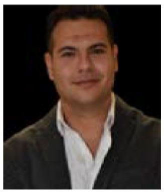
A REVIEW IN TECHNOLOGIES, DEFINITIONS, PROPERTIES AND APPLICATIONS OF ULTRA HIGH-PERFORMANCE CONCRETE (UHPC)



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Concrete technology has changed dramatically during the last decades, where the high-strength concrete concept has gone from 30 MPa to well over 100 MPa. In this paper, a review study has been conducted on ultra high-performance concrete (UHPC), however, researchers have a lot of definitions for this term, but all of them agreed that (UHPC) which refers to cement-based materials exhibiting superior properties, including compressive strength higher than 150 MPa with high ductility, and excellent durability. This paper reviews the theoretical principles of UHPC, definitions, raw materials, mixture design methods, successful mixture components with the required properties, challenges, and some of the successful applications of UHPC, focusing on bridge applications. The paper concluded by summarizing the benefits of using UHPC, the future of this superior concrete, current challenges and some recommendations for wider use.

Keywords: UHPC, UHPC definitions, UHPC mixtures, UHPC applications

1. INTRODUCTION

Since Roman times, concrete has been the most used material in construction; construction materials development does not stop, day by day, concrete expresses new applications and an advanced improvement in the construction industry, one of the quanta leaps in concrete structures achieved by developing the ultra-high performance concrete technology (UHPC), UHPC is the new concrete technology provide a high level of qualities that had never been possible before. During the 20th century, the development of concrete technology was significant. In 1950, concrete with 34 MPa 28-day compressive strength was considered a high-strength material. At present, these values can reach well over 200 MPa. A timeline of concrete development is shown in Table 1 (Buitelaar, 2004; EFNARC, 2005).

The significance of this paper is to review and present the crucial components and characteristics of ultra-high performance concrete (UHPC); highlighting the UHPC definitions, design methodologies, features, challenges, and some successful applications in construction. *(Table 1)*

2. UHPC DEFINITIONS

Researchers defined the term UHPC in different forms; definitions have been given to UHPC according to their major components, Farzad et al. (2019) define ultra-high-performance concrete as a cement-based material created with an enhanced gradation of granular components, with less than 0.2 water-to-cement ratio (w/c) and significant internal portions of fibre. Azmee & Shafiq (2018) mentioned that UHPC is a fibre-reinforced, super plasticized, silica fume-cement mixture with a very low water-to-cement ratio, with a presence of fine quartz sand instead of the coarse aggregate. Mishra & Singh (2019) concluded that UHPC is a particular type of concrete consisting of a high fine-grained reactive admixture, including fine quartz and silica fume, fibres and superplasticizers while having low w/b ratio and a high binder content. Ahmad et al. (2016) define the UHPC as a concrete mixture produced using high cement contents, silica fume, superplasticizer, and very fine quartz, quartz powder, and fibres without coarse aggregate. Nematollahi et al. (2012) also define the term of ultra-high-performance concrete with a cement-based composite material with less than 0.25 water-cement ratio, which consisting fine materials with optimized grading curves and very high strength discrete micro steel fibres.

In the other hand, a lot of researchers defined the UHPC based according to its superior durability and mechanical properties. Bajaber & Hakeem (2021), defines UHPC as a new generation of cement-based material which has very high compressive strength, high ductility, and sustainability based on the optimization of fine and ultrafine aggregates (such: the silica fume and sand), low water to cement ratio with added superplasticizer, and reinforced by a high strength steel fibre. Li, J. et al. (2020) defined the UHPC term as an innovative composite material that can be a potential candidate for concrete structures exposed to aggressive environments. Aroraa et al. (2019) define the UHPC as a multi-scale microstructure material tailored for high mechanical properties, i.e., very-high compressive strength, high flexural tensile strength, and high ductility material compared with ordinary concrete. Moreover, some of the researchers adopt comprehensive definitions combining both characteristics. For example, the Association Francaise de Genie Civil (AFGC) defines UHPC as a material with a cement matrix and a characteristic compressive strength in excess of 150 MPa and containing steel fibres in order to achieve ductile behaviour. The Japan Society of Civil Engineers (JSCE) defines the UHPC as a type of cementitious composite

