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Case study

Ultra-high-performance fiber-reinforced concrete. Part IV: Durability properties, cost assessment, applications, and challenges

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A R T I C L E I N F O

Keywords:
Ultra-high-performance fiber-reinforced concrete (UHPFRC)
Durability properties
Cost assessment
Applications
Challenges

A B S T R A C T S

Ultra-high-performance concrete (UHPC) is a type of cement-based composite for new construction and/or restoration of existing structures to increase service life. It is an innovative composite material that can be a suitable alternative to concrete structures exposed to aggressive conditions. After decades of research and development, a wide range of commercial UHPC compositions have been produced worldwide to cover a growing number of applications and a growing demand for high-quality construction materials. UHPC has significant advantages over regular concrete, but its use is limited due to limited design codes and prohibitive cost. Therefore, a comprehensive investigation of the durability characteristics of UHPC is essential to provide fundamental information for material testing requirements and procedures and expand its practical applications. Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. Part III reviewed the fresh and hardened properties of the UHPFRC. This Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC. This review is expected to advance the fundamental knowledge of UHPC and promote further research and applications of UHPC.

Abbreviations: CFD, Computational fluid dynamics; CRC, Compact reinforced composites; DEM, Discrete element method; FHWA, Federal Highway Administration; GVR, Grand View Research; HPFRCC, High-performance fiber-reinforced cement composites; HSM, High-strength mortar; PWD, Public works departments; RC, Regular concrete; RCPT, Rapid chloride permeability test; RPC, Reactive powder concrete; SF, Silica Fume; SRA, Shape retention ability; UHPC, Ultra-high-performance concrete; UHPFRC, Ultra-High-Performance Fiber-Reinforced Concrete; US, United States.

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1. Introduction

UHPC is a high-strength, high-durability cementitious material. It has the potential to be a viable solution for improving the "sustainability of buildings and other infrastructure components [1–7]. UHPC has grown in popularity in many countries over the last two decades, with applications ranging from building components, bridges, architectural features, repair and rehabilitation, and vertical components such as windmill towers and utility towers, to oil and gas industry applications, offshore structures, hydraulic structures, and overlay materials [8–11]. Among all of these applications, road and bridge construction are the most common for UHPC use. UHPC is used in a variety of nations, including Australia, Austria, Canada, China, the Czech Republic, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Switzerland, and the United States (US) [8,12,13]. The majority of projects in the aforementioned countries were inspired by government entities as pilot projects to stimulate future implementation. However, with tardy follow-up implementation, most countries' demonstration programs did not achieve the desired acceptability" [14–19]. The lack of design codes, inadequate knowledge of both the material and production technology, and expensive costs appear to be limiting the implementation of this excellent material beyond the early demonstration projects [8,20–22]. Both the business and public sectors are increasingly paying closer attention to and pushing for greater efforts to make use of this novel and promising material.

Several varieties of "UHPC have been developed to date in various countries and by various manufacturers, including Ceracem+ , BSI+ , compact reinforced composites (CRC), multiscale cement composite (MSCC), and reactive powder concrete (RPC) [23–28]. In Malaysia, UHPC began its industrial-commercial penetration as a sustainable construction material under the brand name Dura+ in late" 2010 [25,29–32].

Throughout the world, successful successes in the application of UHPC can be seen. However, there are still obstacles that limit its application. Ongoing study and investigation efforts are filling knowledge gaps in order to commence innovative, affordable, sustainable, viable, and economical UHPC in the future, which will have a significant impact on its acceptability. This paper provides a general introduction to UHPC as well as the most up-to-date information on its definitions, development, applications, and problems.

Many researchers have "conducted studies on UHPC, but information on the materials and structural properties of UHPC is still limited. This review includes five parts. Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. Part III reviewed the fresh and hardened properties of the UHPFRC. This Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC. The purpose of this review is to summarize previous research and to suggest some needs for future" research.

