionally, the following benefits of UHPFC can be summed up (Schneider, 2002):

1. The removal of coarse aggregate improves homogeneity.
2. Increasing the packing density via granular mixture optimization using a broad range of powder size classes
3. Enhancing the matrix's characteristics by including a pozzolanic admixture, such as silica fume.
4. Improving matrix characteristics by lowering the water to binder ratio.
5. Improvement of the heat treatment of the microstructure.
6. Increasing ductility by using tiny steel fibers.
7. Increasing compressive strength

There is a weak transition zone between the aggregate and paste in conventional concrete and UHPFC [37]. The aggregates in UHPFC are a collection of inclusions in a continuous matrix, and their sizes are extremely tiny. As a result, the matrix may transfer the compressive force rather than a stiff skeleton of aggregates, which lessens the stresses that form at the paste-aggregate contact. In UHPFC, the transmittal of stresses by the surrounding matrix and the aggregates results in a much more uniform stress distribution, which can lessen the likelihood of shear and tensile cracking at the interface [25].

The stiff framework in typical concrete also inhibits some paste shrinkage, which increases porosity. However, in UHPFC, aggregates only partially prevent paste shrinkage, therefore deleting both fine and coarse aggregates is not fully advantageous, according the hypothesis of maximum paste thickness. Cement paste is constrained by aggregates. The compressive strength of the composite actually falls as paste thickness between particles increases [38]. In order to preserve the best possible compressive strength, fine aggregate is kept in UHPFC. Improvements to aggregate gradations and the use of a superplasticizer with high-range water reduction led to the development of UHPFC materials.

A typical UHPFC mixture contains sand, cement, silica fume, crushed quartz, fibers, superplasticizer, and water in the ranges shown in Table 2. It shows a typical UHPC mixture with the mixing components.

Table 2: Range of UHPC mixing components [39].

Component	Typical range of k/m³
Sand	(490-1390)
Cement	(610-1080)
Silica Fume	(50-334)
Crushed Quartz	(0-410)
Fibers	(40-250)
Superplasticizer	(9-71)
Water	(126-261)

2. Applications of UHPFC

UHPFC is used in structural and architectural applications due to its ideal mechanical properties. The development of UHPC was initiated in the early 1990s to meet the most demanding structural applications. The superior properties of UHPFC, which have enabled the redesign and optimization of structural elements as well as enhancement of durability, have permitted lengthening of design life and potential use as thin overlays, claddings, or shells [40]. In 1997, the first UHPC structure was constructed in Canada. Since then UHPC has mostly been used in the construction of pedestrian and road bridges [41], protective panels [42] [43], and architectural applications [44]. In the past, architectural designers have been moving to avoid the use of synthetic cladding systems or metal, therefor the UHPC is a novel solution for designers to be used as a cladding system. UHPC panels are flat, thin, lightweight, and easy to install. Moreover, UHPC has high resistance to abrasion and low porosity resulting in reduced maintenance requirements. [45].

In recent years, UHPC has been widely used among construction committees due to its high mechanical properties, such as compressive strength and durability, as well as high workability, self-placing, self-densifying properties, and non-brittleness behavior. The rising demand for UHPC applications as construction materials led to the development of a UHPC formulation for use in commercial industries. UHPC is the ‘future’ material for improving the sustainability of buildings and other infrastructure components [46].

Syed [47] demonstrated that UHPV can be used for architectural applications where the aesthetics are a preference for a huge structures such as the facades. Also, UHPC can be used for structural applications due to its high mechanical properties of UHPC in comparison to conventional reinforced concrete. [48] mentioned that due to the high compressive strength and high durability of UHPC, it is an excellent material that can be used for architecture and construction such as thin façade elements, balconies, joints of prefabricated elements, and staircases. Furthermore, UHPC can be used for a building when the durability of the structure is a concern.

UHPC has been utilized in different countries for multiple reasons; In Malaysia for durability and low maintenance purposes, in the Netherlands for fast and hinder-free construction purposes. Also, in Switzerland UHPC has been widely used as a rehabilitation solution for concrete bridges in zones exposed to severe environmental due to the low permeability and high mechanical strength of UHPC [49]. The following section presents illustrations of the applications of UHPFC.