Table 1: *Development of concrete materials (in terms of strength)*

Year	History
1824	Portland cement is first developed.
1849	Reinforced concrete evolves with the addition of metallic reinforcement.
1950	Concrete with 34 MPA strength was considered as high strength.
1960	High-strength concrete developed in the laboratory reached 80 MPa.
1980	Army Corps of Engineers for the United States were the first user of UHPC in the 1980s, though UHPC did not become commercially available in the U.S. High-performance concrete for use mainly in security and defence applications was developed in Denmark compressive strength 100 Mpa.
1985	The first research program was conducted on the application of UHPC.
1997	The first bridge partly composed of UHPC was constructed in Canada
2002	First recommendations for using UHPC were published in France.
2005 and forward	Many research programs are looking at the use of UHPC in different structures worldwide. At least 90 bridges have been built and the use of UHPC has been implemented in many other types of structures.

reinforced by fibres with characteristic values more than 150 MPa in compressive strength, a minimum first cracking strength of 4 MPa. ACI 239R (2018) defines UHPC as a fibre-reinforced concrete that has a minimum compressive strength of 22 Ksi (150 MPa) with high durability, tensile ductility, and compliance with the toughness requirements.

3. UHPC MATERIALS

The general formulation of UHPC consists of a high binder content, including Portland cement, the essential factor in achieving better UHPC is optimizing the mixture's micro and macro characteristics. Cement, silica fumes, and sand grain size distributions must be tuned to create high capacity and, hence, a thick matrix with extremely low permeability (Salahi et al., 2021). Materials are carefully selected to ensure mechanical homogeneity, maximum particle packing density and minimum size of flaws (Balázs, G. L., 2015); (Schmidt et al., 2005); (Vernet, 2004); (Shah, Weiss, 1998); (Wille et al., 2011); (Shi et al., 2015). Thus gravel or coarser aggregate is usually replaced in UHPC mixes to avoid the formation of high voids and to create a densified interfacial transitional zone around the aggregates, thus, eliminating the weakest region within the matrix (Morcus, Akhnoukh, 2007), (Akcaoglu et al., 2004).

3.1 Binders

Generally, Portland cement is used as the primary binder to produce UHPC. For UHPC, cement content is usually (about/more than 700 kg/m^3), about double the cement amount in the normal strength concrete. Cement was chosen for many reasons, the low C3A content, which minimizes the water demand of cement, ettringite formation, and heat of hydration, as indicated by De Larrard (1994) and Richard, Cheyrzy (1995). It also has low alkali content, low to medium fineness, and availability.

3.2 Fillers and aggregates

Fine sand and coarser aggregates are generally inexpensive inert materials used as fillers when making concrete. In concrete technology, especially UHPC concretes grading fillers and aggregates, maximum and minimum sizes are crucial. Quartz sand is used in the mix because of the high hardness, good paste aggregate interfaces, and chemical inactivity in the cement hydration reaction (Koh et al., 2018). The mean particle size is often smaller than 1 mm. Right proportions will result in a denser, more packed mix with a lower water demand due to fewer free inter-particle spaces, eliminating the coarse aggregates and improving the durability of UHPC. The optimization will yield a higher compressive strength, better rheology and lower water demand, which are essential characteristics of UHPC properties.

Using inert materials and coarser fillers will also decrease the concrete's shrinkage since the cement paste's volume is smaller, resulting in lower autogenous shrinkage and, thus, lower cracking risk (Wu et al., 2017).

3.3 Micro fillers

The most commonly used micro fillers are silica fume which reacts with CH (Calcium hydroxide) through pozzolanic reaction, and quarts fillers, which can be activated when exposed to high curing temperatures. Other micro fillers investigated and used are pulverized fly ash, lime-stone, metakaolin or micronized, and phonolite (Cwirzen, Panttala, 2006).

The smallest component, with a 0.2 μm diameter, serves three basic functions in UHPC, it fills voids between cement grains, forms hydration products by pozzolanic activity, and enhances the rheological characteristics. Silica fume reacts with the cement hydration product of portlandite ($Ca(OH)_2$) and water, which forms calcium silicate hydrates (C–S–H), this formation known as the pozzolanic (Oertel et al., 2014). The pozzolanic reaction makes the cement matrix denser, ultimately enhancing and improving the mechanical properties of UHPC (Zhang et al. 2016).

