Recent trends in ultra-high performance concrete (UHPC): Current status, challenges, and future prospects

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Abstract: Ultra-high performance concrete (UHPC) combines advanced fibrous and cementitious material technologies to achieve high strength and exceptional durability. The material tends to have microscopic pores that prevent harmful substances such as water, gas, and chlorides from entering. UHPC can also achieve compressive strengths above 200 MPa and tensile strengths above 20 MPa. It also shows significant tensile strain hardening and softening behavior. Owing to all these characteristics, UHPC has excellent performance, making it a potentially attractive solution for improving the sustainability of construction components. Despite UHPC's outstanding mechanical properties, superior toughness and ductility, and extraordinary durability, various challenges prevent its widespread use. At the same time, several challenges are currently being faced in the applications of UHPC, which include i) design aspects such as material properties; ii) production technology for large-volume and/or long-span elements with low workability, high spalling, and high shrinkage strains; and iii) unknown durability characteristics after the appearance of long-term concrete cracking. With a lack of industry experience, UHPC specialists face additional challenges in spreading hands-on practice to concrete industry professionals so that the latter can be well versed in applying this sophisticated concrete technology. For these reasons, a comprehensive literature study on recent development trends of UHPC should be conducted to determine its current status and prospects. This article scientifically reviews the current status, carbon capturing capabilities, sustainability aspects, challenges and limitations, and potential applications of UHPC. This state-of-the-art review is aimed at helping scientific researchers, designers, and practitioners widen the use of UHPCs in advanced infrastructure applications. This review will help specialists to develop the design guidelines to enable the widespread application of sustainable UHPC. In doing so, design engineers will be provided with an assurance to fully exploit the high strength and other special properties of UHPC and develop models that can efficaciously estimate the ultimate bearing capacity of UHPC sections under various loading conditions.

Keywords: carbon capturing, cementitious materials, challenges, durability, fibers, limitations, sustainability, ultra-high performance concrete

List of nomenclature

APAC	Asia-Pacific
BP	Basalt powder
CAC	Calcium aluminate cement
$CaCO_3$	Calcium carbonate
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2U	Carbon dioxide utilization
CSA	Calcium sulfoaluminate cement
DCP	Dehydrated cementitious powder
DOH	Degree of hydration
DSP	Dense silica particle
FA	Fly ash
FRC	Fiber-reinforced concrete
GGBS	Ground granulated blast furnace slag
HPC	High performance concrete
HSC	High-strength concrete
ITZ	Interfacial transition zone
LP	Limestone powder
MDF	Macro-defect-free
MK	Metakaolin
MP	Marble powder
NSC	Normal strength concrete
OPC	Ordinary Portland cement
PSBCs	Prefabricated segmental bridge columns
RC	Reinforced concrete
RHA	Rice husk ash
RPC	Reactive powder concrete
SCM	Supplementary cementitious material
SF	Silica fume
UHPC	Ultra-high performance concrete
UHSC	Ultra-high-strength concrete

1 Introduction

Ultra-high performance concrete (UHPC) is an enhanced fibrous and cementitious concrete with high compressive strength (120–250 MPa) [1–6], particle packing density (0.825–0.855) [7], tensile strength (15–20 MPa) [3,8–13], and extraordinary durability [14,15]. UHPC has 300 times the ductility and energy absorption of high performance concrete (HPC) and three to sixteen times the compressive strength of regular concrete [16]. Because of its outstanding mechanical qualities as well as its superior ductility and toughness under tension, UHPC is often regarded as the material of choice when it comes to seismic design reasons [9,10]. UHPC is a feasible option for enhancing the long-term viability of buildings and infrastructure facilities [17].

UHPC is produced with a low water/cement (w/c) ratio, which typically ranges between 0.15 and 0.25 [18]. Given the low water content, superplasticizer agents are required to improve the packing of the composite material's particles, which results in increased fluidity and workability of the mixture [19]. In most UHPC manufacturing scenarios, silica fume (SF) and ordinary Portland cement (OPC) are used as cementitious binders [4,5]. During the period 2018–2022, the global UHPC market is expected to develop at a multifactorial annual growth level of close to 7% (Fig. 1) [20]. The demand of UHPC has grown in recent years; as the large carbon footprint of OPC has become a worldwide concern, the need for more environment friendly cementing binders has increased considerably [21].

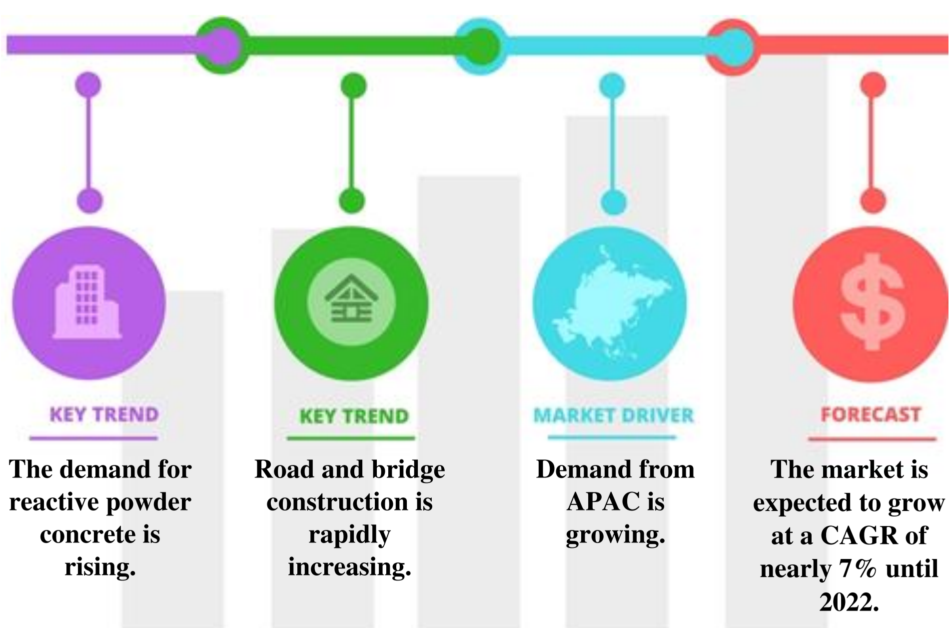


Fig. 1: Global UHPC market (Adapted with improvement from [20])

The mechanical properties of UHPC makes it a perfect material for applications where strength is a primary design criterion and concrete structural element sizes can be lowered to make them smaller, thinner, and more aesthetically acceptable [22,23]. It is commonly composed of Portland cement, fine aggregate, SF, a water-reducing additive with a high range of effectiveness, and fibers [24]. UHPC may be a suitable material for concrete constructions that are exposed to harsh environments [25]. UHPC is widely used in bridge engineering, ultra-high-rise building, and long-span objects [26]. In an outdoor or severe climate-exposure situation, the better endurance and longevity of UHPC improves service life and lowers maintenance cycles [27]. It is possible to achieve high tensile ductility and ultra-high compressive strength in concrete materials by employing the use of synthetic fibers in UHPC [28]. Although the technology and development of UHPC have been thoroughly explored and established from micro to macro level, its extensive promotion remains challenging because of complex manufacturing process and high cost [29]. The complicated manufacturing process is mostly because too many components are used, resulting in difficult handling and high costs [30]. UHPC technology introduces a novel product that enables infrastructure developers to expand their product and service offerings [15,31]. The fundamental tenet of this technology is introducing systematic solutions to overcome inherent flaws in conventional concrete [32]. This novel concrete is the better choice as it exhibits better ductile behavior, with a high capacity to distort and support tensile and flexural loads even after early cracking patterns [33]. The higher performance properties of UHPC are the result of upgraded mineral matrix microstructural features and optimization of the bonding between concrete matrix components [34].

Since more than 20 years ago, UHPC has received growing interest from the construction sector, with the focus on the following: construction bridges [35–38], unique architectural designs, skyscrapers [39], damaged concrete components [12,40], vertical elements (e.g., wind turbines and windmills towers) [17,41,42], facilities related to gas and oil industry applications, offshore constructions [43,44], hydraulic structures [38,45,46], and overlay materials [47]. The usage of UHPC are prominent in all these applications and in addition to bridge and road constructions [25]. UHPC is particularly well suited for bridge building in tough conditions because its composites possess high strength and the need for rehabilitation during service life is low [48]. UHPC is also a desirable choice for bridge construction in high-traffic areas as it provides long and stronger spans and thus creates additional space available for use. The quality of used materials and manufacturing precision have a substantial influence on the performance of UHPC though [49]. The high cement content of UHPC is another aspect that contributes to carbon dioxide (CO_2) emission, which increases the concerns on environment issues [7,15]. As a cement replacement, SF incorporating fillers (such as quartz powder and limestone) can tremendously improve the workability of ultra-high-performance fiber-reinforced concrete (UHPFRC) and enhance the effectiveness of steel fibers in the material [50]. Furthermore, the use of fillers can reduce the amount of micro silica required, which is important for UHPFRC in terms of cost, energy, and environmental impact [50,51]. SF has a wide variety of physical and chemical properties depending on its sources, so further research and standardization are warranted [5,50].

UHPC may also be more sustainable because the higher concrete durability allows for reduced maintenance [22,52]. Despite the lack of UHPC applications to reliably compare the life-cycle durations and costs of UHPC with those of conventional concrete [12,17,39–44,38,45,47,46], most studies indicate that UHPC's exceptional durability should boost structural serviceability while lowering maintenance costs [35,53,54]. In contrast to normal-strength concrete (NSC), UHPC may, according to the findings of various studies [55], be recycled multiple times or utilized as granular in the construction of roads. This recyclability is a result of the fact that not all of the cement in UHPC is hydrated during the hardening process, which leaves unhydrated cement accessible for future reactions [56].

For UHPC, the changing properties of SF is considered crucial, necessitating a more exact mix set-up [27]. Other challenges of utilizing SF are its fast rising cost and its impact on the surrounding ecology as SF dust is hazardous to employees and unfriendly to the environment [55–57]. SF warrants extra caution and an effective strategy in the stages of transportation, storage, and inclusion in UHPC [58]. Another critical component of UHPC is steel fibers, which are commonly utilized to increase the fracture and ductility properties of UHPC. The inclusion of steel fibers needs more accurate control though in terms of synthesis, embedding, and distribution within UHPC systems. Using high content of steel fibers in UHPC may raise the production cost (Fig. 2) [9,25,59,60]. In addition, the poor distribution can slow down the hydration process and introduce extra air into the concrete mixture [61]. The key to ensuring good engineering properties and low cost of UHPC is to improve the effectiveness of SF and steel fibers in the matrix [7,22,62]. The effect of calcium sulfaluminate cement (CSA) addition on the microstructure matrix of UHPC is studied. The addition of 5–15 percent CSA appears to reduce the autogenous shrinkage of UHPC [63] and leads to the creation of a denser matrix [64]. Similarly, the addition of calcium aluminate cement (CAC) as a cementing binder in UHPC shows better performance at high temperatures than natural UHPC, which usually fractures at temperatures of ~400 °C [65]. Given the constraints of the current UHPC [66,67], a novel type of UHPC is developed, with more advanced mechanical and durability performance, excellent fresh properties, ease of application, low cost, enhanced eco-friendliness, and worldwide available components [1–3,7,14,15].

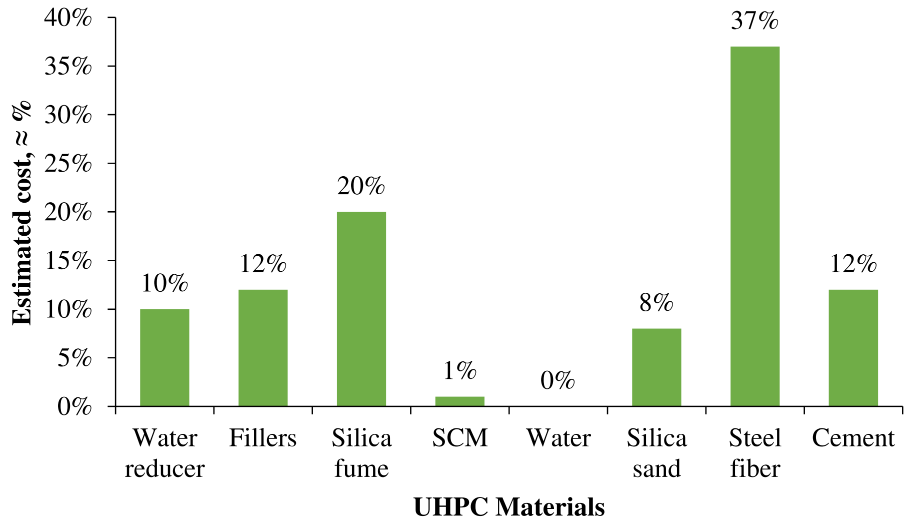


Fig. 2: Estimated cost of UHPC materials (Data adopted from [54,68–72])

Moreover, UHPC offers a diversified product line that can be used in infrastructure and large projects such as federal roads, highways, bridges (Fig. 3), water conservancy facilities, marine facilities, military facilities, and precast structures [73–82,36]. As a result of the deterioration of many service facilities and infrastructure globally, innovative UHPC solutions such as UHPC bridge overlays, prefabricated bridge components [83–85], seismic columns [86,87], bridge girders [30,88–90], piles [91,92], cladding [75,93], link slabs [22,52,94,95], and waffle deck panels [80] are gaining popularity and acceptance within the construction industry. The advanced development of UHPC enables designers and architects to introduce several designs and engineering solutions such as structural and decorative punctured facades in lattice style or mesh designs; ultra-thin [75], lightweight panels [35]; puncture levels surpassing 50%; and full facades with multifaceted shapes, textures, and curvatures [33]. This remarkable progress seems hindered though by limited design codes, insufficient information on raw materials and manufacturing technologies, and expensive production costs [75].

Nevertheless, the use of UHPC as an innovative and promising material is gaining growing attention from many stakeholders, including researchers and construction companies [7,66,90,96–102]. However, the wide use of UHPC is prevented by various challenges. Examples are production technology for large volume with low workability, high spalling, and high shrinkage strains and unknown durability after the appearance of long-term concrete cracking. Owing to a lack of industry experience, UHPC specialists face additional challenges in spreading hands-on practice to concrete industry professionals so that the latter can be well-versed in the application of sophisticated concrete technologies. For these reasons, a comprehensive literature study on recent developments trends of UHPC should be conducted to determine its current status and future prospects.

This article scientifically reviews the background, carbon capturing, sustainability, challenges, limitations, and potential applications of UHPC. The findings of this state-of-the-art review likely help specialists establish the design guidelines for the cutting-edge and sustainable UHPC. In doing so, design engineers are given assurance to fully exploit the high strength and other special properties of UHPC as well as develop models that can efficaciously estimate the ultimate bearing capacity of UHPC sections under various loading conditions. In particular, design engineers can create a reliable measure for UHPC's ultimate bearing capacity. This review can help scientific researchers, designers, and practitioners widen the use of UHPCs in advanced applications.

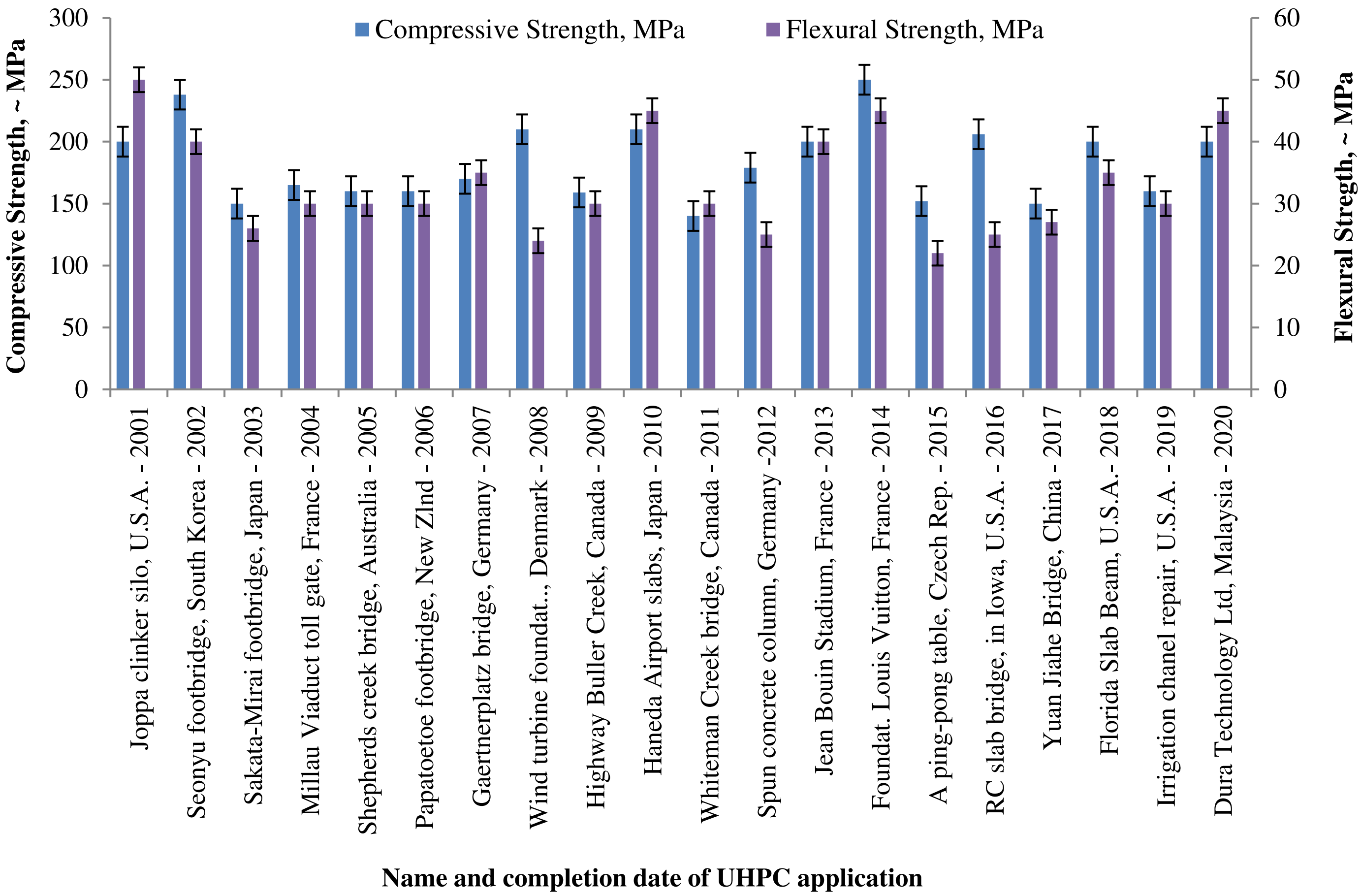


Fig. 3: Typical applications of UHPC worldwide

2 Historical background

The history of concrete can be dated back to the Roman Empire, but modern concrete is widely estimated to originate in 1824 when Joseph Aspdin developed a substance known as Portland cement [103] (Fig. 4). The term "concrete" now refers to the substance formed by the specific design mix of cement, water, fine aggregates, coarse aggregates, and other minerals [4,5,104]. The concept of concrete was first introduced in 1849 when French gardener Joseph Monier [105] prepared reinforced flowerpots by blending steel wire mesh with a mortar shell to solve problems with concrete. This instance is now considered the origin of RC constructions [106]. Including steel reinforcement enhances not only the strength of the concrete structure but also its ductility markedly [26,99,107]. The low tensile strength and high stiffness of concrete are the primary downsides of this material. Since its origin in the 1930s, high-performance concrete, or HPC, has been developed with the intention of increasing the compressive strength of regular concrete components as well as their durability under bearing loads [75].