1.4Structural applications

2.1.1 Pulaski Skyway

The Pulaski Skyway, a 5.6 km long bridge in the north-eastern US state of New Jersey, provides a direct link to New York City via the Holland Tunnel. It was opened in 1932 and is listed in the National Register of Historic Places. When the decision was made to replace the bridge deck, because of the critical importance of the Skyway to the region's transportation, and the narrowness of the structure making it difficult to perform maintenance without impacting traffic, the New Jersey Department of Transportation wanted to ensure that the new bridge deck would have a service life of 75 years and need little maintenance during that time period Ultra-high performance concrete (UHPC) is currently being extensively used in the on-going replacement of the Pulaski Skyway deck. The unique properties of UHPC allow simple and rapid installation of a durable deck system, despite the challenging conditions and limited space.

The employment of UHPC for nearly all the precast panel connections means that the connections are no longer the weak points in terms of strength and durability that they were traditional. Instead, the connections are the strongest and most durable points of the deck system, stronger and more durable than precast deck panels with shop-cast concrete and corrosion-resistant rebar [50].

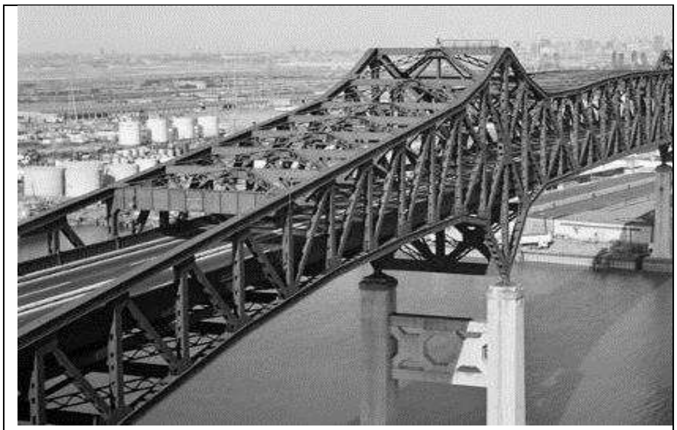


Fig. 2: Partial Elevated View of the Pulaski Skyway

2.1.2Sherbrooke Footbridge, Canada

The Sherbrooke Footbridge in Sherbrooke, Quebec, Canada, completed in 1997, was the world's first major UHPC structure. The bridge is of post-tension open space truss design and 60m in length. Using UHPC in the bridge allowed the top deck to be only 30 mm in thickness [51] [52].

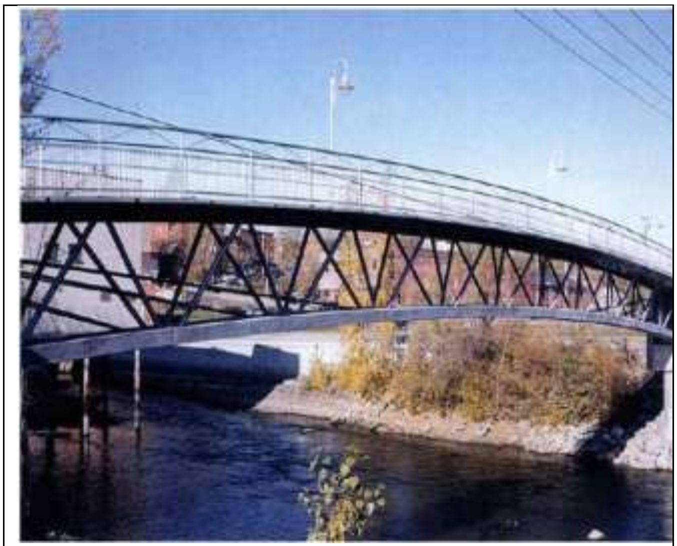


Fig. 3: Sherbrooke Pedestrian Bridge Quebec, Canada [53]

2.1.3Footbridge of Peace, South Korea

The Footbridge of Peace in Seoul, South Korea was the first bridge in the world where UHPFC was used as a full replacement for normal concrete. The bridge, which was completed in 2002, is 120m long and has arch height of about 15m with 30 to 100mm deck depth Fig. 4 [54] [55].