3.4 Fibres

UHPC behaves in a linear-elastic manner along the largest part of the stress-strain curve under loading and has a failure mode with very limited post-crack behaviour, which causes a rigid failure. The incorporation of fibres mainly aims to bridge forming cracks and transfer loads to induce ductile behaviour and to increase flexural strength (Cwirzen, Panttala, 2006). Seyam et al. (2020) mentioned that incorporating 16% of steel fibres and 0.75% polypropylene fibres according to cement weight increased the compressive strength by 28%

and the flexural strength by 58%. Shehab et al. (2016) mentioned that longer fibres (length to diameter (l/d)=50) increased compressive and flexural strengths slightly more than shorter fibres (l/d=30) with the same diameter of the fibre. Shin et al. (2021) studied the effect of the shape of steel fibres and mentioned that the twisted steel fibres had a greater pull-out resistance than straight steel fibres with a circular cross-section, and its efficacy increased as the number of ribs increased. In comparison, the straight steel fibre demonstrated the best flexural behaviour in both uniaxial and biaxial stress states, but the six-times twisted steel fibre displayed the poorest flexural behaviour due to the composites' high bond strength.

One of the more significant problems related to using fibres in concrete is ensuring correct fibre orientation and an even distribution within the binder matrix. When poured, fibres tend to orient themselves in the direction of the concrete flow, which, if done improperly, can cause the fibres to orient themselves in unfavourable directions leading to worse mechanical properties (Schmidt, 2005**).**

3.5 Chemical admixtures

The UHPC mixtures require a relatively high dosage of chemical admixtures, specially high-range water reducers (HRWR), HRWR commercially known as superplasticizers (Akhnoukh, Buckhalter, 2021). Superplasticizers are long-chain polymers or co-polymers with negative charges used as high-range water reducers in the concrete mixture. It's a material used to disperse cement particles and silica fume, which improves the workability of UHPC mixes (Voo, Foster, 2010). Adding superplasticizers not only improves concrete workability or flowability but also the particle dispersion homogenizes the concrete material significantly (Zhu et al., 2021).

Thus, superplasticizers facilitate the achievement of using a lower water/binder (w/b) ratio without affecting the workability of the mixture. In the case of UHPC, the optimum amount of superplasticizer is relatively high and its dependent on the w/c with a solid content that is approximately 1.6% of the cement content (Ghafari et al. 2016).

3.6 Water

UHPC effectiveness mix could be made not by minimizing water content but by maximizing the relative density (Tayeh, Abu, 2013). The minimum w/b ratio for a workable concrete mixture is about 0.08 (Ghafari et al. 2016). By increasing the w/b ratio to above 0.08 to about 0.13, air will be replaced by water without increasing the volume of the mixture. In case of increasing the water-to-binder ratio beyond 0.13, the volume increases due to the additional water and as a result, the density of the mixture decreases dramatically. Thus, the optimum w/b ratio should be practically tested and selected to be slightly toward the higher values of the w/b ratio to ensure that the w/b ratio of the real mix is slightly higher than the theoretical optimum (Graybeal, 2006).

Richard and Cheyrezy (1995) found that the optimum w/b ratio is 0.14 as the optimal for UHPFRC, which is almost the same conclusion for De Larrard and Sedran (1994) study, where a solid suspension model was used. The result also agrees closely with that of Gao et al. (2005), where an optimum w/b ratio of 0.15. As mentioned, most of UHPC's previous mixes standed to trial mixes, which could achieve superior performance by a higher w/b ratio in the presence of additive materials.

3.7 UHPC mix design

One of the most significant aspects of UHPC manufacturing is the mix design. It focuses on improving the qualities of fresh and hardened concrete and optimizing the concrete properties. Optimizing particle packing density for the granular components of UHPC has been regarded as the essential idea for mix design in improving workability, strength, and durability (Schmidt and Fehling, 2005). When fibres are added to UHPC to improve its ductility and energy absorption capability, but negatively affects the workability.

In general, compressive strength of UHPC is higher than 150 MPa; the specific mix design procedures are not commercially available as they are for conventional concrete. Most researchers have provided mixture proportions of UHPC after many trials with no specific design procedures reported (Yu et al., 2014), (Shi et al., 2015).

In reality, trial and error modification of current UHPC recipes from the accessible literature is widespread for UHPC mix creation. This practice›s success is hampered by the fact that the input materials come from a variety of sources. Several difficulties are associated with initiating a UHPC design utilizing area market materials. Figures 1 and 2 show the mixing proportions for UHPC mixes, which succeeded in producing concrete with compressive strength 150 MPa and more.

The procedure of defining the concrete mixture proportion is different for every researcher, but most of them have the same concept, for example, Richared and Cheyrezy (1995), Alkaysi and El Tawil (2016), Seyam et al. (2020), Habel et al. (2006), Aoude et al. (2015), Deeb et al. (2012). Azad and Hakeem (2013), Ma et al. (2002) and Wille (2013) go to the same way of replacing the coarse aggregates by fine aggregates with a high amount of binder and low b/w content. Table 2 shows the range of UHPC constituents materials used in various studies to produce UHPC successfully.