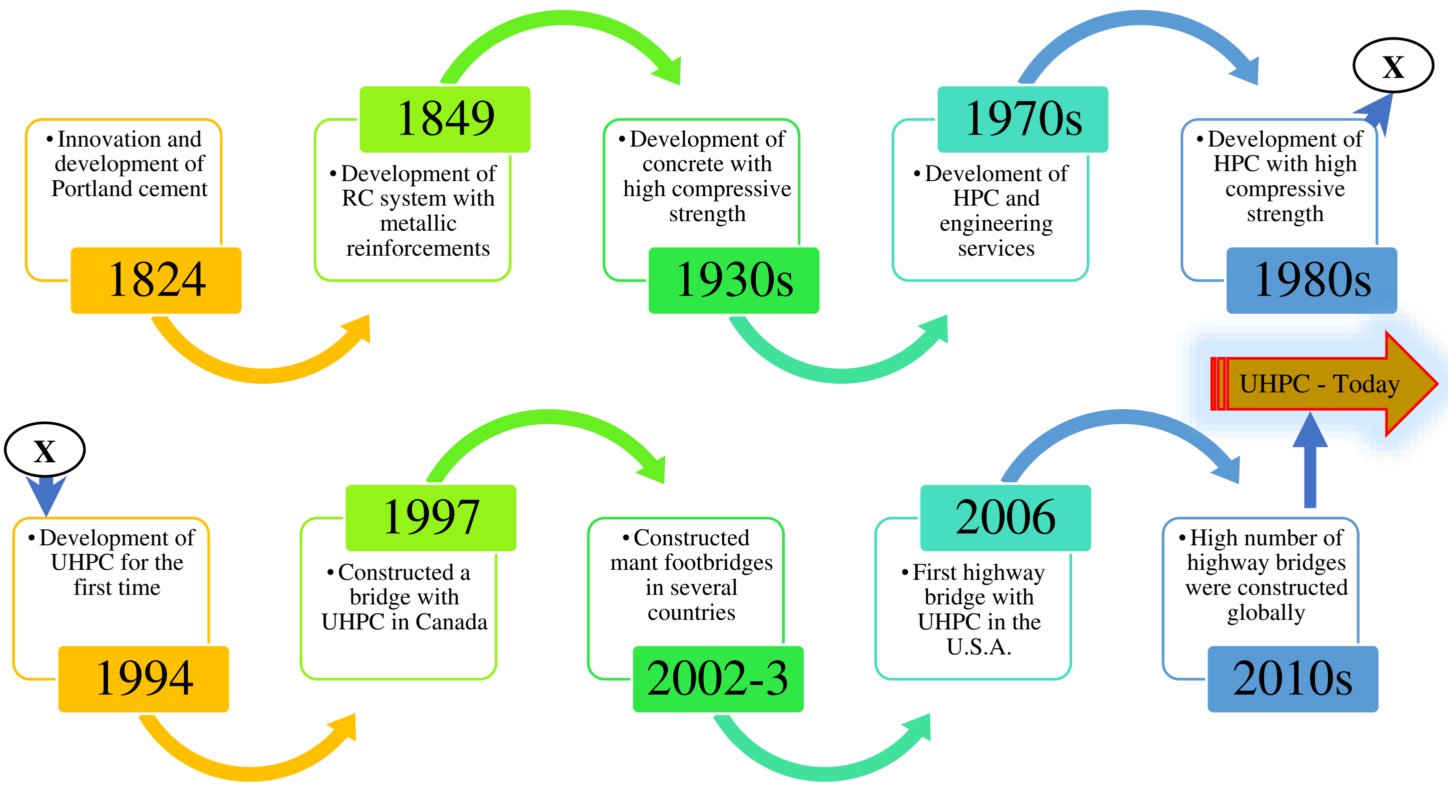
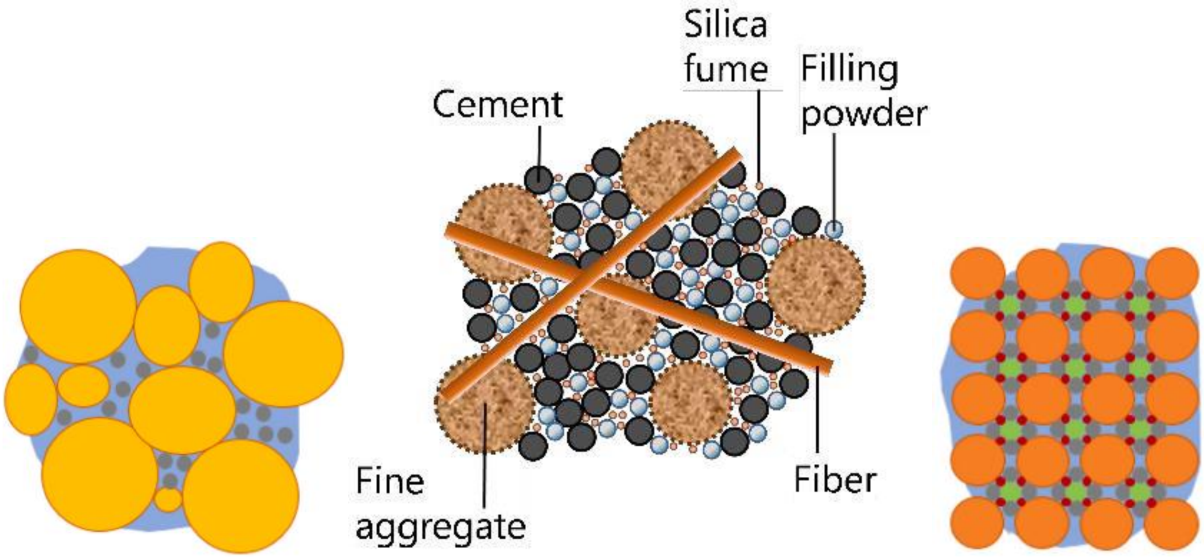


Fig. 4: Historical development trends of UHPC

Eugene Freyssinet demonstrated at the time that increasing the compactness of cementitious matrix can increase the compressive strength of concrete elements [108]. However, the real interest in HPC emerged during the 1970s [104]. It has been stated that developing HPC can be accomplished by lowering the w/c ratio to a value that falls between 0.2 and 0.3. [109]. Up to the 1980s, there was a persistent interest in developing this new idea of HPC. During this time, various proposals were made to increase the performance of the new type of concrete. For instance, research was conducted for the very first time on how effective it is to use additives [110,111]. Because the use of steel fibers improves the performance and qualities of concrete, this type of concrete is referred to as macro-defect-free, or MDF concrete [112–115], optimized UHPC composite with dense structure [114,115], clay-modified concrete [116], dense silica particle (DSP) concrete [15], and reactive powder concrete (RPC) [117] (Fig. 5).



a) Low particle packing of NSC, b) Details of composition of UHPC, c) Higher particle packing of UHPC

Fig. 5: Particle packing (composition) of NSC and UHPC (Adapted from [7,117,118]**)**

Various challenges concerning concrete became more apparent as the demands placed on the building industry increased. Instability and unevenness in the matrix, a low tensile-to-compressive strength ratio, a high weight-to-strength ratio, low ductility, and poor durability are some of these problems [104]. The development of a new type of concrete known as HPC in the 1970s was made possible through utilization of low w/c ratio, critical selection and gradation of aggregate particles, and addition of water-reducer admixtures to achieve compressive strengths ranging from 50 to 120 MPa [36,119] and increased durability [104]. Consequently, HPC was found to be brittle. In the early 1980s, "fiber-reinforced concrete" (FRC) was created by incorporating fibers into high-strength concrete [111]. The incorporation of fibers into concrete results in considerable improvements to the material's tensile strength, toughness, ductility, and fracture strength.

In 1994 [120], employing an optimum particle size distribution of cement in combination with fine and ultrafine particles was discovered to enhance the compressive strength of concrete to higher than 120 MPa [120]. The resulting concrete is known as ultra-high strength concrete [121,122], and it is distinguished for its great durability, self-compactability, and high strength. The concept of UHPC was first introduced by Larrard in 1994 [123]. UHPC is a novel type of concrete recently developed for its superior strength and durability (Fig. 6) [124,125].

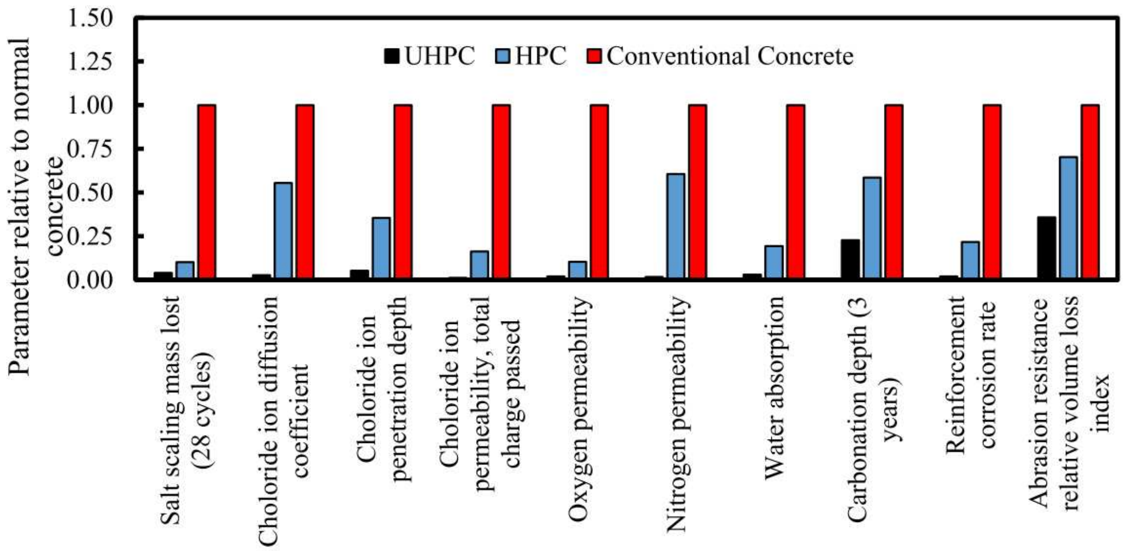


Fig. 6: Durability of UHPC compared with HPC and traditional concrete (Adapted from [7,124]**)**

In addition to structural repair and expedited construction of bridges, UHPC can be used in a variety of other applications. In 1997, a pedestrian bridge in Canada was the first use of UHPC. UHPC was used in the construction of the Seonyu footbridge in South Korea in 2002. The bridge has a span of 120 meters [77]. The following year, UHPC was used to construct the Sakata Mirai footbridge with a 50 m span in Japan [126]. The Seonyu footbridge is the world's longest span bridge made from UHPC. Its perforated superstructure webs save weight and provide aesthetic attractiveness [36]. The use of UHPC allowed for the construction of the Seonyu footbridge structure with approximately half of the amount of material that would have been required for its construction if it had been built with conventional concrete. UHPC offered the same level of strength performance but was smaller in size. [79].

UHPC was utilized to build the Wapello County Mars Hill Bridge in 2006 [49]. In addition, UHPC was employed to rehabilitate and fortify the Kinzua Dam Stilling Basin. Subsequently, more than 34 research initiatives across several research institutes were conducted with the goal of making UHPC a dependable, commonly available, economically viable, and widely used material [127]. Afterward, the use of UHPC saw a wave of growing interest in the bridge construction sector in many countries including Austria, Croatia, New Zealand, Germany, Switzerland, China, Australia, Japan, Italy, South Korea, Slovenia, the Netherlands, and Malaysia [12,17,39–44,38,45,47,46]. In 2005, A German research establishment launched a $15 million research program that included 34 projects at over 20 local research institutes [128]. This project was started with the intention of raising public knowledge of UHPC so that it may be marketed as an alternative for use that is practicable, easily accessible, economically feasible, and already well known. A research initiative focusing on UHPC has also been started in South Korea. The Korean Institute of Construction Technology provided funding for an investigation into the use of UHPC in cable-stayed bridges in the amount of 11 million dollars in 2007 via a program named Super-200 m. [129]. The outline of UHPC was initiated by Dura Technology in 2006 in Malaysia by launching the first bridge constructed with UHPC, which was completed in 2010 [130]. Since 2010, Dura Construction Company has conquered the UHPC industry in Malaysia as a company specializing in this sector. More than 90 UHPC bridges were constructed, with another 20 currently under construction [131] [47]. Up to now, this technique has enabled the construction of concrete structures that are lighter, larger, or have a greater span than conventional designs. Owing to its exceptional workability, the new concrete can be cast in irregular or extremely thin shapes to create structures with a unique aesthetic look or finish.

3 Current status

UHPC is a novel class of concrete introduced within the last few decades that features superior strength and durability characteristics (Fig. 7) [1–3,7,14,15,110,132–146]. To date, there is a considerable demand for effective and long-lasting repair of bridge decks that have been damaged because of the freeze–thaw cycles, high vehicle traffic, increased vehicle loads, delamination of concrete cover, deck cracking, and reinforcing steel corrosion [99]. The development of UHPC continues day by day and it is considered the most outstanding concrete materials at this time, having the most distinguished properties (Table 1).

Many researchers also tested the benefits and current status of UHPC in terms of its own performance and the buildings constructed from it [147]. Despite UHPC's advantages, its widespread application in construction is limited by a lack of design guidelines and requirements for predicting performance and the need for unique batching, mixing, and curing [99]. The potential of employing UHPC mixes in bridge building is explored from a different perspective, taking into account the smaller cross-sections produced for bridge structural elements poured using UHPC mixes [148]. For UHPC bridge construction, smaller sections, longer spans, and fewer bridge girders are required [30]. Thus, costs are down in terms of labor and materials, and smaller construction equipment are needed [149]. The advantages of UHPC can be enhanced by employing welded wire reinforcement in bridge girder fabrication and bigger prestress strands for tension reinforcement [59]. With the continuous related research, UHPCs are being used in a growing number of applications because of their superior performance and the diversity of relevant additives that may be employed to improve UHPC parameters and overcome UHPC shortages [150].

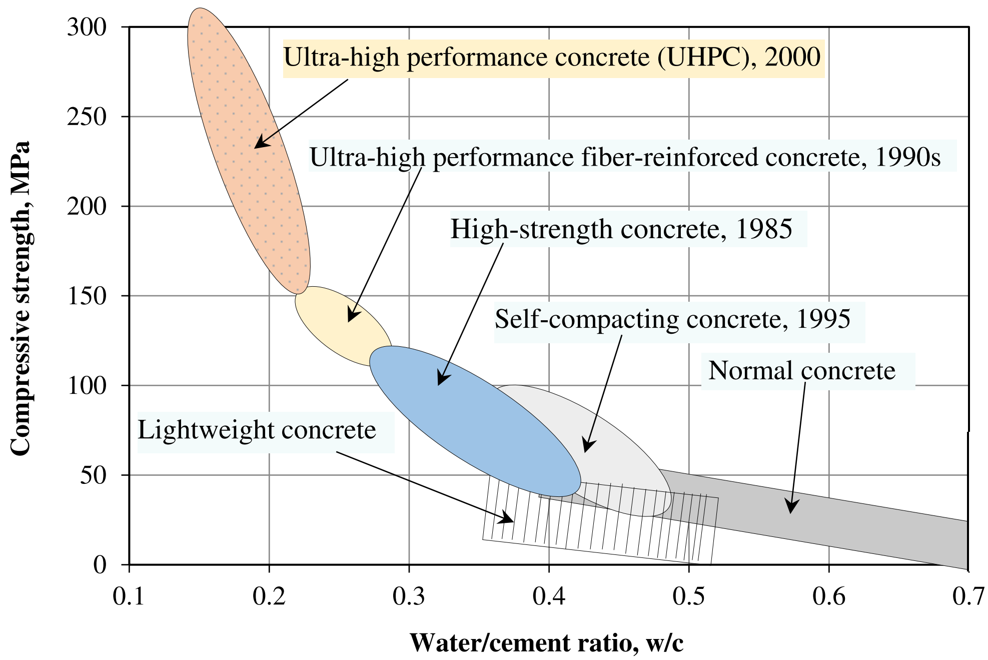


Fig. 7: Comparison between the UHPC with the other concrete grades (Data adopted from [1–3,7,14,15,110,132–146,151]

Numerous investigations are undertaken to improve the strength and failure behavior of HSC [151,152] and UHPC concrete [1–5,7,78,111,112,153,154]. The development of paste/concrete using DSP and MDF ingredients is one way to improving the strength qualities of UHPCs [111]. According to Sharma et al. [112], the compressive strengths of concrete made with DSP paste and concrete vary from 120 to 270 MPa, while the compressive strengths of concrete made with MDF paste and concrete are larger than 200 MPa. Two distinct techniques are also introduced in previous studies aimed at developing the optimal UHPC mix design [7,78]. The first strategy is "densified tiny particles," and it refers to developing a granular matrix with a compressive strength of 150–200 MPa [1–5]. This strategy is based on the inclusion of mineral additives and fibers, but due to the inclusion of additives and fibers (Table 2), this matrix has low porosity. The second strategy refers to the matrix-free macro defects [4]. This approach contemplates the addition of a modified polymer to the mix to limit the number of pores. Owing to polymer hardening with time, this type of concrete mix becomes sensitive to water infiltration and creep [155]. Research on the first strategy continues, despite the fact that both approaches result in a compact and brittle material [153]. To overcome the ductility shortage, the trend was to insertion of more short fibers [154].