Fig. 4: Footbridge of Peace in Seoul, South Korea

2.1.4Seonyu footbridge, SUPER BRIDGE 200, Pedestrian cable-stayed bridge, South Korea

In 2002, the Korea Institute of Construction Technology completed a project that used UHPC to construct a hybrid cable-stayed bridge that was intended to be low cost, increase the normal span by about 20%, and have a longer lifetime. The compressive strength of the UHPC was 180MPa and the tensile strength was about 10 MPa. UHPC allowed the thickness of the two front girders to be reduced to 70mm compared with the 180mm thickness of the rear OPC girder. The deck dimensions were 2.7x7m as a precast segment [56].

Fig. 5: UHPC Girder Pedestrian Cable-Stayed Bridge.

2.1.5Sakata-Mirai footbridge, Japan

The year 2002 saw the completion of the Sakata-Mirai UHPC footbridge Fig. 6 in Japan, a structure of low weight and aesthetically pleasing appearance that used perforated webs [41].

Fig. 6: The Sakata-Mirai footbridge in Japan

2.1.6Bourg les Valence Road Bridge, France

Bourg les Valence Road Bridge, France Fig. 7 was the world's first UHPC road bridge. Its construction was supported by the FWG (French Working Group) which in 2002 introduced the first guidelines for bridge design [44].

Fig. 7: Bourg les Valence Road Bridge, France

2.1.7Shepherd Creek Road Bridge, Australia

Australia's first UHPC application was the four-lane Shepherd Creek Road Bridge Fig. 8, completed in 2004. The bridge was constructed entirely from UHPC, replacing NC. The bridge consists of formwork overlain on a reinforced concrete deck. The beams were 15m in length by 600 mm in depth and spaced at 1.3m. The formwork panels were 25mm in depth and the weight of the beams was reduced by about half compared to the replaced NC beams [57].

Fig. 8: Shepherd Creek Road Bridge in New South Wales, Australia.

2.1.8Mars Hill Bridge, Iowa

Mars Hill Bridge was completed in 2006 and replaced a 73-year-old truss bridge Fig. 9 [58]. It comprised 33m prestressed UHP beams. Its construction was supported by the Federal Highway Administration in collaboration with Iowa State University (Graybeal, 2006). As a part of a monitoring program, the bridge was then monitored for two years to study its behavior under loading [59].

Fig. 9: Mars Hill Bridge in Wapello County, Iowa

2.1.9Gaertnerplatz Bridge, Germany

Gaertnerplatz Bridge in Kassel, completed in 2007, was the first UHPC application in Germany Fig. 10. The structure comprises three steel trusses combined with longitudinal girders and deck slabs. Prefabricated elements were used that consisted of prestressed, fiber-reinforced UHPC. The bridge has a span is 132m in length with 85mm slab thickness [60] [61]. Similar to Mars Hill Bridge, this bridge has since its construction been monitored to clarify the design assumptions, material and load-bearing behavior, based on the collected data. Furthermore, the data has complied with the expectations of the design phase [62].

(a) under construction

(b) in use

Fig. 10: Gaertnerplatz Bridge in Kassel

2.1.10 Haneda Airport Runway D, Japan

Haneda Airport Runway D expansion, which started in July 2007, was a most impressive realization created over the sea to increase airport runway capacity. UHPC pre-stressed slab was assembled by post-tensioning in a perpendicular direction, supported by a metallic structure [63]. Walraven [64] and Resplendino [65] claimed that the bridge is an instance of a significant reduction in structure weight and increased sustainability with respect to environmental destruction. as compared with conventional concrete, UHPC resulted in a 50 % reduction of the overall weight of the structure [66].

Fig. 11: View of Haneda Airport Runway D

2.1.11 Route 31 Bridge in Lyons, New York - Field-cast UHPC

On Route 31 Bridge in Lyons, New York, completed in 2009, field-cast UHPC was used for the connections between precast deck panels Fig. 12 and also used between the top flanges of deck-bulb-tee girders as longitudinal connections [40].