Table 2: UHPC components (Ghafari et al., 2015)

Components	Weight (kg/m^3)	Volumetric (%)
Binder / Cement	693-1114	22-35
Sand	733-1340	28-51
Crushed quartz	0-208	0-9
Silica fume	116-273	5-13
Fibres	79-234	1-3
Superplasticizer	14-40	1.4-4
Water	140-240	14-24

4. UHPC APPLICATIONS

The increased strength and durability of UHPC are primarily attributable to improved particle gradation, which results in a highly densely packed mix, a very low water-to-powder ratio, and the utilization of steel fibres. UHPC is a desirable material due of its unmatched strength and durability and it became an attractive material for bridges construction, In 1997, a brave application was made in Canada, the very first prestressed hybrid pedestrian bridge over the Magog River in Sherbrooke was built using UHPC, this use for UHPC opens the door for using this superior concrete in bridges. In 2001 France constructed Bourg-les-Valence bridge made for cars and trucks, a year after South Korea built a bridge with a main span of 120 m using UHPC, in 2003 Japan also joining

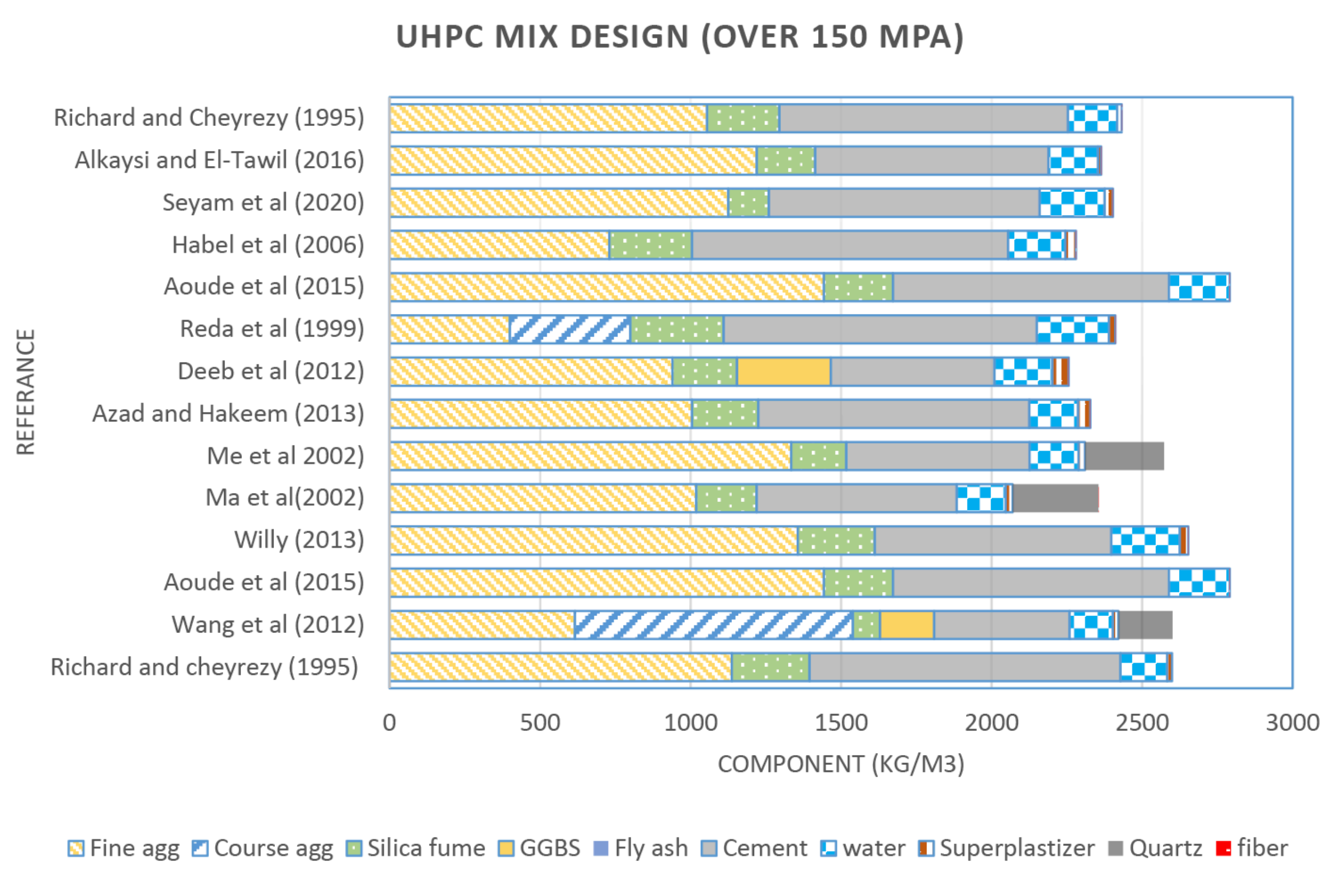

Fig. 1: UHPC materials and mixture proportions

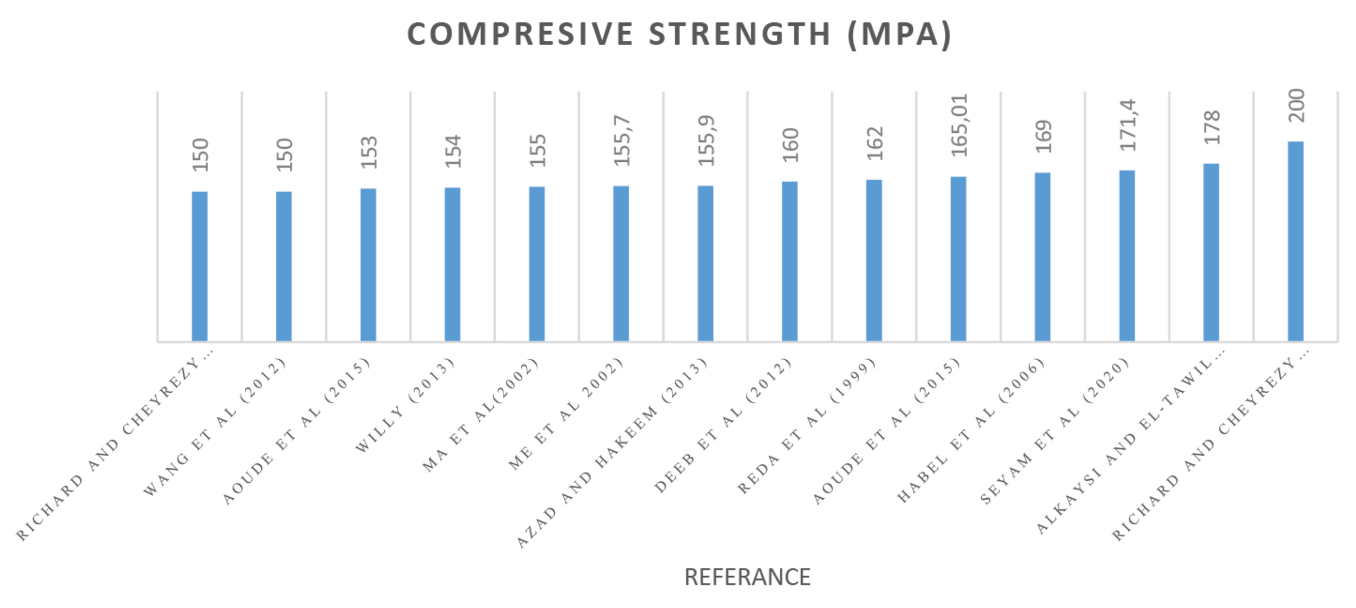

Fig. 2: The compressive strength of each researcher´s mix