2. Durability

Because of its "dense matrix, UHPC has higher durability. The technical requirements, characteristics, typical values, and test procedures for evaluating the durability of UHPC are listed in" Table 1.

2.1. Water permeability

The term "permeability" refers to "the general movement of fluids into and through concrete. Because of the high water permeability of concrete, chemical compounds such as chloride ions can infiltrate the material, resulting in corrosion of steel rebars and/or fibers. Using W/B, use of supplemental cementitious materials (SCMs), pore diameter, and pore connectivity all have a significant impact on concrete water permeability [47–55]. The typical permeability coefficient of UHPC was about 0.0005 at 98 days due to its exceptionally low porosity, whereas the typical permeability coefficient of regular concrete was about 0.0015 at 98 days, a difference of an order of magnitude," as shown in Fig. 1.

The permeability "coefficient in hydrated cement paste is controlled by the size and continuity of the pores at any time during the hydration process. As a result, the low permeability of UHPC may be explained by the small and discontinuous holes seen in the extremely homogeneous, compact, and dense pastes. The capillary network became progressively convoluted as linked holes were

Table 1
Test methods, specification, and suggested value of UHPC durability.

Test method	Parameters	Specification	Suggested value	Reference
Alkali-aggregate reaction	Expansive percentage	ASTM C1567	< 0.1%	[33,34]
Rapid chloride permeability	Charge Passed	ASTM C1202	< 100 Coulombs	[35,36]
Fire resistance	Residual f_c'	ASTM E119	< 20%	[37,38]
Carbonation	Carbonation depth	ISO 1920–12:2015	< 3 mm	[39,40]
Freezing-thawing resistance	Durability factor Mass loss	ASTM C666	> 95% < 0.6%	[41,42]
Water sorptivity	Sorptivity coefficient	ASTM C1585	< 0.044 kg/ m^2/h0.5	[43,44]
Water adsorption	Permeability	ASTM C642	< 0.005	[45]
Sulfate resistance	Length change	ASTM C1012	≈ 0	[39,46]
Abrasion resistance	Wearing depth	ASTM C944	< 1 mm	[39]

blocked by the development of C–S–H, potentially resulting in a continuous" fall in permeability coefficient [45,56–63].

2.2. Chloride ion permeability

Chloride ions that "diffuse through concrete can be dissolved in the pore solution or chemically and physically bonded to the hydration products [12,13,29,30,64]. Depending on the binding mechanism, the chlorides might be classified as free or bound. Chemically linked chloride ions can react with a cement mixture to produce salt products. The entrance of free chloride ions into steel/fiber-reinforced concrete causes depassivation of the steel rebars and/or fibers, as well as the commencement of the corrosion process, which leads to the degradation of concrete structures [46,65]. Because of the passivation in high alkaline pore solution, steel reinforcements in concrete are protected from corrosion. The passive layer on the steel surface will be destroyed due to aggressive chloride ions and/or neutralization of the" environment around the reinforcements. As a result, steel reinforcements corrode, and concrete buildings deteriorate and lose service life [66–74].

To determine the chloride "ion permeability of concrete, accelerated testing procedures such as the rapid chloride permeability test (RCPT) [75] and Nordtest method NT Build 443 [76] are often employed. In the Nordtest method NT Build 443, the chloride ion diffusion coefficient is used as an evaluation indicator. Table 2 compares the chloride permeability coefficients of UHPC from various publications. Depending on W/B, curing regime, medium solution concentration, steel fiber volume, and testing age, the chloride ion diffusion coefficient of UHPC ranges from 0.2×10^{-13} to 4.1×10^{-13} m^2/s. It is difficult to conduct a quantitative comparison of the chloride permeability of various UHPCs due to the different testing settings and mixture proportions employed in the" literature. It is worth noting that the chloride ion diffusion coefficient of UHPC is at least one order of magnitude lower than that of HPC or CC [77–82].