Fig. 12: Longitudinal connections cast between deck-bulb-tee girders on Route 31 Bridge in Lyons, New York

2.1.12 Glenmore/Legsby Pedestrian Bridge, Calgary, Alberta, Canada

The 53m single-span Glenmore Pedestrian Bridge, Alberta, Canada in 2007 Fig. 13 has 8 lanes and consists of T-shape girders made of UHPFRC. The girders are 33.6m in length with 1.1m in depth at mid-span and the deck width is 3.6m. The two supported cantilevers are made of high-strength concrete. A passive reinforcement was used in the form of CFRP (Glass fiber reinforced plastic bars) [58].

Fig. 13: Glenmore Pedestrian Bridge. (NPCA).

2.1.13 Kampung Linsum Bridge, Malaysia

The medium-span Kampung Linsum Bridge, completed in 2011, is to date the longest UHPFC composite bridge application in Malaysia. It consists of a single U-trough girder that is 1.75 m in depth and 2.5 m in width at the top, topped with a 4 m wide cast in-situ 200mm thick RC deck Fig. 14. Compressive strength of UHPFC was used in the application to achieve 180 MPa with 30 MPa tensile strength [21].

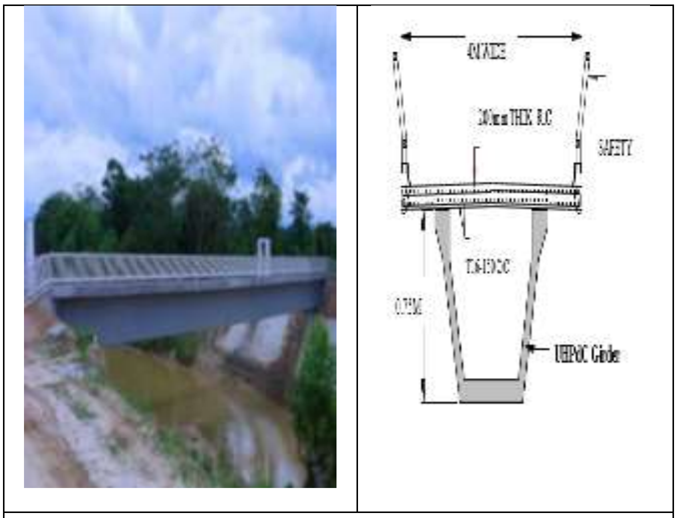
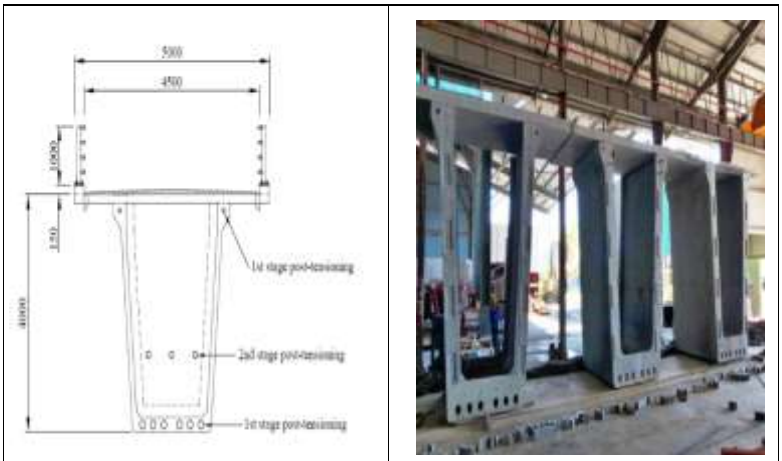


Fig. 14: Kampung Linsum Bridge, Rantau, Negeri Sembilan

2.1.14 Batu 6 Bridge, Malaysia

This 100m bridge, completed in February 2015 in Gerik, Perak, Malaysia, consists of 40 – 4.0-meter-high precast segments Fig. 15 that were transported to the site for placement and tensioning after casting in the factory. The thickness of the webs between the segment ends is 150 mm. The bridge weighs 770 tons, the average prestress on the sections is 17.1 MPa compression, the stress at the top and bottom of the sections at mid-span is 19.3 MPa compression, and the stress at the bottom is 15.0 MPa. Moreover, the measured hog was 50 mm compared with 34.8mm for the theoretically calculated hog [67].