Table 1: Compositions and properties of UHPC, HSC, and NSC

(Raw data adopted from [3–5,7,11,56,110,132,135–142,151,156])			
Compartments	**NSC**	**HSC**	**UHPC**
Raw materials (*approx.*, ≈)			
Cementitious materials	RHA, FA, MK, GGBS, RM	RHA, FA, MK, SF, GGBS, RM	SF, RHA, FA
Chemical admixtures	Water reducing agent	High range water reducer/ Water reducing agent	High range water reducer
Silica fume	Designated	≈ 40	≈ 50–300
Reinforcement/Fibers	Designated	< 40	40–250
Super-plasticizer (SP)	Designated	10	≈ 10–70
Water	> 200	≈ 100–150	110–260
Fine aggregate (sand)	≈ 700	600	≈ 1000–1200
Cement	< 400	400	600–1000
Maximum aggregate size	19.0–25.5	9.5–12.5	≈ 0.15–0.6
Coarse aggregate	≈ 1000	≈ 900	Designated
Main parameters (*approx.*, ≈)			
Water/cement (w/c)	0.41–0.70	0.25–0.40	0.15–0.28
Water/binder (w/b)	Designated	< 0.28	< 0.27
Properties (*approx.*, ≈)			
Compressive strength, MPa	20 -42	> 42 – 100	> 100
Flexural strength, MPa	1.5 – 5	5 – 22	22 – 53
Tensile strength, MPa	2 - 5	> 5 - 10	> 10 - 45
Permeability coefficient	10^{-10}	10^{-11}	$10^{-(12\ \text{to}14)}$
Durability	Medium	high	Very high
Ductility	Low ductile	Medium ductile	Highly ductile
Toughness	Medium	High	Very high
Impact loading	Medium	High	Ultra-high tough
Impermeability	Low	Very low	Nil
Freeze-thaw protection	Air entrainment	Air entrainment	Air entrainment
Abrasion resistance	Medium	High	Very high

Annotations: *Ultra-high performance concrete (UHPC), High-strength concrete (HSC), and Normal strength concrete (NSC).*

According to the reports, UHPC offers exceptional strength and durability capabilities, in addition to having a very low porosity, high packing density, and low permeability [65,157]. To achieve UHPC with super strength properties, high durability, and more sustainability, several factors should be considered such as removing coarse aggregate of more than 5mm, minimizing w/c ratio via superplasticizers, and substituting OPC with a number of other possibilities of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS), fly ash (FA), metakaolin (MK), rice husk ash (RHA) [4,5,158,159].

Removing the larger coarse aggregate and lowering the w/c ratio result in a more compacted matrix and homogeneous microstructure [65]. Several investigations recently show that incorporating fibers into UHPC improves several strength indices, including flexibility and ductility [160].

Table 2: Properties of fibers used in the development of UHPC, as reported by previous researchers

Type	Size, (µm)		Relative density, (g/cm^3)	Elongation, (%)		Young modulus, (GPa)		Tensile strength, (MPa)		Refs.
	Max.	Min.	Average	Max.	Min.	Max.	Min.	Max.	Min.	
Carbon	7	18	1.7	1.2	1.6	200	480	1800	4000	[11]
Glass	10	16	2.75	2.5	3.5	60	80	1400	2500	
Nylon	20	30	1.17	15	20	4	5	900	960	
Polyester	10	80	1.3	10	15	6	15	735	1200	[12]
Polyethylene	800	1000	0.95	3	5	5	6	200	300	
Polypropylene	20	70	0.92	15	28	3.4	11	300	700	
PVA	1.10	1.50	1.35	5	50	5	50	600	2500	[13]
Steel	250	1000	7.8	0.5	4	200	250	280	2800	

Replacing cement with SCMs converts $Ca(OH)_2$ to C-S-H, C-A-H, or C-A-S-H, increasing net-zero CO_2 targets [65]. Furthermore, the inclusion of fiber reinforcement may greatly enhance the flexural, tensile, and shear strengths of UHPC, hence improving its ductile behavior under tension [30]. Additionally, the steel bars may have a significant quantity of steel fibers added to them in order to form a workable filigree, which will ultimately result in a reinforced concrete building that is both strong and lightweight. This can happen in specific conditions [17]. In the case of partially replacing OPC with RHA in a UHPC mix, the $Ca(OH)_2$ content is reduced by 45% after 28 days and 65% after 91 days [108]. On the other hand, the use of SF results in a reduction of the calcium hydroxide concentration by as much as 70% after 28 days and 90% after 91 days [136]. Compared with RHA, SF has a greater potential to decrease $Ca(OH)_2$ at later ages [158]. In addition, the pozzolanic reactivity of SF doesn't begin for around three days after the first hydration process has been completed [159].

Regardless of the availability of raw materials for pozzolanic additions, past research emphasize selecting the kind of additive depending on the required early and late-age strength. Recent research advocate lowering SCM particle size to boost pozzolanic reactivity. Nano silica 100 nm or less is stronger than micro silica in UHPC systems [161]. Fig. 8 shows the global UHPC market size by application in 2016 [162]**.** The reliability of girders produced utilizing UHPC mixes is examined, and bridge girder reliability indexes are calibrated to guarantee that they comply with current AASHTO LRFD design equations [54]. According to a relevant study, the shear and flexure reliability of NU I-girders synthesized with UHPC is compliant with the current AASHTO LRFD standards [88].

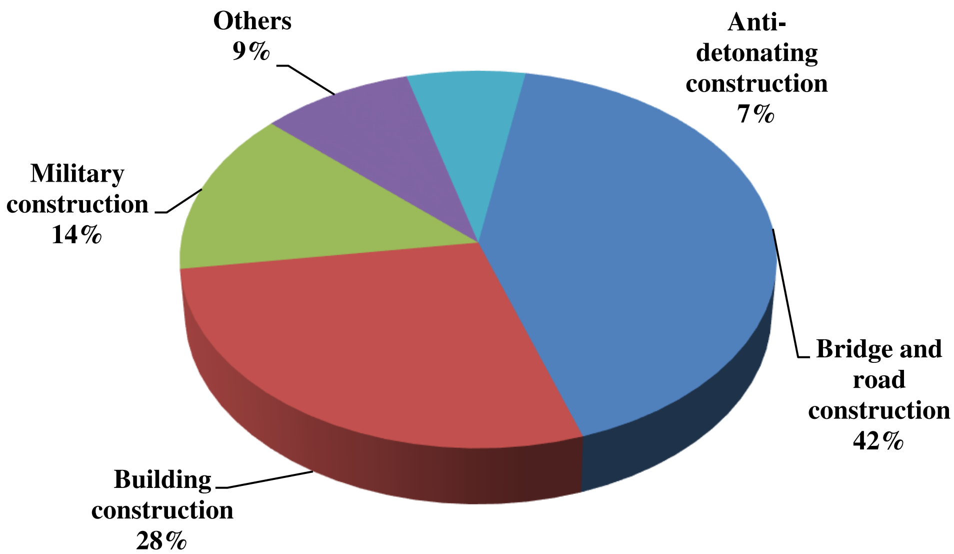


Fig. 8: Global UHPC market size by application, 2016 (≈ %) (Data adapted from [162])

Increasingly, researchers throughout the globe are studying how to make UHPCs while simultaneously reducing their carbon footprint and up-front material costs. Fig. 9 depicts the connections between embodied CO_2 (e-CO_2) emissions and UHPC compressive strength [163]. The graph shows a considerable positive association between UHPC compressive strength and e-CO_2. Both the slope for e-CO2 and the strength of the UHPC are very low, which is in line with what was discovered in the past. The e-CO2 levels produced by UHPCs are noticeably lower than those produced by other HPCs. The environmental effect of UHPC may be reduced by optimizing the addition binder and curing strategies [163]. Various approaches are used to achieve this goal [7] including: (1) decreasing the amount of cement in the mixture (850 kg/m^3) by using fillers and a large quantity of SCMs [156–158], (2) decreasing the amount of binder in the mixture (1200 kg/m^3), and (3) exchanging finely ground quartz sand for quartz sand or regular concrete sand [32,164,165], (4) using hybrid fiber systems [166,167], and (5) utilizing standardized curing in place of heat curing for inferior energy consuming [168,169]. These efforts minimize production cost, making UHPC systems more commercial and usable [69,170]. Despite the environmental benefits of using SCMs such as FA, RHA, and GGBS as cement replacement and the positive effects on strength parameters and durability of UHPCs, several researchers indicated that the variety of chemical compositions still represents a challenge as they result in inconsistent performance [171]. The variety of chemical compositions is attributed to the purity and efficiency of raw materials in production plants [172]. For this reason, the current commercial application of UHPCs with SCMs as cement replacement remains limited comparatively [7]. The development trends of the strength of UHPC as reported by previous studies are shown in Table 3.

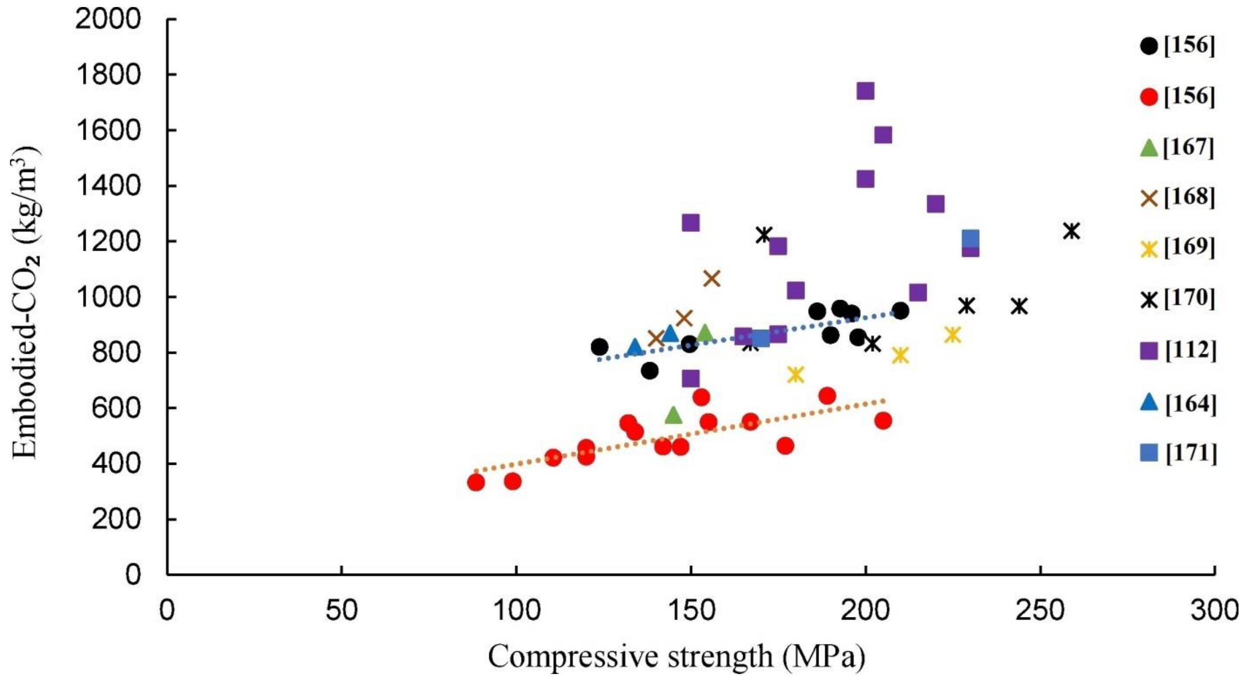


Fig. 9: E-CO_2 emissions of different sustainable UHPCs reported by previous researchers (Adapted from improvement from [117,163,170,173–177])

Table 3: Development trends of the strength of UHPC, as reported by previous researchers

Refs. [178]	**Year of production**	**SF (%)**	**FA (%)**	**GGBS (%)**	**Curing Methods** **1.** Autoclave **2.** Standard **3.** Steam **4.** Fog curing	**Compressive strength, MPa, 28 days**
[179]	2007	-	20 and 60	-	2	146 (90 days)
[173]	2008	35	10, 20, 40, and 60	10	1	248–262
[180]	2009	30	20, 40, and 60	-	1, 2, and 3	270
[181]		-	20	-	2 and 3	243
[182]		-	10 and 20	-	4	185 (91 days)
[182]	2010	-	20	-	4	185 (91 days)
[6]		-	20, 40, and 60	-	2 and 3	378
[57]	2011	0, 5, 10, and 15	5, 10, 15, 20, and 30	-	4	210 (91 days)
[183]		10	15	-	2	198
[174]		15–26	10, 20, and 30	10	1, 2, and 3	268–70
[184]		9	15	-	1 and 2	148
[185]	2012	-	16.7	-	-	170 (90 days)
[165]		10	20 and 40	20–40 LP	1 and 2	178–183 (1 year)
[6]		0 and 11.5	10 and 23	-	2 and 3	162

Refs. [178]	**Year of production**	**SF (%)**	**FA (%)**	**GGBS (%)**	**Curing Methods** **1.** Autoclave **2.** Standard **3.** Steam **4.** Fog curing	**Compressive strength, MPa, 28 days**
[186]	2013	-	25	-	2	164
[187]		-	17	20	1 and 3	212 (360 days)
[188]	2014	25	15, 30, and 50	-	2	160
[189]		4, 8, 12, and 20	4, 8, and 12	-	2	157
[45]		17	45	-	2	164
[70]	2015	20	20 and 24	-	2	172
[190]		10, 20, and 30	10, 20, and 30	-	2	180
[191]	2016	-	25	-	2	146
[192]		-	5, 10, 20, and 30	-	3	-
[193]		0 and 5	10–35	2.5 MK	2	153
[175]		5, 10, 15, and 20	30	-	2	140
[194]	2017	25	20, 40, and 60	-	1, 2, and 3	182
[195]		-	9	54 LP	1 and 2	142 (56 days)
[196]		-	4, 10, and 15	-	2	57
[195]		-	10, 20, and 30	-	3	110
[176]		4, 8, 12, 16, 19	4, 8, 12, 16, 19, and 23	4	Fog room	137 (120 days)
[197]		12, 14.4, 16.8, 19.2, and 21.6	2.4, 4.8, 7.2, 9.2, and 12	-	2 and 3	230
[198]	2018	0, 10, and 15	10, 15, 20, and 25	10 and 15	2	203 (91 days)
[199]		12.5	10, 20, and 30	-	2 and 3	168
[199]		-	10, 20, 30, and 40	-	2 and 3	122 (1 year)
[200]		10	15, 20, and 25	-	2 and 3	94
[201]	2019	0, 9, 10, and 17	9, 10, and 17	-	1 and 3	190 (91 days)
[202]		-	5, 10, and 15	-	2	165
[8]		15	20, 40, 60, and 80	-	2	168
[203]		5.5 and 20	20, 30, 40, and 50	-	4	148
[5]	2020	0, 10, 15, and 20	40, 60, and 80	-	3	165–181 (90 days)
[23]	2021	0.25–075	4, 10, and 15	25–75	3	113
[39]		0.20–0.30	20–40	30–60	2, 3, and 4	120
[112]	2022	5–60	10–50	5–60	1, 2, 3, and 4	100–270

***Annotations**: Limestone powders (LP), metakaolin (MK), silica fume (SF), ground granulated blast furnace slag (GGBS), and fly ash (FA)*

Nowadays, UHPC is an inanimate object, so it can actually struggle to establish itself as widely used material. It is typically successful at a laboratory scale, but the mixing difficulties increase dramatically for large-scale operations, which may result in the mixer malfunctioning [171]. The volume production of the batch is thus limited. For example, a blade pan mixer with a total capacity of 0.34 m^3 and another blade pan mixer with a total capacity of 0.45 m^3 are employed, but the authorized size of the batch, which is 0.1 m^3 , is insufficient, which results in a significant decrease in construction efficiency [7,204]. In addition, because of the high volume of SCMs and the low w/c ratio of UHPC, the value of drying shrinkage is over 800 με [205].

Besides, under restricted conditions, UHPC structures are in danger of cracking and/or delamination [206]. As a result, despite the fact that high-strength steel fibers are capable of good ductility and flexibility for UHPC, the cost of high-strength steel fibers accounts for around 35% of total manufacturing costs [207]. However, it is difficult to decrease the percentage of steel fiber content while maintaining or improving flexural and tensile performance. This is because of the difficulty in achieving this balance. Additionally, despite the fact that unharmed UHPC has outstanding durability, fractures are inevitable in UHPC buildings that are exposed to outside service loads [7]. This is the case even when unharmed UHPC is in good condition. Durability should also be considered when supplementary raw materials, such as waste glass, porous sand, and coal fly ash, are used because these can induce porosity and expanding gel [208]. Recently, many researchers have employed new raw green materials and innovative technologies to address the related challenges and broaden the use of this advanced fibrous concrete composite while retaining its outstanding short-term and long-term durability features (Table 4).

Table 4: Summaries on the durability properties of UHPC reported by previous researchers

Raw materials	**Rate of addition**		**CS, @ 28 days MPa**	**Influenced property**	**Footnotes**	**Refs.**
	Fibres, kg/m^3	**SCM, kg/m^3**				
Steel fibres and quartz	156	211	150	Freeze-thaw resistance	Lower porosity and permeability are required for improved freeze-thaw resistance and a homogenous microstructure.	[209]
Untreated copper slag steel fibres and quartz sand	156	-	176	Tensile strength, tensile creep	Heat treatment on tensile creep is greater than its effect on tensile strength.	[210]
				Tensile creep	By thermal treatment, the tensile creep is abridged by 57% at 600 ºC for 2 days and 63% at 900 ºC for 3 days.	
PP fibres	-	-	191	Crack resistance	Generating of an explosion at 400 ºC and a maximum crack at 300 ºC.	[211]
					With a 300ºC, it is induced marginal changes.	
				Fire resistance	It is improved the fire resistance.	
Mineral admixtures (SF and FA) and fibers (PP and steel)	1-4%	248	113	Water absorption	It is reported a larger effect on water absorption in the end of the third day.	[212]
				Water absorption	The water absorption was reduced by 39% and 43%, with the addition of 10% and 20% SF, respectively.	
				Water absorption	In respect of water absorption, SF outdoes FA and zeolite.	
Steel and organic fibres, SF and superplasticizer	0.2	-	380 or 0.3% – 0.9%	Chloride penetration and water absorption	The rate of water absorption and chloride penetration was reduced down to the distribution of refined pore size.	[213]

Raw materials	Rate of addition: Fibres, kg/m³	Rate of addition: SCM, kg/m³	CS, @ 28 days MPa	Influenced property	Footnotes	Refs.
				Water penetration	It has dropped by 45% on the depth of the water penetration.	
				Chloride migration	The coefficient of chloride migration was reduced by 28%	
SF and steel fibres	0.2%	0.25%	94 at 7 days	Shrinkage strains	It is found that the retrained shrinkage strains were revealed lower than the free shrinkage strains.	[214]
				Shrinkage resistance	It is found that shrinkage resistance could be improved by increasing the thickness of concrete.	
SF, MK and FA	0.2%	86-393	152	Drying shrinkage	The drying shrinkage could be decreased by the addition of MK and reduce by FA or SF.	[192]
SF, FA and steel fibres	0.2 – 0.4%	150 - 250	150	Chloride ions	It is found that the chloride ions diffused in a range between 10 and 15 m^2/s.	[181]
				Water absorption	It is revealed that coefficient of water absorption is less than 0.6 kg/m^2.	
SF, FA and steel fibres	3.5%	1.1, 0.1, and 0.25	-	Total shrinkage	The rate of shrinkage can be increased with the increase in the heat curing time up to 10 hours and temperature of 900 ºC.	[215]
				Ultimate shrinkage	The ultimate shrinkage attained after 2 days was about 450 mm. Higher fiber rates are better capable to avert the development of shrinkage.	
PP fibres, SF and FA	18.2 - 156	113 - 137	113	Explosive spalling	In essence, explosive spalling is based on the vapour pressure instead of the rate of heating.	[216]
				Explosive spalling	Controlling explosive spalling, but not completely removing it.	
Steel fibres and SF				Spalling strength	Steel fibres can boost the compatibility of aggregates and binder paste by over-checking spalling strength.	
Steel fibre				Shrinkage resistance	Steel fiber volume and form affected UHPC shrinkage.	
Steel fibre				Autogenous and drying shrinkage	The addition of 2% steel fibres reduced drying and drying shrinkage considerably.	[166]
Hooked fibre	1 – 3%	226	152 - 160	Shrinkage resistance	Corrugated and straight fibres were less successful to prevent shrinkage than hooked fibers.	
Steel and PP fibre, SF and FA with a w/b ratio				Permeability resistance, and carbonation	UHPC has remarkable resistance of permeability to chloride-ion and water penetration, and carbonation owing to its compact structure and low w/b ratio.	[25]
Steel and PP fibres, SF and FA	0.2-0.4% PP and 1-4% steel fibers	50 - 380	120 - 200	Chloride ion	In terms of curing regime, mixture proportions, and steel fiber volume, the chloride ion diffusion coefficient is at least one order of magnitude lower than that of HSC.	
Mineral admixtures, PP and steel fibres and FA	0.1 – 0.35 PP and 1-4% steel fibers	0.25%	130	Extreme explosive spalling	Control specimens displayed significant explosive spalling because of their dense microstructure.	[217]
				Explosive spalling	Steel fiber on its own provided almost little protection against explosive spalling, however the	

Raw materials	Rate of addition		CS, @ 28 days MPa	Influenced property	Footnotes	Refs.
	Fibres, kg/m³	SCM, kg/m³				
					addition of 4 kg/m³ of PP fiber significantly reduced UHPC explosive spalling.	
Hybrid fibres (PP and steel)				Permeability	Due to a significant improvement in permeability, the employment of hybrid and steel fibres completely averted explosive spalling even at low fibre doses.	