the UHPC world, by constructing Sakata-Mirai footbridge with 50 m span. Following the success of UHPC bridge construction, in 2005 the construction of four bridges started at the same time, the Papatoetoe footbridge in New Zealand, the Shepherds Gully Creek Bridge in Australia, the Bourd-les-Valence bridge in France, and the Horikoshi C-ramp bridge in Japan. Since then UHPC application in bridges became more and more popular around the world. In 2013, 55 bridges in total have been built using UHPC in United states and Canada in addition to around 22 in Europe and 27 in Asia and Australia and more recent bridges mentioned in *Table 3.*

UHPC can be used as beams, girders, deck panels, protective layers, field-cast joints between different components, etc. (Tirimanna, 2013), (Graybeal, 2013), (Musha et al., 2013), (Park et al., 2013), (Brugeaud, 2013), (Kim et al., 2013). Compared to standard reinforced concrete bridges, most bridges constructed using UHPC components or joints have a slender shape, a considerable reduction in volume and self-weight, a speedier construction process, and increased durability (Graybeal, 2006). The majority of UHPC constructions need less than half the section depth of conventional reinforced or pre-stressed concrete components, resulting a huge weight reduction (Perry, 2006). This lighter-weight construction and materials efficiency used in UHPC structures lead to a sustainable structure through its lower carbon footprints (Voo, 2010).