(a) : Batu 6 Bridge cross section

(b) : Batu 6 Bridge factory cast segments

(c) : Batu 6 Bridge after completion of Abutment A.

Fig. 15: Gerik, Perak, Malaysia.

2.1.15Precast Ultra-High Performance Concrete Cantilever Retaining Wall (2016)

This precast ultra-high performance concrete (UHPC) 40mm thick cantilever retaining wall was designed based on the Japanese Society of Civil Engineers' recommendations for the design and construction of UHPC structures. Two thin UHPC slabs were used to construct the retaining wall. The UHPC cantilever is 2m in length, 2m wide, and 2.5m in height Fig. 16. The wall is strengthened with two 80mm by 100mm steel reinforcing stiffeners spaced at 1.25m along the wall [68].

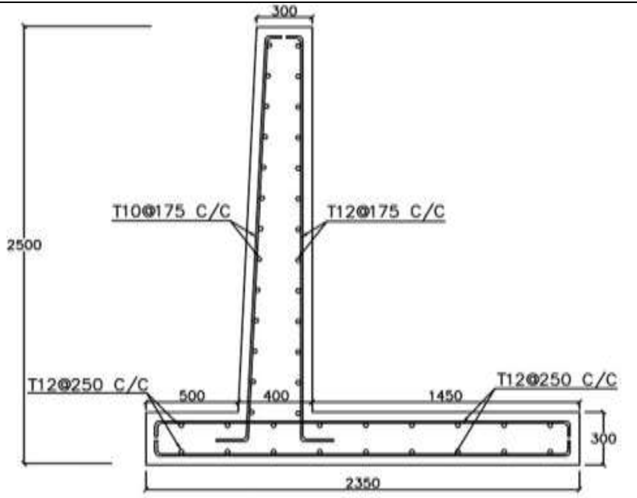


Fig. 16: Dimensions and details of conventional precast RC cantilever retaining wall.

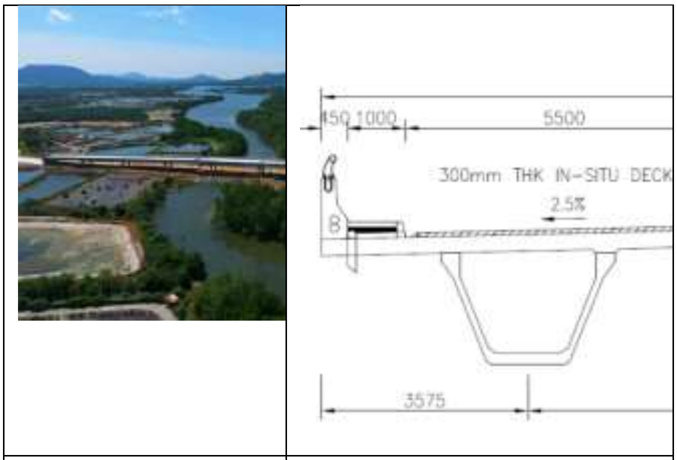
2.1.16 Production of a footbridge with double curvature using UHPC (2017)

This experimental design of a single 10m span bridge used UHPFRC to reduce the structure's thickness to 30-40mm with 1.5 m cross-section width. The bridge comprised a one-piece cast as one prefabricated element. UHPFRC has self-compacting characteristics. The bridge has vertical and horizontal curvatures, with a camber of 0.4 m. Load bearing consists of 45mm thickness at the bottom of the deck and side walls. To ensure shear transfer and anchorage forces from the supports, the bridge deck was designed to be thicker than the support area. Steel fiber reinforcement (U shape) was used in the rest of the structure[69]. [70, 71] state that forever durability can be achieved with a very high cement matrix density, minimum porosity, and unconnected pores. These criteria are provided by tiny particles (slag and silica fume) with a low W/C ratio. Workability is necessary for achieving these perfect material properties.