Annotations: compressive strength (CS).

4 Carbon capturing

Although concrete contributes up to 8% of CO_2 emissions, global urbanization, economic expansion, and infrastructure development in many developing nations continue to drive demand for concrete [218]. Since the beginning of the nineteenth century, CO_2 concentrations in the atmosphere have steadily grown, going from 280 parts per million (PPM) to more than 400 PPM in 2016 [219–221]. Cement is one of the major CO_2 emitters, thus long-term sustainability is vital. CO_2 capture through emission reductions and the use of green raw materials provide the combined benefit of addressing climate change while producing economically viable and more durable products [222]. As public awareness of climate change and the importance of greenhouse gases grows, researchers examine carbon capture and storage (CCS). The CCS separates and stores CO_2 from industrial waste gases in two stages [219].

Geological locations such as saline aquifers, impermeable rock formations, exhausted oil and gas fields, and deep coal seams are often used for CO_2 storage [223,224]. However, the efficacy of this technique is limited because of the high initial expenditures, undetermined prospective storage capacity, unexpected long-term implications and stability of the store, rising public resistance to this plan, high energy prices, and the related indirect repercussions [225]. Minerals may also be carbonated using another method. It involves a more expedited type of weathering naturally occurring silicate rocks that are abundant in calcium and magnesium. These rocks have the ability to trap CO_2, and as a result, they generate carbonates that are stable and useful [226]. Each technique has drawbacks. Geological storage is limited by its high cost and unreliability. [219]. The cost of the mineral carbonation approach is increased since reactions take place at high temperatures, under high pressure, and/or after undergoing chemical treatment [219]. An alternative and sustainable solution for capturing CO_2 is via concrete, which is becoming known as CO_2-based concrete. Concrete has the ability to store CO_2 emitted by cement manufacturing plants. Instead of transferring CO_2 to remote geological storage (often depleted oil and gas reservoirs), CO_2 captured from cement factories can be injected into concrete systems, where it combines with free calcium ions to produce calcium carbonate ($CaCO_3$) [221].

The global strategies for adopting CO_2 utilization are depicted in Fig. 10 [222], where the market for CO_2-based concrete may quadruple by 2025 (from \$50 billion to \$200 billion), increasing CO_2 reduction by 15 times (from 0.2 billion tonnes to 0.7 billion tonnes) [222]. Similarly, actions that are both purposeful and timely have the potential to have a major influence on the size of the market as well as the capacity to minimize CO_2 emissions for goods that are based on CO_2. In addition to mineral ions like Ca^{2+} and Mg^{2+} that are dissolved in the pore solution, CO_2 may react with calcium-rich hydration products like Portlandite (CH) and C-S-H to create $CaCO_3$. This reaction takes place in the presence of CO_2 [227,228]. Strategies for capturing CO_2 in concrete include the carbonation of component minerals, the sequestration of hydrated carbon, and rapid carbonation during the carbon curing process. Mineral carbonation accounts for the majority of CCS production.

- Policies can help build CO_2U markets. Government support for R&D, carbon price, tax incentives, mandates, pipeline and other infrastructure development, government procurement, product labeling, regulatory and voluntary program credits, and support for certification can affect main policies. Local circumstances can play a significant role in promoting CO_2U products in different jurisdictions.

- CO_2 curing of cement offers a superior product and price. It should move quickly if the following strategic actions are to: (a) ensuring financing for conversions of precast concrete facilities, (b) focusing on converting incumbents' practices rather than creating competitive companies, (c) identifying the most cost-effective places to capture CO_2 for this purpose, and (d) building an infrastructure to deliver CO_2 – pipelines.

- Carbonate-based aggregates offer a large CO_2 sink but face entrenched competitors and a price-sensitive market. The strategic actions are to conduct detailed market surveys to determine optimum places to begin deployment country-by-country starting with core material sources, to research needs to ensure that core material that may be hazardous is properly contained by carbonate and the intended use, to ensure that appropriate certifications are obtained for the material produced to be used in concrete, and to identify CO_2 sources and delivery systems to support deployment.

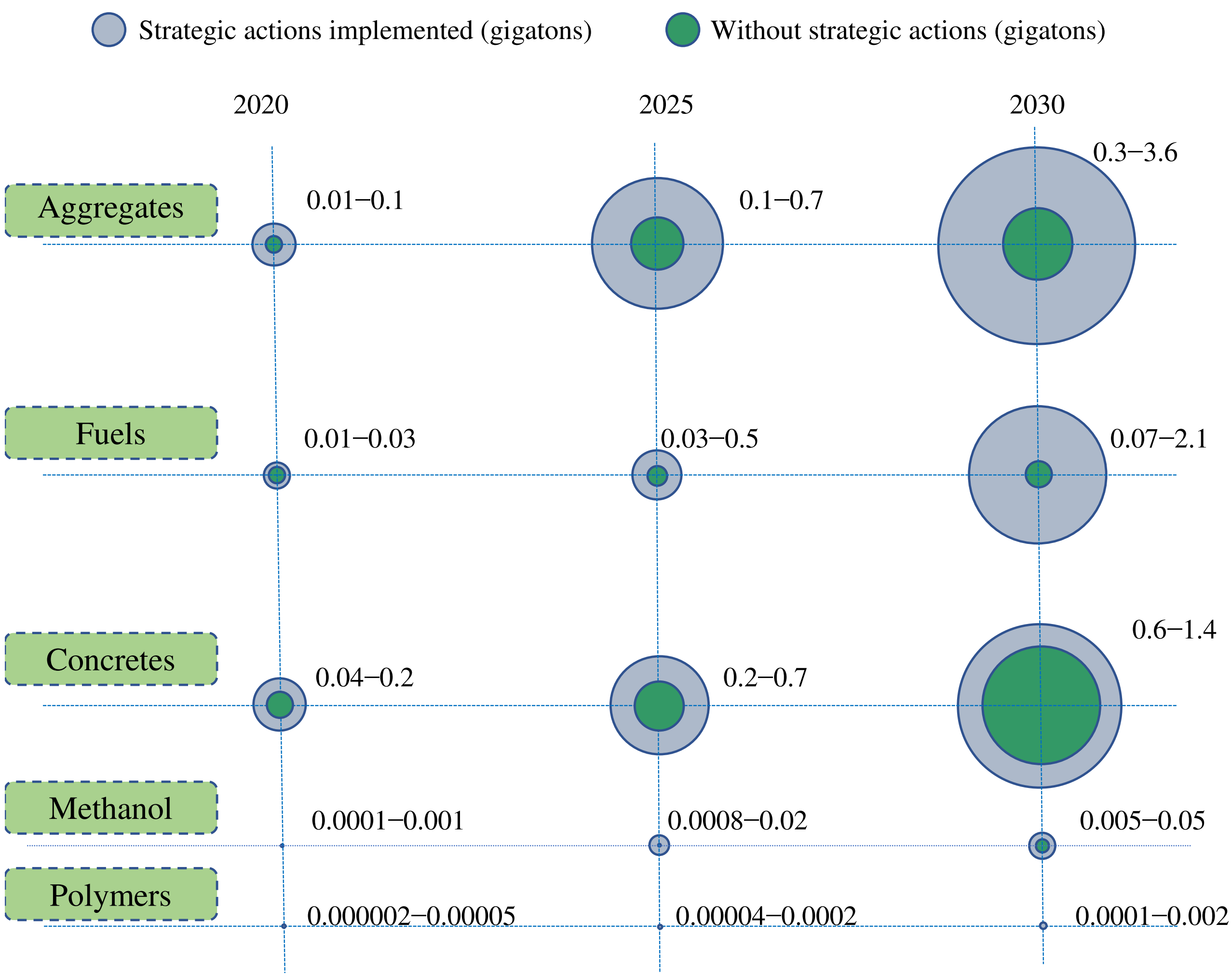


Fig. 10: Potential CO_2 reduction by implementing strategic actions (Adapted with improvement from [222])

Owing to its high surface area and high porosity, recycled concrete/aggregate from construction waste is also investigated as a potential CO_2 capturing strategy [225,229,230]. However, given acceptable service life exposure conditions and insufficient cover concrete, because the consumption of CH lowers the pH and dissolves the protective coating surrounding rebars, carbonation may render reinforcements more prone to corrosion [231,232]. Although decreased carbon footprint can be achieved by trapping CO_2 in concrete, the carbonation of concrete cover exposes the reinforcing steel, hence leading to its corrosion. Nevertheless, UHPC has a thick microstructure, low permeability, and low porosity, can be used as an alternative option [219]. Several equations are devised to estimate the effectiveness of concrete in capturing CO_2. Tu et al. [233] calculated the ratio of actual CO_2 absorption by samples to the theoretical maximum that may be gathered by the cement in the mixture is the measure of degradable organic carbon. It is defined by the following equation:

$$DOC = CO_2 - \text{Captured} (\%)/C_{max} \times 100 (\%), \quad (1)$$

When using thermo-gravimetric analysis, the mass loss due to decarbonation is measured as a percentage of total mass. Using the following equation, Cmax is the greatest level of carbonation that may be achieved in cement:

$$C_{max} = 0.785 (CaO - 0.7SO_3) + 0.93 K_2O + 1.09 MgO + 1.42 Na_2O \quad (2)$$

Calculating CO_2 absorption using DOC values shows that carbon-cured materials absorb more CO_2 [219]. Additionally, an adequate assessment of the emission consequences of CO_2 technologies must take into account a variety of parameters, including the efficiency of the CO_2 capture, energy inputs, feedstock, emissions from treatment, and end-of-life of the CO_2-based product (Fig. 11) [234]. By subjecting new UHPC mix to pressured carbon curing, it is possible to store up to 80 kilograms of extra CO_2 every liter of UHPC.

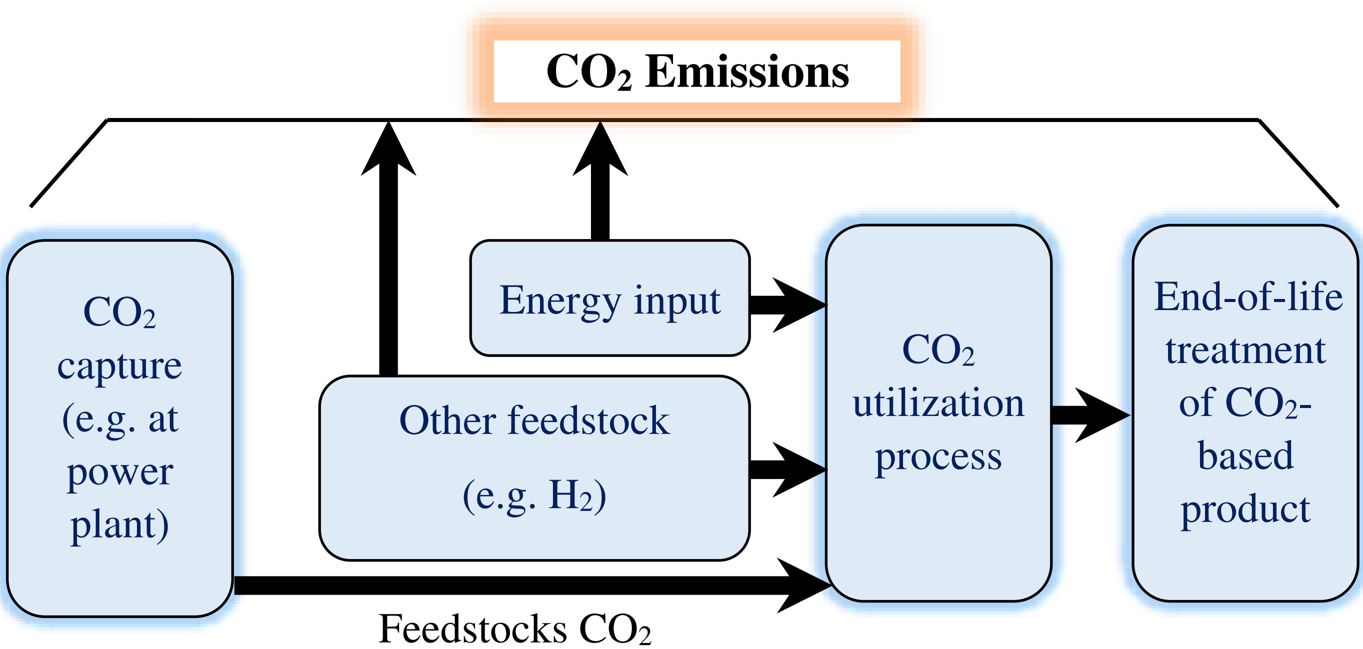


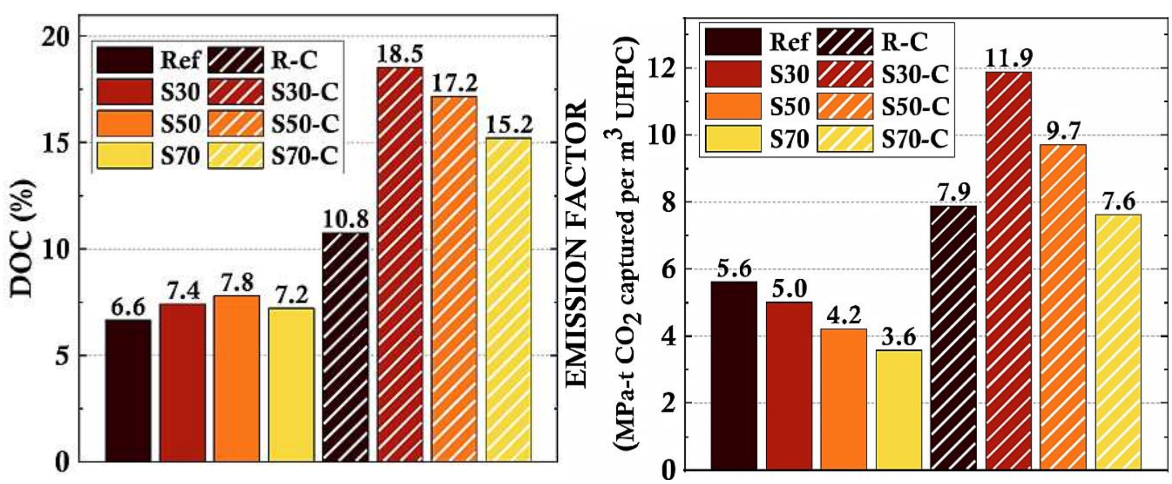
Fig. 11: Emission sources for CO_2 technologies (Adapted from improvement from [234])

In comparison to conventional concrete, ultra-high performance concrete (UHPC) possesses very high compressive and tensile strengths, in addition to higher durability [117]. These qualities are a result of the low water-to-cement ratio, the high cement content (which is more than 800 kg/m^3), the use of fine components such as SF and quartz powder (QP), and the use of fine components [16,102]. UHPC is endowed with outstanding durability in terms of carbonation, corrosion, and transport capabilities as a direct result of the combination of these traits, which combine to produce a thick, homogenous matrix with very minimum porosity [16,235]. The lower w/c ratio gives UPHC remarkable carbonation resistance owing to its low permeability [236]. Indeed, the CH concentration in UHPC is typically low due to the consumption of CH by highly reactive SF during pozzolanic reaction [237]. Because of its deep microstructure, UHPC is resistant to carbonation, making it ideal for capturing CO_2.

In addition, the high cement content of UHPC contributes to its expensiveness as well as its significant carbon impact. However, by using different materials in place of cement, either one or both of these costs may be reduced. In UHPCs, the degree of hydration (DOH) of cement is roughly 40% [16,117]. The replacement of cement with other materials in an effort to increase the DOH is a challenging problem because to the possibility of a decrease in mechanical strength. Unreacted SCMs particles, due to their low pozzolanic reactivity compared with cement particles, can act as weak spots inside the concrete matrix, thus resulting in nonhomogeneous microstructure and low strength performance [18]. GGBS is an excellent SCM and an alternative to cement in terms of reducing carbon emissions [188,219,238–241], however, it shows slowing down in early-age strength because of its latent pozzolanic reactivity. In this regard, autoclaving can boost compressive strength to more than 250 MPa while maintaining a high GGBS concentration [6]. A combination of GGBS and electric-arc furnace slags for the replacement of cement and fine aggregate is also studied [188].

Additionally, it has been found that increasing the percentage of furnace slag used in place of cement may enhance both the tensile and compressive strengths, but if the replacing level exceeds this limit, the strength begins to decrease [8]. Increasing the replacement levels of cement with furnace slag enhances UHPC's workability. Several SCMs are studied to create a UHPC with high performance and minimal carbon footprint. Besides GGBS, a wide range of industrial materials such as copper slags [242], phosphorous slags [22], and lithium slags [243], are proven to be viable alternatives for constructing sustainable UHPCs. Additionally, the alkaline nature of slags contain relatively high content of Mg and Ca, in contrast to pozzolanic materials (FA, SF, etc.), so the extra hydration processes do not require a large amount of portlandite (CH) [244]. Since carbonation consumes CH, using an alkaline alternative binder like GGBS is a superior way to capture CO_2 in UHPC while reducing cement content [245]. As illustrated in Fig. 12a, DOC in carbonated samples containing GGBS is clearly rising. The carbon-cured reference mix (10.8%) is over 60% higher than the Ref. (6.6 percent), whereas DOC in GGBS blends rises by more than 100% [219]. The cement replacement process has a diluting effect, which makes more space for the development of hydration products but also increases the products' exposure to CO_2 in the environment. This study suggests that Ca^{2+} ions play an important part in the process of CO_2 sequestration, and cement provides a bigger supply of Ca^{2+} ions than GGBS does. Carbon curing results in a significant improvement, as seen in Fig. 12b [219]. Carbon curing and GGBS blends double emission factors. As mix S30 (30% GGBS as cement replacement) offers the greatest carbon capture values and equal strength to mix R-C, CO_2 sequestration by early age carbon curing in UHPC operates best at a 30% cement replacement with GGBS.