2.3. Corrosion of steel reinforcement

The main cause of "deterioration is chloride-induced corrosion of steel reinforcing in concrete composites. UHPC is very resistant to corrosion due to its extremely low chloride ion permeability. The accelerated corrosion test was performed by Ghafari, Arezoumandi, Costa and Julio [84] to analyze the corrosion rate of steel bars in HPC and UHPC. The time it took to crack in HPC was less than half that of UHPC. The corrosion rate for steel bars in UHPC was reported to be 0.01 lm/year, which was significantly lower than the previously reported limit of 1 lm/year [43]. Fan, Meng, Teng and Khayat [85] studied the effect of brass and zinc-coated fibers on the electrical resistance and corrosion resistance of conventional cured UHPC and implanted steel bars. The electrochemical test was carried out on UHPC specimens that had been immersed in 3.5 wt percent NaCl solution for a year. The results showed that no chloride was discovered and that the corrosion current density was roughly 0.01 lA/cm^2, indicating that the steel bar was not corroded. Furthermore, the open circuit potential-based ASTM standard C876 was found to be unsuitable for assessing the corrosion status of embedded steel bars in UHPC. Rafiee and Schmidt [86] simulated the corrosion of macro cell steel in cracked UHPC exposed to chloride solution for 360 days. The predicted anode corrosion current and cross-section loss were within 0.5×10^{-6} 2.5×10^{-5} and 0–4.5% of the experimental measurements, depending on the exposure time and concrete cover" thickness.

Nanoparticles are "used in UHPC to improve durability by utilizing their unique physical and chemical properties. Mohd Faizal, Hamidah, Norhasri and Noorli [87] investigated the corrosion potential of UHPC implanted with steel reinforcement using nano-clay (1%, 3%, and 5% by weight of cement). The specimens were immersed in a 3% sodium chloride solution for 91 days. It was discovered that as the nano-clay content increased, the corrosion potential reduced, delaying the onset of corrosion. The inclusion of nano-silica reduced the corrosion rate of steel bars implanted in UHPC" significantly [84].

2.4. Carbonation

In the presence of "adequate moisture, carbonation is the chemical reaction of CO_2 in the atmosphere with hydration products such as calcium hydroxide Ca(OH)2. This reaction generates CaCO3 and reduces the pH of concrete to roughly 9. At such pH levels, the

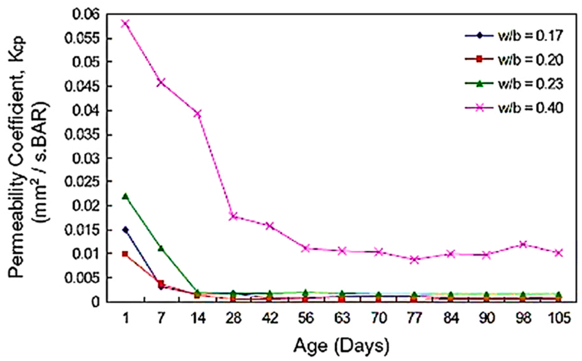

Fig. 1. Water permeability of UHPC at various ages with varied water-to-binder ratios [45].

Table 2
UHPC chloride ion diffusion coefficient.

Curing condition	W/B	Medium solution	Steel fiber volume	Testing age	Chloride ion diffusion coefficient (10–13 m^2/s)	Ref.
20 C for 2 d + 90 C curing for 2d	0.12	Seawater	2%	28 d	1.3	[83]
Heat treated at 90 C for 3d	0.21	3% NaCl	2.5%	63 d	1.3	[36]
90 C steam for 1d then 90 C hot water till room temperature	0.15	10% NaCl	2.6%	–	4.1	[77]

protective oxide layer surrounding the reinforcing steel deteriorates, resulting in steel corrosion and, eventually, concrete structure” breaking [88].

Carbonation of concrete can lower “alkalinity and degrade the passive coating on the surface of reinforcing steel, making the reinforcing steel prone to rust. UHPC has an exceptionally low water-to-binder ratio, and its internal structure is exceedingly dense, making it difficult for CO_2 to infiltrate into concrete. As a result, UHPC has good carbonation resistance. Long, Xie, Wang and Jiang [89] discovered that carbonation could not occur on UHPC after sealed, standard, or heat curing conditions. Another study discovered that the 28-day mean depth of carbonation in UHPC was less than” 0.30 mm [40].