Fig. 17: Transport of final 1:1 mock-up of the footbridge in upside-down position

2.1.17 KG. Baharu-Kg Teluk Bridge (KB-KT)

UHPFRC precast sections have been used in KG. BAHARU-KG TELUK BRIDGE (KB-KT). The prestressed girders in the bridge are one of the longest multiple-span bridges in the world. Located at Ayer Tawar, Manjung, Perak, completed in 2017 and spanning 420 m long, Kg Babaru-Kg Teluk (KB-KT) bridge consists of 20 UHPFRC precast U-beams. The span of each beam equals 41.5m with six segments consisting of two end/anchorage segments spanning 4.75-meter and four standard intermediate segments spanning 8m. the dimensions of the segments is 2m deep, 3m wide at the top surface, and 1.4 m wide at the bottom flange. The average and characteristic compressive strength after 1-day were 89 Mpa and 78 Mpa, respectively. Furthermore, the average and characteristic compressive strength after 28-day were 167 Mpa and 154 Mpa, respectively. Regarding flexural strength, after 28 days the strength reached 29.1 MPa and 24.5 MPa, respectively for the average and characteristic flexural strength. The average elastic modulus was 50.7 GPa and Poisson’s ratio was 0.2 [72].



(a): KB-KT Bridge. (b) : Cross-section of KB-KT Bridge.

Fig. 18: KG. Baharu-Kg Teluk Bridge (KB-KT)

2.2 Architectural applications

2.2.1 Martel Tree Sculpture, France

The Martel Tree, completed in France in 1999, is a sculpture made completely from UHPC . Some of the elements were only 60mm in thickness [54].

Fig. 19: Martel Tree sculpture made of UHPC [54]

2.2.2 Shawnessy LRT Station with UHPC canopies, Canada

In 2003, Canada constructed a series of renowned UHPC structures in the form of canopies at Shawnessy LRT station in Calgary. UHPC gave the architects the flexibility to realize their desire to design such a free-flowing form. To clarify the satisfactory behavior of the twenty-four UHPC canopies, each 20mm in thickness and supported by a single UHPC column, full-scale tests were conducted prior to their installation [63].

Fig. 20: Shawnessy LRT station with UHPC canopies [63]

2.2.3 Cover of Millau Toll, France

The 98m Millau toll structure in Millau, France was built in 2004 Fig. 21. It is 28m wide and has two thin 100mm slabs that are joined together by 12 prestressed beams. The cover was built using UHPC and comprises 53 match-cast pasted prefabricated elements assembled on a hanger with longitudinal pre-stressing [73]. The project was an example of UHPC's capabilities in terms of producing complex shapes and a thin covering [65].

Fig. 21: Overview of the cover of Millau Toll [73]

2.2.4 *Wilson Hall, Malaysia*

In the year 2008, a prefabricated UHPFC system was used at the Wilson Hall building in Malaysia to construct the entrance frame which had a 1,861 m2 roof area. The transverse width of the building was 67m and the longitudinal length was 42.7m. UHPFC Portal frames were spaced at 12.2 m c/c. Furthermore, the building consisted of eight pieces comprising UHPFC prestressed columns, internal rafters, cantilever rafters, and connections, as shown in Fig. 22 [74]. Voo, et al. [75] claimed that this building was the first in the world to replace conventional steel beams with UHPFC prestressed beams/columns.

Fig. 22: Wilson Hall during the construction [74]

2.2.5 *Stade Jean Bouin, France:*

This stadium, which opened in 1925 and seats 12,000 people, was closed temporarily for an expansion project that began in the summer of 2010. The stadium reopened in 2013 with an increased capacity of up to 20,000 spectators. Ruddy Ricciotti used UHPC as a solution to achieve this technically difficult objective, creating a precast UHPC lattice-style façade system that is light and airy. The result is a remarkable, totally asymmetric envelope, undulating in three dimensions. New technical challenges were presented by the combination of glass and ultra-high performance concrete (UHPC), which makes the project very original, and the construction of a watertight envelope that would cover the stadium's entire surface area.