When developing a mix for practical applications, consideration should also be given to other aspects, such as microcracks that appear at an early age [246]. Microcracks induced by hydration heat are a problem, particularly in low w/c combinations like UHPC [247]. Owing to their lowest reactivity compared with cement, high volume SCMs offset side effects resulting from rising hydration temperature, limiting a fast change in temperature gradient and reducing early age microcracks [248].



a) Degree of carbonation for admixtures after 24 h   b) Factors of emission for different admixtures

Fig. 12: Carbon capture in UHPC using hassled CO_2 curing (Adapted from [219])

Compared with normal concrete, CO_2 curing can reduce the compressive strength of carbon capture concrete (CCU) concrete. In such cases, CCU concrete demands more OPC to achieve the equivalent compressive strength of normal concrete. CO_2 emitted from OPC production are significant. Increasing OPC in concrete mixtures increases upstream cement manufacture CO2 emissions, which may offset the benefits of CO_2 trapped and utilized in concrete fabrication. An uncertainty assessment undertaken early in the technology development process may assist identify the most effective research options for solving CO_2 hotspots.

5 Sustainability

5.1 Green materials

Environmental concerns such as climate change and depletion of natural resources are increasing dramatically because of the increase in non-environmentally friendly activities. As a result, the focus on sustainability aspects in the construction sector, such as the recycled or recyclable materials has become more urgent [249]. Recycled materials are usually referred to as "green materials" because they consume less energy and enable manufacturing of high-performance, eco-friendly cement and concrete [250]. UHPC often has a higher content of cement than normal concrete, which increases the amount of consumed energy CO_2 emitted [45]. The same condition is applicable to steel fibers. However, they permit the construction of thin and lightweight buildings [17,35], which may result in less concrete in the foundation and fewer emissions from material transportation. The Paris Climate Agreement established reduction targets for global CO_2 emissions for all countries and industrial activities [31]. For example, Norway vowed to cut greenhouse gas emissions by 40% by 2030. [251]. In addition, by 2050, emissions from transportation infrastructure must be decreased by 50% below 2005 levels [252]. To accomplish this goal requires breakthroughs in the manufacture of materials, building design, and building maintenance. Given the high emission rate of concrete, the construction sector has a significant responsibility to play in the effort to reduce these emissions [253]. Extreme temperatures and cold periods destroy infrastructure [39]. For many buildings, using UHPC may minimize the quantity of construction materials required [99]. UHPC has a larger cement content per cubic yard than conventional concrete, although structural parts frequently need less material. Therefore, the total quantity of cement used for UHPC design solutions is equivalent to or less than conventional concrete [254].

Due to its capacity to tolerate violent and severe environments, sustainable UHPC is an effective way to boost building sustainability [255,256]. According to the carbon footprint assessment of UHPC with dehydrated cementitious powder (DCP), the developed UHPC is considered a sustainable and clean product. Fig. 13 [257] shows the CO_2 emissions per unit of green UHPC with various DCP contents and the CO_2 emissions/compressive strength ratio per unit of green UHPC. Fig. 13 shows the rise in CO_2 emissions per unit of green UHPC compressive strength, hence indicating the increase in the amount of CO_2 produced during manufacturing. Moreover, the increase of DCP addition is advantageous for further enhancing the UHPC's performance from a sustainable standpoint [15]. The inclusion of DCP into UHPC reduces CO_2 emission, indicating a higher cement utilization rate in green UHPC [7]. Furthermore, by increasing the DCP content, the amount of CO_2 released during UHPC manufacturing can be significantly reduced [170]. For example, the required CO_2 per unit volume for a traditional UHPC with only pure cement is 377 kg, but when the DCP content is increased by 25%, the emissions are decreased to 298 kg [257].

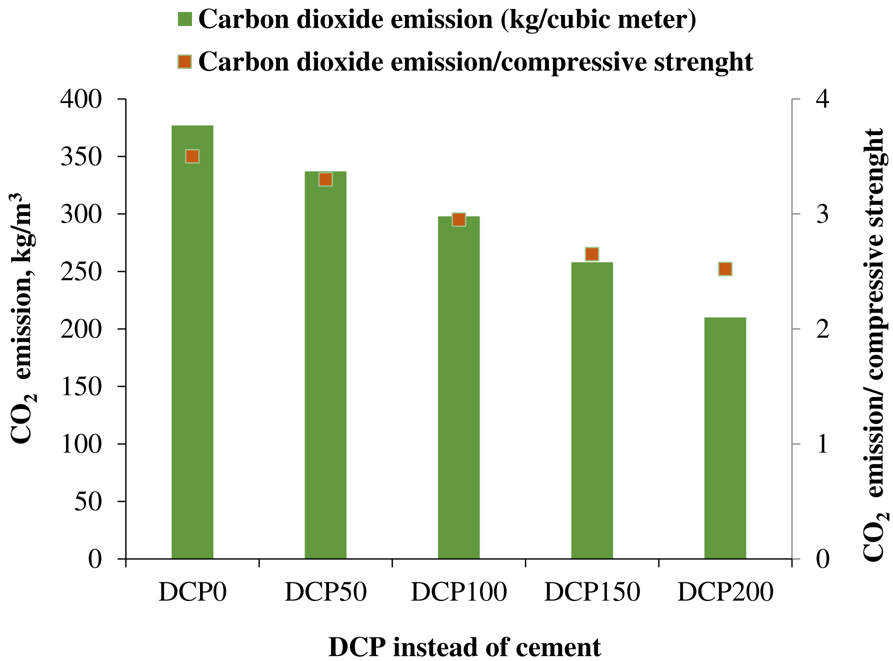


Fig. 13: Rate of CO_2 emissions from a unit of sustainable UHPC (Adapted with improvement from [257])

UHPC has ultra-high strength relative to unit weight, low water permeability, and a thick microstructure, leading in excellent fire resistance and non-explosive spalling at high temperatures [258,259]. All these point to the possibility of reducing the amount of concrete required in construction by employing UHPC. This kind of concrete is differentiated from others by its exceptionally long service life, exceptional strength, and significant ductility [90]. Several studies address UHPC is composed of high cement content (1000 kg/m^3), fine sand (500–600 m), and SF as a proportion of cement weight, according to many researches [75,260]. Micro and macro characteristics of UHPC mixture components that may be enhanced to obtain the greatest practical density by replacing valuable, limited, or unavailable conventional components are investigated [49]. UHPC combines self-compaction, fiber reinforcement, and high-strength concrete [75]. UHPC has compressive, flexural, and tensile strengths of 150, 30, and 5 MPa. In an estimate, using UHPC instead of regular concrete can reduce the overall amount of aggregates used in structural members, including fine and coarse particles, by 30%. The proportion of coarse particles is reduced by 100% [31].

Furthermore, a very low water content can be employed in UHPC combinations, and it can reach 0.08% [49]. The optimal w/c ratio for UHPCs is between 0.20 and 0.13 [261], where part of the cement used with mixing water hydrates and the rest is replaced by QP and other pozzolanic materials [49]. Dead load limits concrete buildings' bearing ability, particularly with large spans [45]. Although UHPC's cement content is twice that of typical concrete, only 44% of UHPC is needed for a broad column, validating Walraven's assertion [71]. Fly ashes, which are utilized in UHPC, are by-products of the power sector and weigh lighter compared with the OPC. Therefore, the UHPC containing by-products such as fly ash is a step toward sustainability because it uses material that would otherwise be discarded. UHPC's improved mechanical strength allows for the creation of slimmer and lighter structures [45,262].

Early studies demonstrate that utilizing UHPC instead of standard strength concrete in bridge design has environmental benefits. The life-cost assessment and energy consumption of an innovative bridge design that use both UHPC and timber are evaluated [263]. The UHPC component of the bridge deck may be maintenance-free for 100 years (or more), resulting in extremely low annual CO_2 emissions because of reduced maintenance works and a smaller overall amount of material used in the design. The construction of three different UHPC bridges in different places is also investigated [264]. UHPC's strong load-bearing capability allows for more thin constructions, and cement, steel fibers, and superplasticizer are the most significant contributors to the production's environmental consequences [264]. The greenhouse gas emissions from a NSC road bridge are also compared with those from a standard concrete road bridge [48]. When only emissions from concrete are considered, a 50% reduction in CO_2 emissions is noted [31]. The repair of a road bridge is modeled using three distinct systems: conventional concrete with a waterproofing membrane, UHPC, and a new type of eco-UHPC [12]. Comparing the same amount of conventional and ultra-HPC, the UHPC's CO_2 emissions are up to seven times higher. The environmental impact of the eco-UHPC and UHPC solutions, however, is less than 60% and 72%, respectively, of the standard solution's environmental impact [31]. A detailed report is compiled for the Federal Highway Administration of the United States, evaluating the most influential research on UHPC up to then [90]. Fig. 14a depicts the GWP for various rehabilitation systems. For the conventional rehabilitation system, cement manufacturing has the greatest environmental impact, whereas steel and waterproofing membrane account for the remaining 35% (Fig. 14b) [12]. In the eco-UHPFRC system, the impact of cement is significantly lower than in that in the UHPFRC system as 50% of cement is replaced by limestone filler with low environmental impact. Consequently, steel fibers are the primary contributor to environmental impact related to raw materials, accounting for two-thirds of the impact [12].

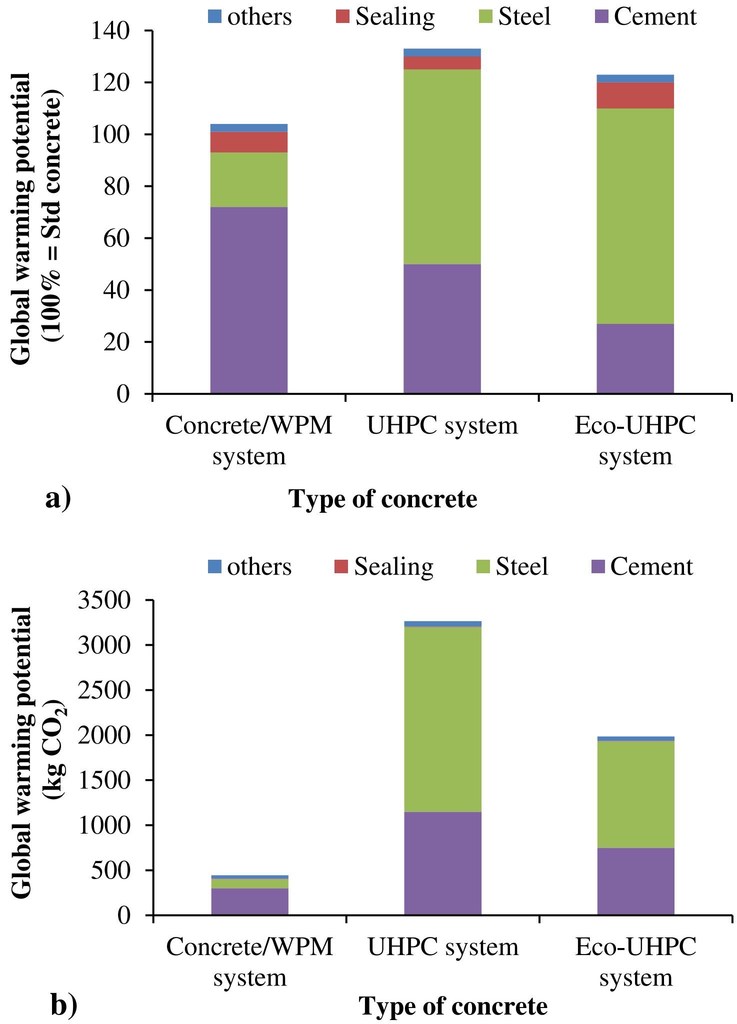


Fig. 14: Global warming potential induced by different solutions: a) materials used during rehabilitation and b) a concrete in m^3 used for a different rehabilitation system (Adapted with improvement from [12])

That the UHPFRC solutions emit five–seven times more CO_2 per cubic meter than the conventional rehabilitation technique is also possible to determine. When the effective volume used is computed (Fig.14a), a substantially smaller volume is required with UHPFRC, allowing only 0.1–0.3 times more CO_2 than for standard rehabilitation systems [12]. From a long-time sustainability perspective, more research should be conducted on technical factors, design practices, and economic and environmental impact effectiveness. Such research is vital to illustrate the potential of UHPC and promote the broad usage of UHPC so as to lessen environmental consequences [45]. In this regard, GWP is reduced by 42% compared with a typical UHPC mixture [31]. A considerable reduction in environmental effect is also observed in terms of the cost-effectiveness and carbon footprint of two models of bridge designs constructed with UHPC and standard concrete [53]. In addition, a number of earlier studies concluded that the UHPC has a less impact on the ozone layer, a lower potential to cause damage to the environment, and generates a smaller amount of emissions of greenhouse gases [31]. UHPC uses 50% less energy than NSC. UHPC has increased durability, ecological aspects, economic advantages, and recycle-ability in many applications, which may minimize energy consumption and maintenance labor compared to NSC [265].

In conclusion, UHPC has the potential to be a sustainable material because of its increased durability, ecological qualities, economic advantages, and recyclability in a wide variety of contexts. The use of additional mineral components and powders in place of cement in concrete applications is another step toward sustainability and contributes to the fulfillment of sustainability mandates that various government bodies may soon enact. This is an important step toward achieving the goal of a more sustainable built environment [266]. Both the carbon footprint and the cost of the UHPC option are beneficial over the course of a person's lifetime. An example of UHPC's many benefits is seen in Fig. 15.

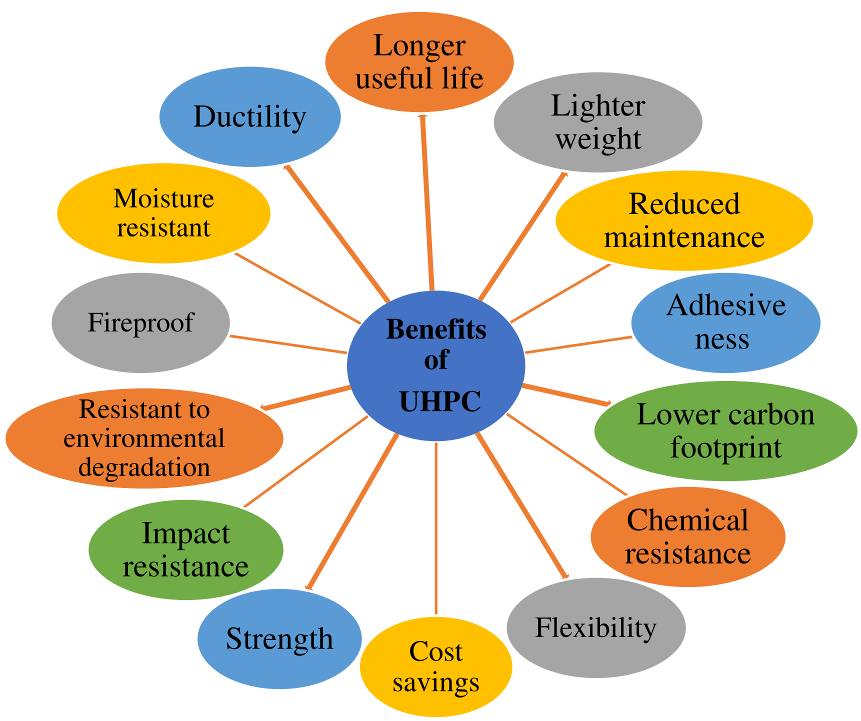


Fig. 15: Benefits of UHPC

5.2 Cementitious materials

Several studies describe UHPC's composition as high cement (1000 kg/m^3), fine sand (500–600 µm) and SF [267]. It contains a very insignificant quantity of water, and the water-to-cement ratio ranges from 0.2 to

0.13 [117]. The lower water content leaves a considerable portion of the cement used unreacted; another percentage of cement is substituted with QP and other SCMs having pozzolanic properties such as industrial by-products and recyclable wastes [49,221,210,222]. These SCMs can be employed in substantial amounts in UHPC blends [267,270]. Using these pozzolanic materials as cement replacement produces significant environmental benefits as well (Fig. 16) [270]. For example, decreasing soil, groundwater, and dust pollutions can simultaneously produce a sustainable UHPC with superior strength characteristics and high durability.

Fig. 16: Ecological benefits of replacing quartz sand with rock dust (Adapted with improvement from [270])

A comparison of the CO_2 emissions produced by UHPC samples containing rock dust and quartz sand is shown in Fig. 17 [270]. It is obvious that the CO_2 emissions produced by UHPC may be reduced over time by increasing the quantity of rock dust that is utilized. It can be seen from the fact that the CO_2 emissions produced by QS0 are 6.8% less than those produced by QS100 that the use of rock dust in UHPC products is both advantageous and sustainable [270]. As each has several advantages when mixed with cement, SCMs improve UHPC's characteristics [271]. By employing these materials with chemical additions, a considerable percentage of OPC may be given or replaced, enabling sustainability [14,272]. Increasing the cement concentration in UHPC mixes contributes to its limited appeal because to economic and technical restrictions [39,69]. A large amount of SCMs decreases hydration temperature, microstructure thickness, and carbonation resistance; it also reduces unit cost per compressive strength [69]. A high replacement volume of FA up to 60% is examined as a substitute to cement, and significant strength and different performance attributes are obtained in long-term ages rather than early ages [273]. Thus, when significant loads are not necessary in the early phases, adopting FA in warm regions is viable.

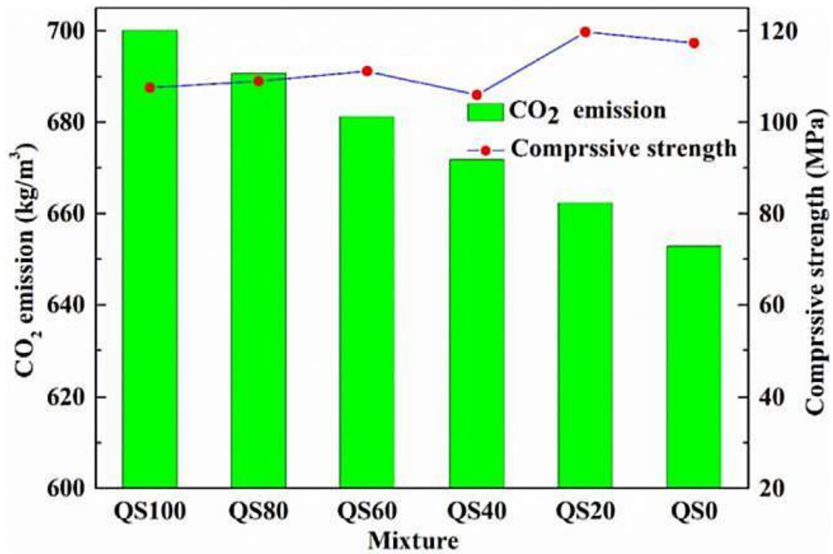


Fig. 17: CO_2 emission of UHPC with different contents of rock dust (QS_n: Test refs) (Adopted from [270])

UHPC is also known as RPC, which refers to the chemical reaction that occurs when the cement is hydrated by water to form $CaOH_2$ [274]. With the presence of reactive silica in SF powder or other SCMs, $Ca(OH)_2$ resulting from cement hydration reacts with the amorphous silica atom, thus generating more C-S-H gel. In addition, the incorporation of quartz sand powder, which supplies dissolved silica, contributes to the formation of extra CSH gel, and QP encourages the formation of xonolite and tobermorite during the process of hot steam treatment [30]. Another factor that contributes to lowering the binder content is achieving the optimum gradation of the employed sand, which reduces the interstitial spaces that can be occupied by binder to a minimum [69]. As it is a nonhomogeneous material, concrete begins to collapse in the area surrounding the aggregate, which is referred to as the interfacial transition zone (ITZ). These zones are fragile and susceptible to cracking, and their thickness increases as aggregate sizes increase [275]. ITZs are the weakest section of the concrete body and act as a gap around the aggregate grains where weak $Ca(OH)_2$ and ettringite crystals congregate, separating the aggregate from the cement binder [72]. When coarse aggregate is deleted and aggregate size is lowered to 45–600 μm, ITZs are reduced or eliminated, which explains why UHPC has less porosity than conventional concretes [49]. Long-term carbonation of UHPC is also researched; it's one of the main causes of concrete deterioration over time, along with steel reinforcement corrosion [27].