2.5. Freezing-thawing resistance

The main cause of “concrete structure deterioration in cold locations is freezing-thawing. Because the structural structure of UHPC is so dense, external water cannot penetrate it. Furthermore, the insertion of steel fibers may limit crack progression [90]. The durability coefficient of UHPC was greater than or equivalent to 100 after 600 freeze-thaw cycles, and mass loss was nearly negligible [40]. As shown in Fig. 2, the relative dynamic modulus of regular concrete (RC), high-strength mortar (HSM), and reactive powder concrete (RPC) decreased by 61%, 22%, and 10%, respectively; their compressive strengths decreased by 57%, 16%, and 6%, respectively; and the bond strength between steel and the matrixes decreased by 35%, 23%, and 5%, respectively. As a result, RPC’s freezing-thawing resistance was higher than that of RC and HSM [91]. However, RPC containing steel fibers demonstrated enhanced surface scaling,” particularly near the fibers.

Furthermore, Smarzewski and Barnat-Hunek [41] observed that the hybridization of steel fiber and polypropylene fiber boosted freeze-thaw resistance at the same volume fraction as single fiber addition.

2.6. Fire resistance

Because of its low thermal conductivity and large thermal capacity, concrete is an excellent fire-resistant construction material.

The explosive spalling “of HPC, ordinary concrete (OC), and UHPC specimens was discovered to occur at temperatures of 600 C, 690 C, and 790 C, respectively [92]. When heated to 200–300 °C, the compressive strength of UHPC gradually increased, but then began to decline [93]. After a fire duration test at a constant temperature of 500 ± 50 C, the compressive strengths of UHPC, HPC, and OC fell considerably, with residual compressive strengths of 62.2%, 46.7%, and 58.5%, respectively, after 60 min of fire. As demonstrated in Fig. 3, their residual compressive strengths remained 55.6%, 34.6%, and 52.7% of their initial compressive strengths after a 120-minute fire. When subjected to the same fire temperature and duration, the interior temperatures of UHPC specimens were consistently greater than those of HPC and OC specimens. This suggests that the temperature difference between the core and the periphery of the UHPC was lower, which could lead to decreased internal thermal stress. When subjected to the same temperature and duration of the fire, the total mass losses of HPC and OC were consistently greater than those of UHPC [92]. As a result, UHPC and OC have higher fire resistance than” HPC.

The increased steel fiber content helps “reduce strength loss by preventing cracking propagation. According to Tai, Pan and Kung

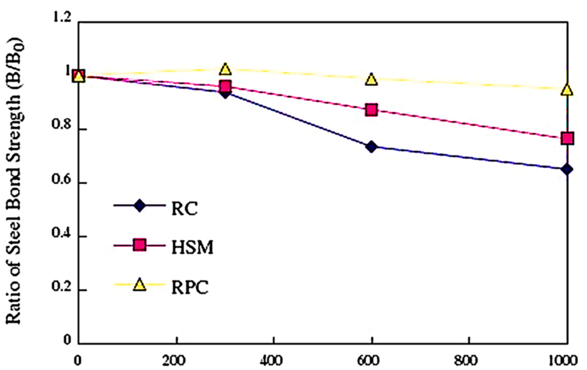

Fig. 2. Steel bonding strength ratio of RPC in comparison to RC and HSM [91].