This 23000 m² envelope includes a 12000 m² roof made of 3,600 self-supporting ductal triangular UHPC panels, each approximately 8 to 9m long by 2.5m wide and 0.45 m thick. The envelope covers the stadium in an amorphic fashion, protecting the spectators from the elements and providing an acoustic screen in consideration of the surrounding neighborhood. This unique project is another prime example of the architectural use of UHPC [76].

Fig. 23: Stade Jean Bouin, open lattice façade allowing sunlight to filter through

2.2.6 *MuCEM (The Museum of European and Mediterranean Civilisations), Marseille, France.*

The Museum of European and Mediterranean Civilisations is a national museum located in Marseille, France. It was opened on 7 June 2013. The MuCEM project was designed by Rudy Ricciotti and Roland Carta and demonstrates the capability of UHPC in the architectural and structural design of a whole building. The structure of the building consists of seven floors, two as the basement or underground areas and five above ground. Entrance to the museum is through a 76 m span and 1.8m high footbridge, designed using UHFPRC, while UHPC structural elements inside the museum include columns and the latticework in the second skin.

In this museum, the main supporting structure in the façade is made of 309 arboreal UHPFRC poles, the trees fabricated in 20 casts of different heights, diameters, and shapes, with three families of trees fabricated. The framework is supported by exterior UHPC brackets, and the latticework is a fine example of the architectural application of UHPC for durable façade elements [77].

Fig. 24: Mega project: MuCEM with UHPC lattice facade, roof and footbridge.

2.2.7 *Fondation Louis Vuitton pour la Creation Paris, France (2014)*

Foundation Louis Vuitton pour la Creation is an art museum and cultural center. The construction began in March 2008, located in the Garden of Acclimation in Paris, France, and designed by Frank Gehry and Ghery partners. The cladding of Fondation Louis Vuitton pour la Creation contains 1900 prefabricated panels cast in white Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). The area of the project is approximately (50 m^2 x 45 m^2), elevated to 45 m of height. the architecture team used UHPFRC as an Iceberg to construct the innovative building [78]. [46] demonstrated that in Louis Vuitton pour la Creation project, the selection of Ultra-High-Performance Concrete was to produce an aesthetic, durable, and light structure.

Fig. 25: Fondation Louis Vuitton pour la Creation Paris, France.

2.2.8 *Fulton State Hospital, Fulton, Missouri USA (2018)*

While under construction Henry and Heaney [45] demonstrated the change in the design philosophy of the project as the hospital first opened in 1851 for aging mental patients. On the other hand, the new massive complex for Fulton State Hospital was designed for safer, modern patient treatments in the years to come. The area of the hospital is approximately 22.25 hectares (222500m^2), containing 11,612 square meters of façade constructed to form the UHPC rain screen panel system. Due to the massive size of the building and weight constraints, the architectural engineering team selected UHPC for the high durability and finishing capabilities of UHPC, as the top the panels appear to "dissolve" into the walls and resulting in reduced height and overall size. [45].