Also discussed is concrete's carbonation process. CO_2 from the atmosphere combines with $Ca(OH)_2$ to make $CaCO_3$ [262]. This reaction lowers pH from 12 to 13 to 7 [274]. The steel's protective layer collapses as the acidity of the concrete around it rises. Concrete's electrical conductivity rises, causing corrosion. To avoid this, replace a large amount of the cement in UHPC with other SCMs [274]. Because pozzolanic processes consume $Ca(OH)_2$, more and stronger cementitious gels such as CSH and SASH gel are created, reducing concrete permeability and preventing CO_2 from passing through the structure [276].

Despite UHPC's ultra-high strength, this concrete remains a fragile material when subjected to overbearing or dynamic loads [260]. Utilizing rebars provides it with sufficient and appropriate ductility so that it can sustain a variety of loads. Rebars can be utilized in conjunction with UHPC to form a composite section, which minimizes the concrete sections, thus resulting in cost savings overall [277]. UHPC structures subjected to chlorides are also investigated. The low permeability and low void ratio in the UHPC structure result in strong resistance to chloride penetration and, ultimately, high resistance to steel reinforcement corrosion [278]. In this regard, several studies explore the influence of substituting cement content with FA, RHA, and other SCMs to resist chloride penetration [279,280]. Fig. 18 indicates that replacing 30% FA for cement improves chloride penetration resistance by 8%. (UHP2.1) [281]. However, increasing the replacement fraction to 50% enhances chloride penetration resistance by 1.9% [281]. In UHP 1.1 mix, regular cement (CEM I) is better than synthetic blast furnace cement (CEM III) by 11.4% [281].

Mixed cement, which comprises by-product materials, is also explored, and it may be used to minimize the void ratio in UHPC [282]. The chloride penetration of concrete synthesized from three types of cement, namely, blast furnace cement CEM III/A [283], sulphate cement also investigated: SRC, OPC, and FA. The findings of a quick chloride penetration test using ASTM C1202 [284] reveal that concrete made from blast furnace cement is superior than concrete made from any of the other two types of cement in terms of its resistance to chloride penetration [284]. Evaluation of chloride ion penetration is considered an essential test because it allows to determine concrete durability and concrete ability to resistance chemical attacks, thus determining the concrete's service under harsh conditions [56].

The colorimetric method, which is a simple and quick procedure, is employed in numerous studies. Although few studies utilize this method to determine the degree of chloride penetration, earlier research indicates three colorimetric methods that mostly use silver nitrate salt ($AgNO_3$) [285]. This technique involves spraying a 0.1 mol/l solution of silver nitrate over the inner surface of the concrete to determine the chloride penetration depth [286,287]. Spraying potassium chromate (K2CrO4) and silver nitrate ($AgNO_3$) combined helps identify chloride-containing concrete [288,289].

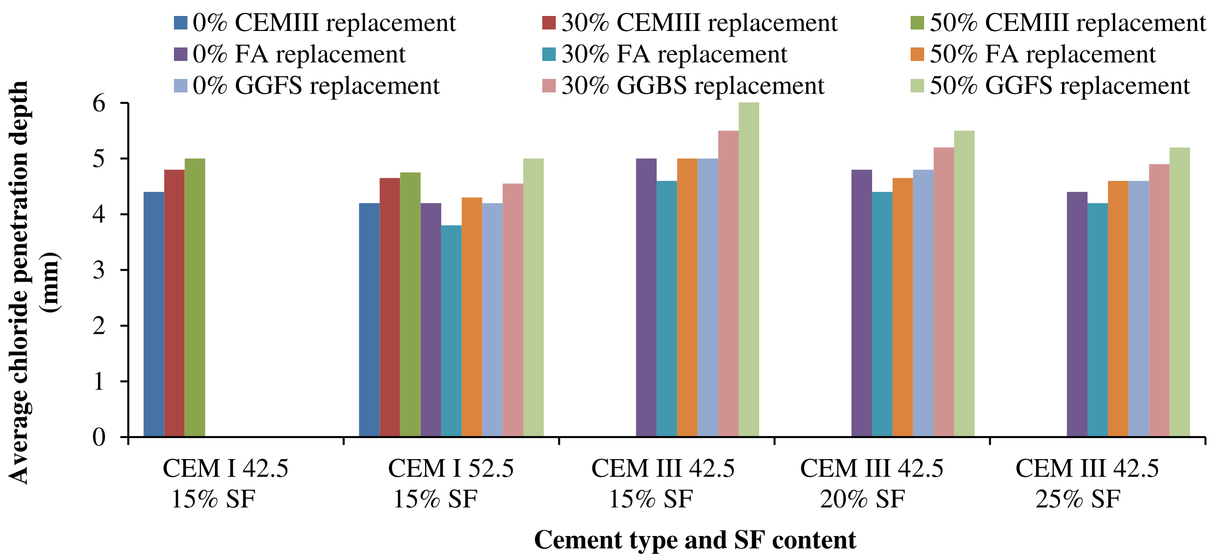


Fig. 18: Average depth of chloride penetration for all mixtures (Adapted with improvement from [281])

Spraying fluorescein/silver nitrate solution offers better and deeper results [290]. Chemical assaults on UHPC may also be assessed by calculating the decline in compressive strength produced by such attacks by comparing the sample's compressive strength after exposure to the attack to its original strength, thereby determining the sample resistance to chemical attacks [56]. Immersing concrete samples in a sulphate/chloride environment for 6–18 months, followed by expansion and mass loss tests, determines concrete's capacity to withstand chemical assaults over time [291]. Chemical resistance may be altered by cement replacement with SCMs (Table 5), replacement levels, SCM type (FA, GBFS, etc.), chemical composition of concrete materials, and w/c ratio [292].

Table 5: Summary of cementitious materials used to design UHPCs, as reported by previous researchers

Type of cementitious materials	Rate of substitutions of admixture by wt% of cement	Particle size (µm)	Cement content (kg/m^3)	Compressive strength, MPa	Flexural strength, MPa	Tensile strength, MPa	Refs.
Nano-silica	1, 2, 3, 4, and 5	Slurry form	~440	135	25	-	[293]
POFA	17, 30, and 40	~2.06	1128	131.4	-	-	[294]
Glass powder	100 of QP	~25.80	735	153–221	-	-	[295]
Nano-silica	1, 2, 3, and 4	~0.015	950	125–143	-	-	[177]
FA cenosphere	FA cenosphere replaced 10,	0.2–20	965	72–88	-	-	[296]

Type of cementitious materials	Rate of substitutions of admixture by wt% of cement	Particle size (μm)	Cement content (kg/m^3)	Compressive strength, MPa	Flexural strength, MPa	Tensile strength, MPa	Refs.
	20, 30, 40 cement			(90 days)			
Waste bottom ash	25 of fine aggregate	0.4–200	~613	156	-	-	[294]
GGBS	~30	–	692	135–180	-	-	[297]
GGBS	20, 40, 60, and 80	31–50	960	-	11.2–13.6 kN	9.8–13.6 kN	[8]
MK and nano-MK	1, 3, 5, 7, and 9 replace 10% of cement and nano MK.	–	800	-	-	-	[298]
Copper slag	Grade I – 76.93% Grades (II and III) – 23.06%	Grade I → 2000–1000 Grade II → 1000–500 Grade III → 500–90	~848	162–191	12.34–32.43	-	[242]
Class F FA	10, 20, 30, and 40	20–600	657	122.4	-	-	[199]
Class F FA	20, 40, 60, and 70	0.1–105	935	198.9	-	-	[299]
RHA	16.66, 33.33, 50, 66.66, 83.33, and 100 with SF	~11	920	119.3–136.6	16–31	-	[176]
RHA	Quartz replaces 50 and 100 percent of RHA as a reactive filler.	~10	800	145–160	-	-	[201]
Steel slag Carbonated steel slag	15, 30, 45, and 60 cement replaced by steel slag	0.4–500	925	150–162	-	-	[300]
SF	25%	1.8–5.3	788	107.4–135.4	8.8–11.1	7.0–8.4	[259]

6 Potential applications

Owing to its satisfactory sustainability and remarkable superior performance, UHPC is increasingly being used in infrastructure projects, construction, and other structural applications in recent years [75]. The simplicity of implementation of HPC projects and the ability to reduce structural element dimensions have also increased the popularity of UPHC in many nations. According to the concrete's market survey, the global UHPC market size was estimated at $892 million in 2016 and is projected to increase by 8.6% to $1,867.3 million by 2025 [301]. The market of UHPC has garnered global interest in various nations, such as Austria and Australia [302], New Zealand [303], South Korea [304]. Germany [128], Italy [305], France [128], Canada [73,78], Japan [97], Malaysia [306], the Netherlands [307], Slovenia [308], and the United States [89,309].

Over the last two decades, researchers and engineers throughout the world have conducted comprehensive research in an attempt to commercialize UHPC technologies as sustainable building materials [75]. Literature shows more than 200 completed bridges using UHPC components. New building construction, structural strengthening, retrofitting, precast components, and other unique applications use UHPC. The application of UHPC as a future sustainable building material is currently gaining the attention and initiative of businesses and governments [310,311]. Fig. 19 shows some of the potential applications of UHPC.

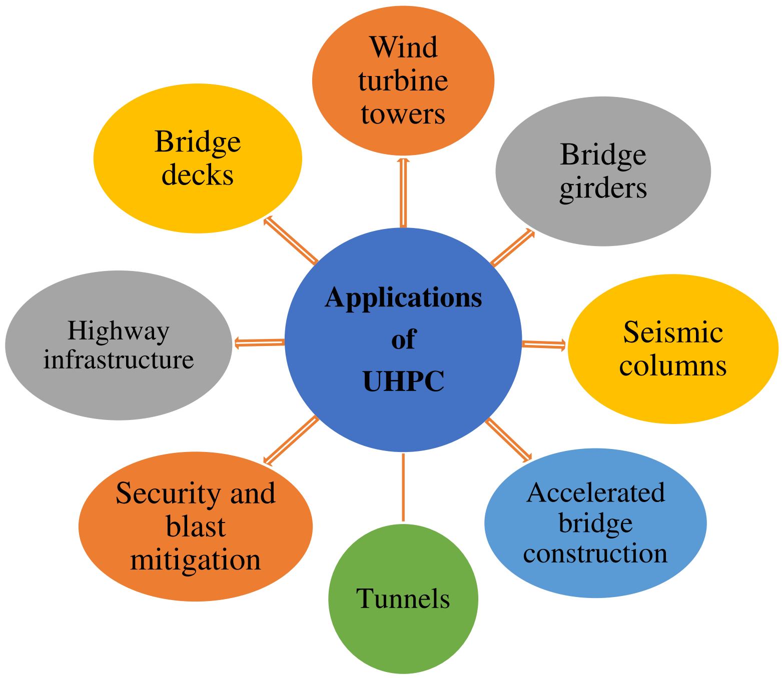


Fig. 19: Potential applications of UHPC

6.1 Bridges

Using UHPC in newly constructed structures, structural strengthening, restoration, and civil infrastructure has been the hotspot of study by researchers and engineers. UHPC is widely utilized in bridge structures [79,312], comprising cast in-situ connections [84,85], columns [86,87], long-lasting bridge girders [89,90] and decks [24,35]. Due to its excellent mechanical qualities and advantageous long-term performance, UHPC is widely employed in domestic and worldwide construction industries, notably in high-rise buildings, long-span precast or prestressed bridge girders, and maritime, aviation, and military construction applications [99]. UHPC is now being used in a number of countries, some of which include Canada, Australia, Austria, China, France, the Czech Republic, Italy, Japan, Germany, Malaysia, New Zealand, the Netherlands, Slovenia, Switzerland, South Korea, the United States of America, and the United Kingdom [12,17,39–44,38,45,47,46]. The majority of the projects in the countries listed were initiated by government bodies as pilot projects to stimulate the future adoption of UHPCs [90,96]. However, the implementation of some of these UHPC-based projects in the mentioned countries is slow; they aim to create a very attractive environment for this type of concrete and motivate other countries and companies to adopt this approach more effectively [131]. As conclusion of the previous constructed projects using UHPCs, this review highlights some of them as follows (see Fig. 21):

- Sherbrooke, Quebec, Canada was the location of the building of the world's first pre-stressed hybrid pedestrian bridge in 1997, and UHPC was one of the companies that worked on the project [73]. The 100 m Batu 6 segmental box girder bridge was also developed with UHPC [75]. In France, UHPC replaced corroded steel beams of Cattenom and Civaux nuclear cooling towers. [74].
- In 2001, the UHPC was used to build the Bourg-Les-Valences bridge in France [76].
- UHPC was used during the building of the Seonyu pedestrian bridge in South Korea, which was finally completed in the year 2002 [77].
- In 2003, the 50-meter-high Sakata Mirai pedestrian bridge in Japan was completed with UHPC. The bridge demonstrates how the perforated mesh in the UHPC superstructure can reduce the weight of the structure and exhibit unique and attractive aesthetic features [36]. There are also bridges similar to the Sakata Mirai Bridge built in Europe, the United States, Canada, Asia, and Australia. [78].
- In 2005, the Shepherd's Gully bridge in Australia is the first UHPC-built road bridge [307,313], the Bourd-Less-Valence bridge in France [128], and the Horikoshi C-ramp bridge in Japan [36].
- The Mars Hill Bridge in Wapello County, Iowa, was the first UHPC road bridge to be constructed in the United States. It was finished in the year 2006 [80].
- The Tokyo International Airport was the location of the construction of the world's first segmental UHPC composite deck road bridge in 2008 [97], which is considered the longest road bridge constructed with UHPC in the world [36].
- In 2009, in Canada, the Highway 105 bridge over Buller Creek used joint fill between box beams and UHPC curbs.
- In 2010, utilizing joint fill between adjacent box beams and between precast UHPC curbs, Route 17 was built over the Eagle River bridge in Canada. The bridge crosses the river in British Columbia.
- In 2011, UHPC was utilized in the building of a bridge of Fingerboard Road Bridge over the Staten Island Expressway in the United States.
- In 2012, in Hawkeye Canada, Creek Tributary Bridge located on the Highway In order to fill the space between adjacent box beams and precast curbs made of UHPC, joint fill was constructed.
- In 2014, the Westminster Drive Bridge project in Canada was completed using longitudinal joints to link superstructure components.

- In 2017, the Kampung Kampung Teluk Bridge (420 m long) held the world record for the longest multiple-span road bridge superstructure built with UHPC precast girders. The bridge superstructure is made up of 20 precast UHPC U-beams [82].
- In 2013, the building of 55 UHPC bridges in the United States and Canada started, some of which are still under construction as well as approximately 22 UHPC bridges in Europe and 27 in Asia and Australia [90]. Girders, deck panels, protective overlays, and connections between components are all possible uses for ultra-high performance composites (UHPC) [24,314,37]. Using UHPC can save up to 70% of the equivalent structure weight built with conventional or prestressed reinforced concrete (RC) parts [77]. UHPC constructions are sustainable owing to their potential of limiting carbon footprint and lowering maintenance costs [311]. Furthermore, most UHPC bridges have an attractive appearance, reduced volume and self-weight, easier implementation, and higher durability than traditional RC bridges [81].

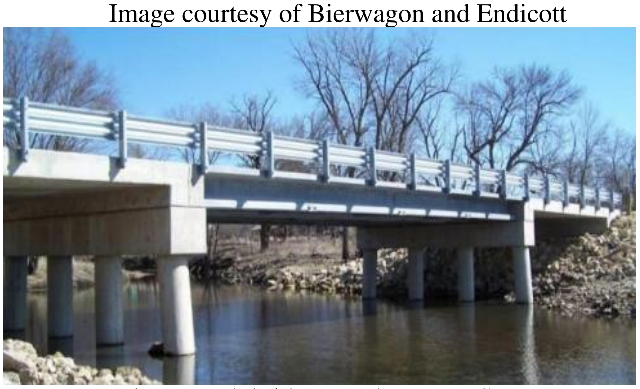
The superior mechanical characteristics and durability of UHPC allow for an evaluation of the standard design methodologies for numerous typical bridge components [315]. The significant study that has been done on the design of UHPC components has led to the creation of perfect designs, which has pushed the usage of UHPC to rise in several different places throughout the globe [316,317]. For example, especially in seismic performance, incorporating prefabricated segmental bridge columns (PSBCs) and ultrahigh-performance fiber-reinforced concrete (UHPFRC) segmented members of bridge structure exhibited more significant energy dissipation capacity dynamic behaviors and impact resistance [315–319].

6.2 Security infrastructures

The UHPC has the potential to be used in the deployment of barrier protection systems or as a key component of important infrastructure in buildings, bridges (Fig. 20), and other forms of security infrastructure. Research on the mechanical properties of UHPC that has been subjected to high strain rates is being carried out on a massive scale [262,320,321], penetration resistance [94,322,323], and blast resistance [95,324]. UHPC is utilized in the production of acoustic panels, such as the subterranean train station in Monaco [325]. UHPC panels include microscopic holes throughout them that produce an atmosphere that is not only visually pleasing but also bright. Other benefits of UHPC are that it is lightweight, impact-resistant, and non-combustible. Because of its resistance to the pollution caused by automobiles and the de-icing salts used in the area, acoustic panels made with UHPC were also erected beside a highway in Chatellerault, France [325].

Mars hill bridge, Wapello, U.S.A.
Image courtesy of Bierwagon and Endicott

Pedestrian Bridge, Quebec, Canada
Image courtesy of Lafarge



Jakway park bridge, Buchanan, U.S.A.
Image courtesy of Brian Keierleber

Glenmore pedestrian bridge, Alberta, Canada
Image courtesy of Lafarge

First Completed UHPC Highway Bridge, China
Image courtesy of HZL HBT Co., Ltd.