The application of UHPC is not limited to bridges; UHPC is recommended for tunnel construction owing of its greater strength and fire resistance, which are critical characteristics for this type of building. UHPC's strength and durability make it an appropriate material for seismic columns as well. This is a novel method of designing earthquake-resistant columns; UHPC components are also employed in green energy, where they are used to build larger wind turbine towers. By increasing the strength and reducing the section size of the towers, we can enhance their production and create more renewable energy.

UHPC is the solution to concerns regarding the degradation, maintenance, and replacement of highway infrastructure. Due to its longer life and reduced lifetime cost, it is the ideal material for repairing and replacing existing roads and bridges.

5. UHPC CHALLENGES

UHPC is used in many applications around the world, but this use is still very limited compared with ordinary concrete, a lot of challenges still face the UHPC for wider implementation, as the benefits of this innovative material are still not well known.

Key challenges that must be addressed to provide a higher level of convenience to stakeholders, designers, contractors, and manufacturers to successfully implement UHPC in the field including, developing a logical and accurate method for optimizing UHPC components and mixture design to ensure the successful development and implementation of UHPC on a larger scale, some properties of UHPC affected by the fibre orientation in the mixture like the flexural tensile strength, therefore, it is necessary to develop a reliable method that allows efficient distribution of fibres in its concrete matrix in the desired direction, especially when the work with small sizes elements.

The shrinkage strains in UHPC mixes are much greater than those in conventional concrete. As a result, specific additives or preventive measures are required to address dimensional stability difficulties, particularly in large-scale structures.

The high strength properties of UHPC's and durability are heavily dependent on heat treatment. As a result, unique measures for on-site and precast heat treatment of the building should be investigated.

Due of the UHPC's extremely low w/c ratio, high-power mixers are necessary to adequately mix its constituents. Additionally, many adjustments to off-site mixers are necessary for the effective manufacture of precast UHPC parts.

The generally acknowledged, simple, and reasonable design requirements for UHPC (reinforced and unreinforced) should be designed to provide the design engineer confidence in the effective application of the UHPC's high strength and other special qualities.

6. CONCLUSION

Ultra high-performance concrete, the new generation for wider concrete applications and solutions, it has a superior level of qualities that had never been thought possible before. After reviewing the subject thoroughly, the following conclusions were found:

Table 3: *Applications in Bridge engineering*

Year	Location	Name
2017	China	Yuan Jiahe Bridge
2015	China	Fuzhou University Landscape Bridge
2013	United States and Canada	55 bridges using UHPC have been built or are under construction
2013	Czech Republic	Celakovice Pedestrian Bridge
2010	Austria	WILD Bridge
2010	Malaysia	Kampung Linsum Bridge
2009	SouthKorea	Office Pedestrian Bridge
2008	United States	Cat Point Creek Bridge
2008	United States	Jakway Park Bridge
2008	France	Pont du Diable Pedestrian Bridge
2008	Japan	GSE Bridge
2007	Canada	Glenmore Pedestrian Bridge
2007	France	Pinel Bridge
2007	Germany	Friedberg Bridge
2006	United States	Mars Hill Bridge
2006	China	Luan Bai trunk Railway Bridge
2005	Japan	Horikoshi C-ramp bridge
2005	France	PS3, Bridge (Bourd-les-Valence bridge)
2005	Australia	Shepherds Gully Creek Bridge
2005	New Zealand	Papatoetoe footbridge
2003	Japan	Sakata-Mirai footbridge
2002	South Korea	Peace Bridge (Seonyu footbridge)
2001	France	Bourg-les-Valence bridge
1997	Canada	Sherbrooke Overpass

It was clear that the majority of researchers at the state-of-the-art highlighted that UHPC exceeds all expectations in terms of mechanical and environmental performance, emphasizing the possibility of more fantastic applications in building.

The mechanical properties of the UHPC are greatly superior to the properties of ordinary concrete. These incomparable values are a function of water to binder ratio, ultrafine powders, optimized packing of particles, method of curing, and microstructural reinforcement.

This technique enables the construction of buildings that are lighter, bigger, or have a greater span than conventional designs. Due to its exceptional workability, new concrete may be cast in irregular or extremely thin forms to create structures with an exceptionally aesthetic look or finish.

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