Fig. 26: Fulton State Hospital, Fulton, Missouri, USA

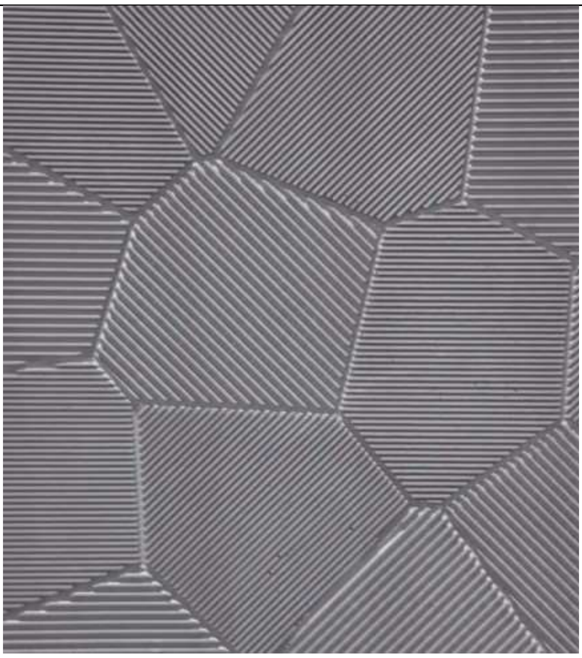


Fig. 27: Grooved UHPC panel used in Fulton State Hospital, Fulton, Missouri, USA

2.2.9 Kimmel Pavilion, New York University, USA (2018)

Henry and Heaney [45] mentioned that Kimmel Pavilion is a medical center added to the main campus of New York University with 77,109 m² in Langone, on Manhattan's lower east side. The interstitial space between floors was covered with thin UHPC rain screen cladding that provided a visual break in the glass curtain wall that surrounds the facade on each level. The thin, high durability and lightweight characteristics of UHPC cladding panels meet the project requirement for a natural finish, as well as the light UHPC, which led to the use of small cranes instead of large cranes. The use of smaller cranes can contribute significantly to cost reduction, site safety, and speed of construction. Each UHPC piece was cast as a C-shaped, 3D element. The UHPC material helped to make the 3D elements very robust and impact-resistant. UHPC panels can resist the wind force as well as the concentrated force from window washing baskets.

ull-size mock-up of the UHPC panel application for NYU's new Kimmel Pavilion

2.2.10 Lewis Farms Fire Station, Edmonton, Canada

In Edmonton, Canada, the low freezing temperatures in the winter as well as the very high temperatures during some summer days made the UHPC cladding panel an evident solution. These panels were chosen due to the high durability and high resistance to freeze-thaw, high density, and low porosity of UHPC which attributes to the low permeability characteristics that prevent water molecules penetration into the matrix. The high durability of the UHPC exterior façade would provide superior resistance to impact, chemical attack, abrasion, fire, and seismic activity.

The Lewis Farms Fire Station, Edmonton, Canada project had an art component by using a custom design of the facade's textured panels [45].

(a) : Lewis Farms Fire Station, Edmonton, Canada

(b) : UHPC Panel Customized Texture

Fig. 29: The Lewis Farms Fire Station, Edmonton, Canada project

3. Conclusion

This review paper describes UHPC applications and their benefits when applied to structural and architectural work. Many countries, including Japan, Malaysia, Australia, France, America, and Canada, have used UHPC in construction applications. These applications in different countries demonstrate the huge benefits worldwide regarding sustainability and increased service life offered by the use of UHPC. UHPC has high strength, low permeability, very high density, and very low porosity, with unconnected pores, which in combination lead to fast curing time, very low w/c ratio high flow ability, and high durability, with steel fibers providing high levels of flexural strength. The unique properties of UHPC permit reduction of the cross-sectional dimensions of the structural elements and let to reduce weight. Also, it has demonstrated enhanced behavior in terms of low vibration along with a reduction in cross-sectional dimensions, drying shrinkage, and creep. Using UHPC for connections means that these connections are no longer the weak point in terms of strength and durability that they traditionally were. Moreover, UHPFRC can be used for critical joints of existing structures, allowing low water infiltration and ductile behavior with minimal maintenance. UHPC is used as canopies and rain screen cladding due to the light weight, watertight and thin layer of UHPC. All these abovementioned efforts indicate the potential of UHPC as a construction material for present and future use. Furthermore, UHPFC offers an ideal solution for improving the sustainability of buildings and other infrastructure components. However, applications of UHPC have so far been limited due to its high initial cost, lack of clear design codes for UHPC, and UHPC mix design difficulties, which have hampered its commercial development and application in the construction industry.

4. Recommendations

- More studies should be conducted to address the issue of the high cost of UHPC, potentially using alternative cheaper materials with similar functions.
- Design standards and codes should be established for UHPFC. Due to the lack of codes and standards for UHPC, more studies must be carried out to develop a UHPC design code.
- Further structural applications should be carried out for UHPC in the future. Structural elements such as columns, beams, foundations, and slabs in multi-story buildings, bridges substructure and in concrete dams, etc.
- More Studies should be done on the long-term durability behavior of UHPV.

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