UHPC Pedestrian Bridge in Changsha, China
Image courtesy of B-C. Chen

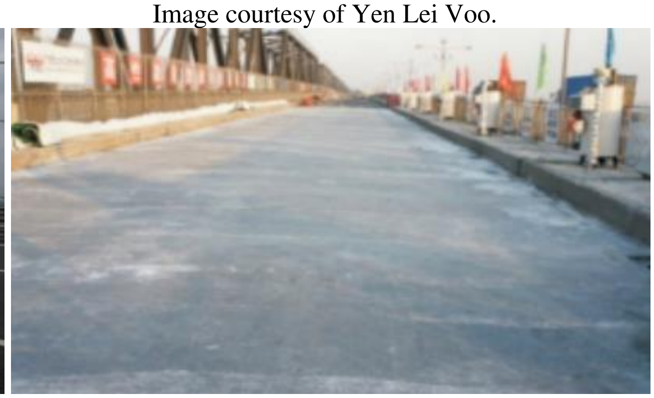
Sakata-Mirai bridge, Sakata, Japan
Image courtesy of Lafarge

Footbridge of Peace, Seoul, Korea
Image courtesy of Rualt Philippe

Celakovice pedestrian bridge, Čelákovice, Czech Republic
Image courtesy of Koukolã-K. Petr

Kampung Linsum bridge, N. Sembilan, Malaysia
Image courtesy of Yen Lei Voo.

Rong Jiang Bridge, China
Image courtesy of X. Sheng



Zhaoqing Mafang Bridge
Image courtesy of Wahsaw

Fig. 20: Some of the constructed bridges using UHPC worldwide (Adopted from [7,73,82,36,90,129,304,326–328]**)**

In 1985, UHPC research and development started [17]. Since then, several technological solutions and UHPC formulations have been created to meet design, structural, and architectural needs [7,17,129]. Future tunnels, wind turbine towers, and nuclear power plants may use UHPC. UHPC's ability to reduce structural element thickness helps build more efficient tunnel systems with larger equipment areas [329]. Similarly, the use of UHPC components allows for the building of wind turbine towers that are both higher and more slender, which results in an increase in the amount of energy that can be generated [41]. UHPC offers greater radiation shielding qualities and stronger blast endurance than other materials, making it ideal for use in nuclear power plants. This contributes to an increase in the level of protection afforded to vital infrastructure [7,330]. Despite UHPC's strong application potential and benefits, a lack of design standards and requirements for predicting performance and the necessity for particular batching, mixing, and curing prohibit its broad usage in the building sector. Urgently update UHPC design requirements.

6.3 Buildings

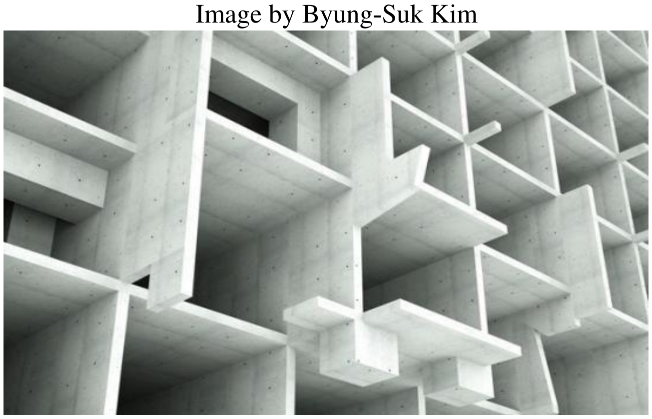
Recent developments at UHPC have led to increased interest in the company's architectural components, namely sunshades, cladding, and roof components (Fig. 21) [75]. Due to developments in UHPC technology, office floors may now have column-free bays of 18.5 m by 18.5 m, allowing for more layout and interior design flexibility. With long-span, residential multistory structures may feature column-free parking on the lower levels, improving space utilisation and occupant safety [331]. The modest structural depth of mechanical, electrical, and plumbing systems optimizes space and story height while being cost-effective, resulting in slender, light, robust, and aesthetic buildings.

In Japan, basic research on this notion has begun in an effort to revolutionize the building sector [332]. For the first time in France, the Foundation Louis Vuitton pour la Création in Paris is using UHPC [333]. This project, which was finished in 2014, is noted by its very intricate geometrical details. The cladding is made up of precast concrete UHPC panels, each of which is created in a different way thanks to the use of vacuum-filling molds. UHPC may also be used for roofs and canopies, as is shown by the Shawnessy LRT station in Canada, which has this material. One example of a similar use may be found at a French wastewater treatment facility, which uses precast thin curve shells [83]; the roofs of the Jean Bouin stadium in Paris and the Olympic museum in Lausanne, Switzerland [334]; the cladding for the Qatar National Museum [93]; and the façade at Terminal 1 of Rabat Airport in Morocco [335].

In addition, the ductile nature of UHPC enables its usage in buildings and structures in seismic regions [336]. Due to the considerable flexibility of reinforced UHPC columns or beams, they are able to spread more energy than traditionally RC structures during earthquakes. This prevents the columns or beams from collapsing [337]. In this context, hybrid components, which blend UHPC with NSC or other materials for seismic stress resistance, are used to lower the high cost of UHPC [338]. Along with its employment in piles, the high impact resistance of UHPC is also the subject of study. Two H-shaped precast concrete piles are successfully driven into clay soils and tested under both vertical and lateral pressures [91,92]. With its outstanding workability, UHPC may be molded into almost any shape. Therefore, molding it into various shapes according to engineering and aesthetic requirements is easy [75]. This kind of UHPC-based precast structure can be implemented with much less time and effort than traditional structures.

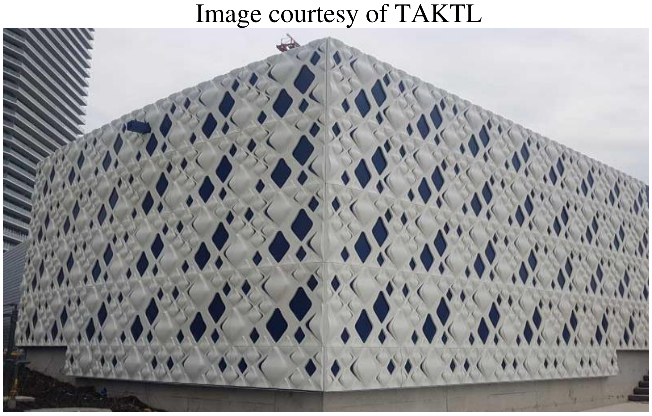
The world's first UHPC pedestrian cable-stayed bridge
Image by Byung-Suk Kim

Waikiki Business Plaza, Honolulu, U.S.A.
Image courtesy of TAKTL



BDA'S Building Solutions Ltd., Bangladesh
Image courtesy of TAKTL

Rabat-salé Airport, Morocco
Image courtesy of Ductal® UHPC



Woodsy Park Pavillion, Toronto, Canada
Image courtesy of Archello

Sitrad Elite Beton Ltd., Casablanca, Morocco
Image courtesy of Sitrad's website

Fig. 21: Some of the constructed buildings using UHPC worldwide (Adopted from [314,335,339])

6.4 Rehabilitation works

Rehabilitating and reinforcing concrete structures that are failing is a major burden from a socio-economic aspect due to the additional expenditures that emerge from the procedures of rehabilitation and reinforcement [40]. The development of new ideas for the restoration of concrete structures is needed. To ensure their long-term viability, concrete constructions of the future will require only preventive maintenance, with no or only small service disruptions [340]. Considering its superior characterization, UHPC is frequently utilized as an overlay to repair old concrete structures, improving the mechanical and durability features of the structure while requiring less maintenance [110,340]. According to Corvez et al. [341], the first known application of UHPC overlay was on a bridge across the La Morge River in Switzerland. In that project, UHPC was used to replace the bridge deck and curbing that was severely damaged. After one year of use, there were no cracks found in the prefabricated UHPC curb installed. With a low porosity, UHPC has a high level of durability, making it suitable for both rehabilitation and retrofitting of RC structures, and new construction, respectively [342].

Furthermore, owing to its remarkable features of high flexural strength and dense microstructure, UHPC has the potential to be used in some conditions that require more span length. On the basis of published reports, UHPC was employed in the construction of cover plates for high-speed railroads in China [110], the retrofitting of nuclear reactor containment walls [341] (Fig. 22) and the construction of the Beaucaire, and Caderousse Dams in France [38]. Since these materials have been so successful in repair and rehabilitation applications, other deteriorating projects may now benefit from the use of comparable technologies. In Japan, UHPC was employed to repair and restore the hydraulic infrastructure of Hosokawa River Tunnel [343] and the Haneda Airport UHPC slab built above water [36]. Concrete constructions that blend normal-strength and UHPC offer a significant deal of potential for rehabilitation and modification, according to studies [344]. UHPC is also utilized in marine environments because of its high resistance to hostile chemicals. Several windmills in the ocean are effectively designed [44,345], and the revitalization of marine signalization structures using UHPC is highly effective [346].

To date, the wide potential of UHPC in a range of applications is attributed to the material's enhanced performance; nevertheless, many applications that make use of the material's increased strength, durability, and flexural capacity have yet to be identified [75]. UHPC provides solutions that are both innovative and cost-effective in a variety of applications, including those involving extreme conditions and marine settings. As a consequence of its strong chloride resistance and long lifespan, UHPC is considered to be an alternative for preventing the corrosion of reinforcement. This is due to the fact that it has a good durability. There are instances of the use of UHPC in maritime projects generating promising outcomes [347]. This is because UHPC has lower permeability, which can limit the intrusion of harmful substances, which in turn greatly increase the durability of composite members compared with conventional concrete [344,348]. Historically speaking, the biggest threat that chloride-induced corrosion presented to RC structures was seen in areas close to the shore.

Additionally, UHPC may be used in the building, overlaying, repairing, and reinforcing of maritime structures such as piers and oil platforms, among other applications.

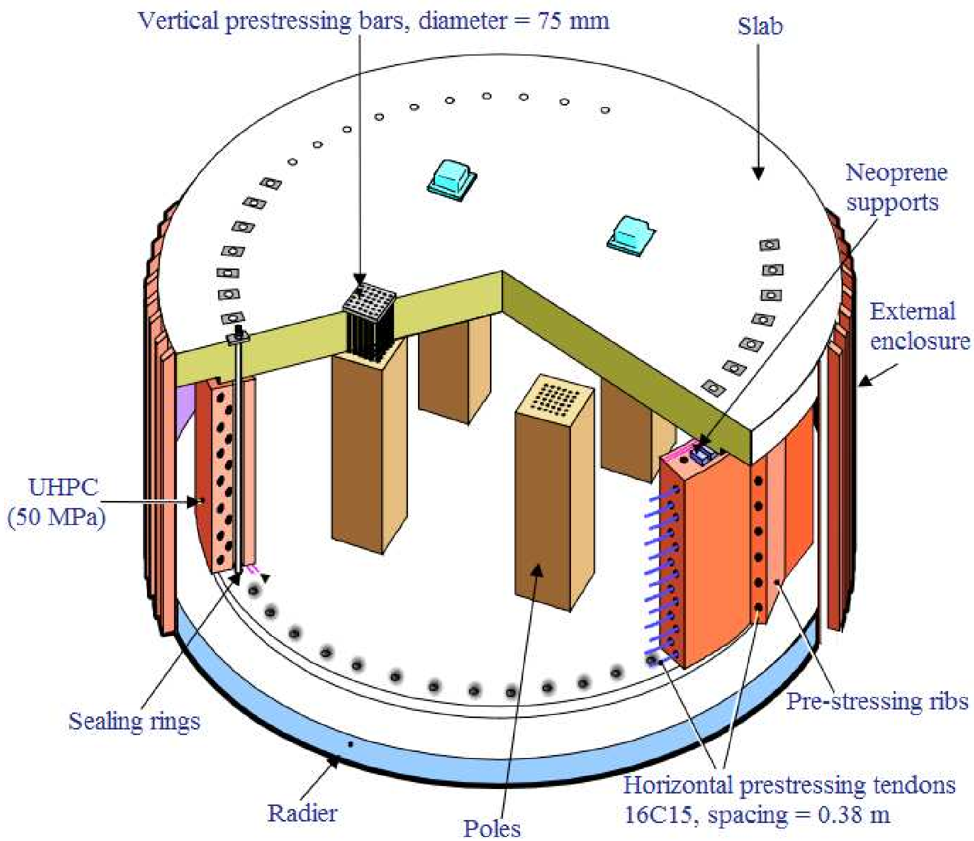


Fig. 22: Retrofit and restoration of nuclear reactor containment walls (Adapted with improvement from [341])

In addition to its resistance to chloride attacks, UHPC exhibits a high resilience to most physical and chemical challenges [75]. Due to its high dynamic modulus value, high bond strength capacity, and better bond durability in comparison to other forms of concrete, RPC has been shown in experimental research to have outstanding repair and retrofit potentials for compressive and flexural strengthening [349]. Based on the aforementioned studies and reports, UHPC is considered an outstanding material for use in outdoor or severely exposed environments because of its great durability and resistance to chemical attacks [75]. UHPC is well suited for use as a standard overlay material capable of withstanding mechanical stresses and hostile conditions because of its exceptionally low permeability, high strength, and outstanding strength qualities [40]. The literature review shows that most cross-sea bridges constructed using UHPC are significantly lighter and more durable, require less maintenance, and have fewer cross-section members [346]. In summary, UHPC is considered a suitable material for sustainable construction in the future, and its use will continue to increase globally owing to its unique engineering and architectural features. When compared to NSC composite, UHPC has the capacity to provide long-term durability, which helps to prevent the need for frequent rehabilitation interventions on concrete structures during the course of their service lives.

7 Future prospects

UHPC has been under development for three decades and is a potential construction material for future sustainable and resilient infrastructure [85]. The growth of the popularity and efficiency of UHPC is boosted by a design that is stiffer and lighter than traditional concrete. UHPC can also provide slender, light, resilient, and visually pleasing structural parts for building construction [75]. On the economic front, UHPC offers innovative and long-term economic solutions in places where traditional concrete suffers numerous durability issues. In addition, UHPC appears to offer great potential for a wide range of new applications, many of which are yet to be discovered. Although UHPC applications will continue to expand, efforts must be made to address the obstacles that currently impede their development [110]. There is currently a trend to simplify low-cost UHPC production methods by substituting affordable local resources for expensive components such as cement, steel fiber, and silica powder [15]. In addition, UHPC consisting of silica sand with a maximum particle size of 500 μm, GGBS, and steel fibers of 13 mm in length can be utilized to augment already existing RC beams [350]. Portable bridge deck panels can be made from the upgraded lightweight UHPC [30,35]. Nowadays, 3D printing is a promising technique in a variety of fields, including the concrete industry. Theoretically, it is simple and quick to construct a complicated three-dimensional structure utilizing concrete extrusion via a printing machine [351]. Several studies have recently been published to demonstrate the viability of employing UHPC in 3D printing [57,158,352]. However, no 3D printing implementation of a UHPC-based project has been recorded. Despite the availability of data on UHPC 3D printing, attempts are currently confined to low-complexity 3D printing. This is due to not only the UHPC's incapacity to be an ideal pumpable and printable material but also the technological limitations in the printing process and configurations (e.g., flow rate, nozzle design, pumping rules, and inclusion of reinforcing bars) [353]. Pumpability, buildability, and extrusion capacity must all be present in the cementitious material certified for 3D printing. Furthermore, to prevent the material sloping after extrusion and carrying the weight of the succeeding layer placed above, it should have low viscosity and strong yield stress and be promptly established to continuous flows during extrusion [354,355].

The development of 3D printing using UHPC composites results in better shape retention than using traditionally cast UHPC. In addition to this, the influence of polyethylene fibers (PEF) on the workability of 3D-printed ultra-high performance composites as well as the mechanical-anisotropic properties of these materials is investigated [356]. In this case, three different fractions of PEF are used to construct the UHPC: 1%, 1.5%, and 2.0% by volume. The printed UHPC with a 1.5% PEF content outperforms in terms of workability and mechanical characteristics. The printed UHPC samples with 1.5% PEF show a smaller drop in tensile strength, tensile strain capacity, strain energy, and crack number than those with 2% PEF [112]. In addition, the printed UHPC sample fails when subjected to a vertical force of 1.2 kilograms, while the conventionally cast UHPC has the capacity to support a vertical load of 0.7 kilograms [353]. The printed UHPC sample has a higher apparent porosity than UHPC manufactured traditionally; the presence of fibers causes the matrix to trap air, resulting in the composite having a larger porosity. During extrusion, the direction of the fiber is usually the same as the printing direction, which results in a 2D orientation, but the UHPC cast in the traditional way has a 3D fiber distribution [112].

Currently, a research project on 3D printing is being conducted at Loughborough University. This project is based on 3D printable UHPC, and it is in some ways comparable with other 3D-printed projects that applied the contour crafting approach [357]. In this approach, the printhead that is used for the deposition of cementitious materials is positioned on an overhead crane and moves in routes that are comparable to contour lines [358]. High engineering performance of UHPC mixture and small extruder diameter (4 to 6 mm) allow for effective geometrical control [357]. Using the tangential continuity approach for slicing completely exploits the capabilities of 3D printing by constructing layers of varied thickness, resulting in vault-like, structurally sounder buildings from a structural standpoint [101]. When there are more than 20 printed layers, the lower layers begin to be severely compressed and distorted because the upper layers have a greater amount of their own self-weight [101]. When preparing the sample for the buildability and mechanical examinations, only 10–11 layers of UHPC are printed at a time. Moreover, the orientation of the fibers becomes more twisted when the fiber content exceeds 1.5% [101]

In Belgium, a precast UHPC pedestrian bridge has been constructed. This bridge is 36 meters long and 4 meters broad, and it is supported by two delicate ribs that are little more than 100 millimeters thick [62]. Additionally, the cladding of the Foundation Louis Vuitton Pour la Creation in Paris, precast thin curve shells in a wastewater treatment plant in France, the roof and canopies at the Shawnessy LRT station in Canada, and the roof of the Olympic Museum in Lausanne, Switzerland are all recent UHPC uses [75,333,353]. According to the findings of a number of studies, well-known models, such as the Andreasen and Andersen model, the compressible packing model, and the linear packing model, may be implemented in the process of creating UHPC design systems [104,359]. These models help achieve the ideal packing density of the UHPC mix while simultaneously lowering the amount of cement required.

In addition to this, it is projected that it will be feasible to maintain a compressive strength of UHPC that is more than 100 MPa [42], that may be used in the building of modern constructions because of its high strength and efficiency. These models address the properties of UHPC materials with compressive strengths over 120 MPa and determine the standard size of specimens for evaluating the mechanical properties of UHPC [1]. However, unified standards are still required for the rapid adoption of UHPC in field applications. With this regard, several research institutes and centers have exerted significant efforts to adopt UHPC standards [62], although relatively few organizations and competent teams concentrating on UHPC designs, as well as those that execute UHPC work, are more concerned with that [112]. The process of determining the minimal bounds of mechanical characteristics that must be met in order to categorize UHPC at a level that is uniform for practitioners all over the globe is still under progress and require more study. The planning and construction methods used for UHPC are distinct from those used for conventional concrete [360].

- Overall expenses may be decreased by cutting construction material, transport and labor costs and lifting and moving equipment use at the construction site [112].
- To provide bridge owners, designers, contractors, and manufacturers an appropriate degree of confidence in using UHPC, further study is required to establish the economic cost of using UHPC for bridges across the globe. UHPC has a high unit weight because of its steel components.
- UHPC has a high unit weight because of steel components. Future research should focus on lowering the unit weight of UHPC to enable its use in lightweight structures as well as repair and rehabilitation applications [7].

Based on recommendations prepared by the U.S. Federal Highway Administration, the following research activities are required, and they are arranged according to estimated order of significance [90]:

  - Standardized testing characterization and requirements for the materials used in UHPC.
  - Research demonstrating the cost-effectiveness of UHPC in a variety of applications.
  - Studies to fill up some of the gaps in the structural design requirements.
  - Enactment of compatible specifications for the design and construction of UHPC-based structures.

- In investigating the size effect in UHPC, fiber size must be considered [102].
- Durability, as a key measure indicating the service life and maintenance costs of structures, is critical to their safety and long-term viability. Some durability indices of nanomaterials combined with UHPC, including fire resistance, carbonization resistance, and dynamic modulus of elasticity, have not been yet investigated [66].

- More study is required to evaluate the long-term performance and life cycle of UHPC manufactured from SCMs.
- As the manufacture of printable UHPC remains unclear for practitioners worldwide, major efforts are necessary to produce accessible knowledge for the use of UHPC for the manufacturing of large-scale structural parts employing 3D printing technology [112].
- Additionally, the gap between two layers of cementitious compositions must be minimized or eliminated when employing 3D printing. The tangential continuity method is superior to fused deposition modeling for large-scale additive manufacturing [101].
- The seeding effect is one of nanomaterials' fundamental roles in UHPC, but its mechanism is unclear. The finite element technique may be used to study it. Therefore, the influence of different nanomaterial sizes on UHPC performance needs further investigation [66].
- Determining the ultimate capacity of UHPC sections in shear and flexure requires more investigation, [99]. The existing standards for UHPC sections do not provide a realistic gauge of UHPC's ultimate capacity [100].
- Further study is required to discover how employing a high volume percentage of RHA affects UHPC characteristics and how $Ca(OH)_2$ depletion affects the alkalinity of UHPC generated with a high concentration of SCMs.
- Free lime in UHPC may be utilized to sequester CO2 and improve its mechanical characteristics and durability. Developing efficient strategies to capture CO_2 with UHPC needs further research [7].
- A uniform design mix of UHPC that ensures perfectly achieving the required design strength has not yet been developed. A large body of literature devoted to UHPC claims that strength limit of 150 MPa is the minimum strength requirement [15,40,67,340,361,362].
- In addition to nanosilica, a number of other nanomaterials, including as nano-clay particles and nano-aluminum oxide, ought to be researched since they have the potential to be used as additives in the manufacture of UHPC. The effect co-addition of different nanomaterials has on the performance of UHPC composites should also be investigated [66].
- A set of criteria must be established for the construction of beams made of ductal precast concrete [98].
- The Japan Society of Civil Engineers recommends ultra-high strength fiber reinforced concrete for UHPC applications [97].
- French associations of civil engineers and traffic and road government agencies have suggested a further improvement of the performance of UHPC applications [96].

- An investigation into the use of different fiber reinforcement (including their properties such as type, geometry, volume, dispersion, and orientation) in UHPC applications is also needed.
- Strategies for related material proportioning should be developed for UHPC such as appropriate distribution methods for fibers as well procedures for component manufacture and structural design concepts.
- For the production of UHPC-class composites with qualities that are satisfactory, more study into the use of either locally manufactured steel fibers or the use of fibers other than steel is required [90].

8 Limitations

As a cement-based engineering material, UHPC offers superior strength properties, great durability, and a dense microstructure, which leads to its increased application in infrastructure development [363]. In most cases, UHPC cannot meet engineering performance criteria and is prohibitively costly compared to typical concrete combinations [16]. UHPC offers outstanding mechanical performance and high durability compared with conventional strength concrete; however, its use is restricted because of its large cement content (up to 1100 kg/m^3), considerable environmental effect, limited design codes, and high initial cost. In addition, the high cost of raw materials, such as steel fibers and fine silica sand, which made up roughly 50 percent of the total cost, limited its applicability [81,117].

As a matter of fact, the manufacture of one ton of Portland cement emits almost the same amount of CO_2 into the atmosphere as the combustion of one ton of coal [364], which unquestionably places a significant strain on the environmental sustainability. On the basis of raw material sustainability, UHPC opposes the present goal of sustainable development, which is to minimize energy consumption and greenhouse gas emissions [365]. The w/c ratio in UHPC is exceedingly low (Fig. 23), and the extent of hydrated cement is quite limited (30%–40%) [366], implying that a large amount of unhydrated cement is solely employed as a costly filler. From an economic point of view, replacing this portion of cement with inert, inexpensive, or even recycled materials makes sense [365]. According to reported data, the global average cement clinker percentage decreased from 85% in 2003 to 77% in 2010 and is projected to fall to less than 70% in the future [367]. By contrast, according to the available literature, the usage of mineral admixtures to substitute cement is expanding the Portland cement concrete and UHPC industry. Numerous investigations demonstrate that various quantities of FA [368,369], RHA [370,371], GBFS [238], SF [368], limestone powder (LP) [372], basalt powder (BP) [373], and marble powder (MP) [374,375] may be used to partially replace OPC. Ganesan [376] stated that within the context of ordinary concrete research, the addition of 30% RHA in place of cement has no discernible negative effect on strength and permeability. Chindaprasirt et al. [375,377] demonstrated that mortar synthesized from a ternary combination of OPC, RHA, and granular FA may outperform better than that developed from one type on SCMs. Therefore, a range of mineral admixtures is suggested as alternate constituents in UHPC-related research such as SF, GBFS, and waste glass powder. In this regard, Talah [375] studied concrete with 15 percent marble powder in a particular chloride environment. The findings suggest that the use of marble powder increases the mechanical qualities and durability of concrete.

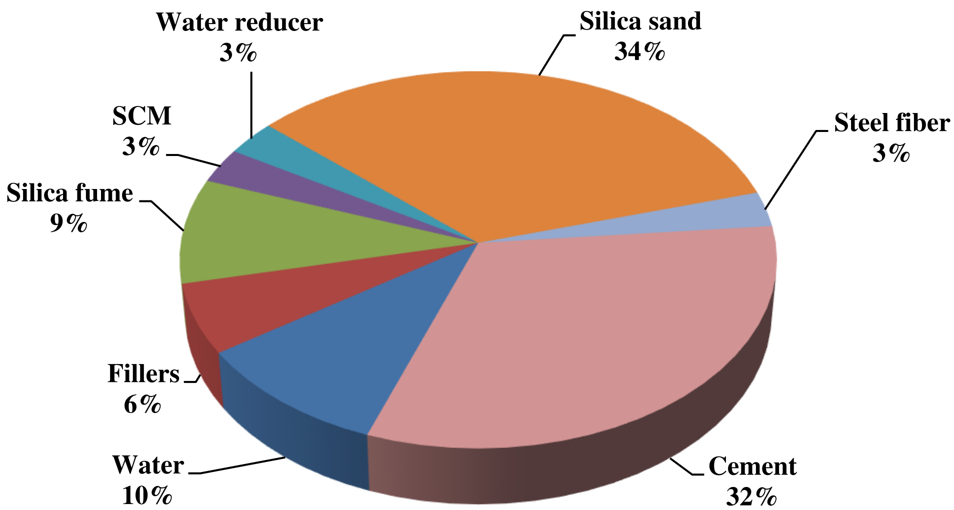


Fig. 23: Average composition of UHPC (Data adopted from [56,68,327,378]**)**

In addition, Haque et al. [379] reported that the optimal cement replacement level is 10%. However, based on typical empirical findings, partial or entire loss of strength in regular or high-strength concrete becomes a common occurrence as replacement rates increase [365]. In the development of optimal UHPC in terms of sustainability and mechanical performance, how to reach a greater substitution level for concrete mixtures without losing the hardened properties of concrete remains a major concern. Certain chemical methods are proposed to remedy the problem, such as the use of a high-efficiency activator and nano-SiO_2 (NS). In this regard, Shi [380] investigated the influence of various chemical activators on the strength of FA and discovered that spot build-up of Na_2SO_4 and $CaCl_2$ may boost the pozzolanic reaction of FA. Similarly, the use of silica nanoparticles to improve hydration is widely reported in the literature [381,382]. However, although the chemical technique preserves the strength of cement-based materials, it raises the cost of concrete, eliminating a crucial key of success factors represented in lowering cost.

Physical approaches also receive much attention. Physical and hybrid techniques that based on industrial waste or by-products are suitable alternatives, and the UHPC development trend has steadily shifted to the category of superior performance and enhanced sustainability. For example, FA, crushed GGBS milling, and LP, can be used to generate UHPC blends with low environmental impact based on the enhanced A&A model [171,299,319]. The use of industrial waste or by-products as a substitute for cement in the environmental production of UHPC not only offers economic benefits and enhances the environment but also has positive effects on long-term strength, reduces self-shrinkage, and improves durability [293,383]. The improved particle packing structure can then be employed to lower the amount of cement in UHPC without losing its superior performance [362,384].

Moreover, several researchers made UHPC with LP instead of 54% cement, and they found that the workability and compressive strength of the material remain satisfactory [61,385,386]. However, if the level of replacement continues to rise, it is not known to what extent UHPC will continue to retain its superior performance. In other words, the maximum percentage of cement replacement permitted without causing in reducing the mechanical performance of concrete is yet to be determined. Most experimental results indicate that an increase in the level of cement replacement with low-cost pozzolanic materials has a positive effect on sustainability especially in terms of the initial cost of concrete production. In addition, UHPC mixes can incorporate up to 2.5% (by volume) of metallic fibers with a length of 13–20 mm and a diameter of 0.16 mm [108]. These metallic fibers are commonly utilized as web reinforcement or to provide higher lateral interlink and more ductility [387]. In this situation, increasing the percentage of fibers provides higher structural ductility values, but increasing the fiber content raises the initial concrete production cost [108]. To date, the following four distinct strategies to minimize the cost of UHPC are reported:

- Reducing the proportion of high-strength steel fibers [107,388]
- Increasing the amount of fine aggregate to decrease the bond content [389]
- Replacing natural curing for thermal curing to reduce energy costs [102]
- Promoting the use of locally available materials that usually have lower costs [70,165,188,389]

In summary, further consistent attempts to lower the cost of UHPC are necessary to achieve compatibility between reaching the required 28-day compressive strength and reducing or replacing the high-cost materials [69,70,112]. In addition, despite the numerous benefits of ultra-high performance concrete (UHPC), its adoption in the construction industry is hindered by a number of obstacles. These obstacles include a high production cost, a lack of design regulations and requirements for estimating UHPC performance, and the requirement for one-of-a-kind batching, mixing, and curing.

9 Challenges

The superior mechanical and durability properties of UHPC have increased its use for resilient and sustainable RC structures [390]. Although UHPC is used globally, its widespread deployment faces obstacles. UHPC is more homogeneous than NSC because of its higher packing density and lack of coarse aggregate. Brittleness and lack of coarse aggregate in unreinforced UHPC lead to straight-line cracks [26]. Micro-fibrous reinforcements improve UHPC's ductility and tensile strength, preventing crack propagation [29]. Low w/b ratio, macro metallic fiber distribution, and low workability make UHPC difficult to cast [327]. Green UHPC faces challenges in achieving early mechanical performance when replacing cement with pozzolanic materials. UHPC stakeholders, designers, contractors, and manufacturers need more research to resolve the following issues [99,327]: A fair and accurate strategy must be established for optimizing UHPC components and mix design (rather than relying on trial mixes) [327]. Due to its low w/b ratio, UHPC requires high-energy mixers. The manufacture of UHPC precast pieces requires field adjustments [99]. UHPC's advanced cracking resistance, strength, ductility, durability, and creep allow for simple connection reinforcement. This improves element constructability and simplifies onsite assembly; further research is needed to accelerate UHPC project implementation [84,312]. Rational design provisions must be developed to use UHPC's high strength and other unique properties properly [49,327]. To archive the successful usage of UHPC, further research is required to address the following major challenges [99,327]:

- The orientation of UHPC fibers affects its flexural properties [369]. Casting thin elements requires a method that effectively distributes fibers in the matrix while maintaining orientation [391].
- Thermal curing strengthens UHPC, but it is expensive. Exploring specific curing processes for onsite construction and precast facilities [260].
- UHPC materials are expensive and energy-intensive, limiting their use. UHPC needs more research to lower its cost and improve its long-term sustainability. Several studies adjust material mixtures by incorporating regional raw resources and waste products to reduce cement, steel fiber, and SP usage [264]. Infrastructure owners will be more interested if UHPC's cost and environmental impacts are reduced.
- Lack of experience with mixing, synthesis, and quality control processes is problematic because UHPC blends with steel fibers require a multi-step mixing process and a specific curing process [99].

- The fraction of nanoparticles that replace cement in UHPC remains low due to difficulties ensuring uniform nanomaterial dispersion within the concrete matrix. Nanomaterial dispersion needs more study to maintain efficacy at higher doses [66].
- Field experience, empirical analysis, and scientific calculations should inform UHPC design and construction criteria. International guidelines are complicated given the different UHPC experiences in different countries [392]. France, Japan, China, Germany, and Switzerland have tried standardizing UHPC to expand its use. France announced its first UHPC standard in 2016 [42].
- UHPC can be self-sensing, self-cleaning, and electromagnetic interference shielding by using nanoparticle functions. This needs more research [7].
- After years of development and mass production, cement materials are cheaper than nanomaterials. Decrease nanomaterial production costs [66].
- Uncracked HPC and UHPC are brittle, so micro and macro fibers should be added [260].
- UHPC constructions deviate from the norms for regular reinforced concrete, and the number of qualified builders, engineers, and specialists is limited; therefore, teams familiar with UHPC technology and design issues are required [392]. There are only about five big players in the UHPC market, mainly in Europe and North America [110].
- Nanotechnology could improve UHPC's performance, including downsizing [75]. Nanotechnology leads UHPC research. Scientists have studied the nanoscale structure of UHPC hydration products. Experiments using nano-silica and nano-fibers improve cement-based concretes.
- Metal fibers, carbon nanotubes, and metal additions make cementitious composites self-sensing. To ensure uniform distribution of functional fillers in UHPC mixtures with low w/b ratios, dispersion agents, mixing processes and consolidation methods must be carefully chosen. A low-cost, reliable, and eco-friendly method for casting large structure components is being researched [393,394].
- Self-sensing Corrosion can affect UHPC's self-sensing capabilities [395]. Temperature and humidity changes can impair UHPC self-sensing in situ, but their long-term efficiency is unknown [60,393,396]. More research is needed to determine whether fibers can retain their electrical properties over time.
- Green UHPC mixtures include slag, fly ash, and SF. Traditional SCMs are becoming rare as coal-fired power plants transition to natural gas. Sustainable SCMs need more research [7].
- Self-sensing concrete techniques are discussed. Their application and efficiency in UHPC are unclear [393]. More research is needed to uncover UHPC self-sensing mechanisms to build self-sensing UHPC [397].

- Given the high amount of steel fibers, expensive SCMs, and high chemical admixture dosages, proprietary UHPC mixes cost \$2500–\$3000/m^3, compared to \$170/m^3 for ordinary concrete [99]. More research is needed to find radical production cost reduction solutions.
- Efforts to promote green HPC in the construction sector should be coordinated to avoid research objectives clashing, expedite green UHPC applications, and develop best practices for long-term sustainability [398].
- UHPC specialists must train concrete industry workers in modern technology [112]. In addition to this challenge, many traditional HPC tests do not always yield valuable information, and the testing errors allowed in contemporary concrete tests often exceed those in UHPC tests [62].

10 Conclusions

This critical review has reported up-to-date development trends of UHPC, exploring that UHPC possesses an incredible set of capabilities that were previously unimaginable. UHPC achieved much greater strength and durability capabilities than other equivalent concrete grades as a result of a large reduction in the volume and size of pores. As a result, UHPC has a long lifespan due to its capacity to withstand the test of time. Given the high level of emissions produced by concrete, the building sector plays a critical role in lowering these emissions. UHPC is one of the most cutting-edge cementing material technologies. UHPC with superior mechanical and durability features as well as sustainability may be manufactured by enhancing uniformity and packing density. With this technology, building structures that are lighter, bigger, or have a greater span than traditional designs is now feasible. Thanks to its unique workability, new concrete may be cast in irregular or extremely thin shapes to create structures with an aesthetically pleasing look or exceptional polish. However, because UHPC is not financially viable to replace ordinary concrete in most applications, using it in construction is restricted. Significant expense of some composite materials (e.g., steel fibers might cost more than the remaining matrix elements combined), maintenance costs, and non-adherence to conventional design criteria are economic factors. Consequently, a growing number of researchers, bridge, and engineers are becoming interested in the applications of UHSC. They acknowledge the material's significant potential for application in bridge construction along with its limited use to date. However, several technological issues, such as restricted design codes and complex manufacturing and curing procedures, have yet to be overcome. Furthermore, the negative environmental effect of cement manufacturing in UHPC is magnified compared to that in conventional concrete.

To fully use UHPC's enormous potential, the sector has to work more closely with academic institutions, governments, building owners, and end-users. Owing to a lack of industry experience, UHPC specialists face additional challenges in spreading hands-on practice to concrete industry professionals so that they can be well-versed in the application of sophisticated concrete technologies. For these reasons, a comprehensive literature study on recent developments trends of UHPC should be conducted to determine its current status and future prospects. This research has systematically reviewed the background, carbon capturing, sustainability, challenges, limitations, and potential applications of the UHPC. The findings of this state-of-the-art review are likely to help specialists establish the design guidelines for the cutting-edge, reachable, and sustainable UHPC. Doing so will enable design engineers to fully exploit the high strength and other special properties of UHPC, and to develop models that can effectively estimate the ultimate bearing capacity of UHPC sections under various loading conditions. It is expected that this review will help scientific researchers, designers, and practitioners in widening the use of UHPCs in advanced infrastructure applications. Based on the significant findings, additional studies are suggested in the following areas:

- Only a few producers have expertise with UHPC for large-scale infrastructure applications. Basic information must be made publicly available, so that interested parties have access to this knowledge.
- Substantial research is needed to optimize UHPC mixes, enhance preparation procedures, and develop design standards and codes. All of which will provide practical advice for UHPC's broader applicability, such as in bridge construction.
- Forecasters must be aware of the need for longer mixing durations than in conventional concrete mixers, longer setting times, modified curing regimes, and xx lower quality control tolerances for popular test methodologies.
- Furthermore, additional scientific studies on UHPC must be conducted to help overcome the limitations and constraints of existing UHPC usage. These efforts may lead to a mainstream "regular" technology, leading to more efficient, sustainable, and resilient infrastructure.
- Owing to its increased strength, ecological and durability properties, and the environmental aspects and economic advantages in the long term and recycling potential in many applications, UHPC can be a sustainable material in the construction of essential infrastructure facilities with strong resilience and durability performance to close the supply-demand gap for the upcoming generations worldwide.

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