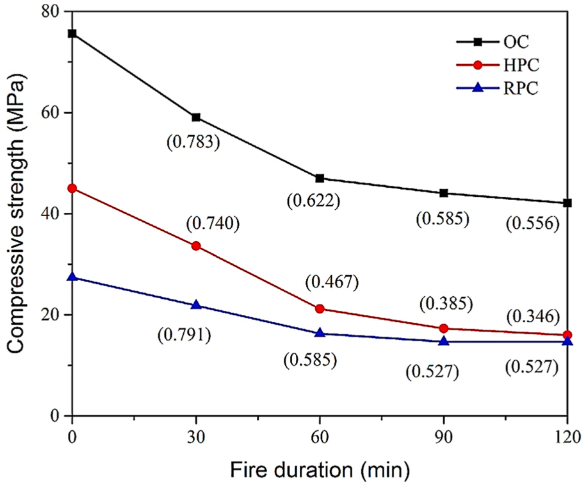

Fig. 3. Changes in OC, HPC, and UHPC compressive strengths as a function of fire duration [92].

[93], compressive strengths of UHPC produced with 1%, 2%, and 3% steel fibers improved by around 24%, 4%, and 7%, respectively, after 200 C heating. The compressive strengths were reduced by roughly 82%, 78%, and 77%, respectively, after 800 C heating, which was approximately 20% of the initial strength. Zheng, Luo and Wang [94] discovered that compressive strengths of UHPC produced with 1%, 2%, and 3% steel fibers were reduced by approximately 28.1%, 26.1%, and 18.8%, respectively, following 100 C heating. After 600 C, the compressive strengths of specimens constructed with 1%, 2%, and 3% steel fibers were approximately 37.9%, 43.0%, and 33.5% of the original strength, respectively. After heating to 800 °C, UHPC suffers from severe compression deformation, resulting in a loss in performance. Furthermore, mass loss after heating from 150 to 800 C of UHPC specimens with varied steel fiber contents was reported to be less than 12% of the starting mass [95]. After the same exposure temperature and duration as CC and HPC, UHPC specimens showed a reduced temperature difference between the outer and inner layers. This resulted in a slightly" spalling of UHPC and decreased mass loss following heating to 800–900 C [96].

The use of appropriate fiber content "with a low melting point helps reduce explosive spalling. This is due to the creation of pores and channels from synthetic fiber melting at temperatures about 150 C, which can release vapor and minimize pore pressure build-up [96]. Zheng, Li and Wang [97] investigated the impact of heating temperature on the compressive strength of UHPC constructed from steel and polypropylene fibers. When subjected to lower temperatures, the usage of polypropylene fiber had a negative effect on the compressive strength of UHPC but had a beneficial effect when exposed to higher temperatures. Under loading, Heinz, Dehn and Urbonas [38] evaluated the fire resistance of UHPC produced with steel fibers or a combination of steel and polypropylene fibers. The authors concluded that UHPC cylinders without polypropylene fibers spalled within a few minutes and were damaged beyond recognition after 90 min. The best results were obtained with UHPC specimens containing 3.05% steel and 0.6% polypropylene fibers. Peng, Kang, Huang, Liu and Chen [98] discovered that using 0.9% polypropylene fibers was the key content for improving UHPC fire resistance. As a result, the combination of steel and polypropylene fiber can clearly reduce or eliminate spalling during fire exposure and significantly reduce strength loss due to cracking [99,100]. According to microstructural research, UHPC with steel and polypropylene fibers demonstrated higher permeability and connectivity due to the creation of pores and channels associated with polypropylene fiber melting [101]. Low thermal expansion aggregates could help to prevent thermal stress spalling [102]. However, due to the additional water introduced, the usage of high moisture conditioned aggregates in UHPC, such as saturated lightweight aggregate, might result in severe violent" spalling.

2.7. Addressing potential durability issues

Water adsorption "and sorptivity studies have demonstrated UHPC's impermeability, which justifies the great resistance to the infiltration of harmful chemical ions (e.g., Cl^- and SO_4^2) and CO_2 [34,103]. However, there are durability difficulties that can be ascribed to: (1) improper usage of porous materials (e.g., SAP and porous sand); and (2) crack development under service loads. The next sections examine potential remedies" to these issues.

2.7.1. Optimize the content of porous materials for dense microstructure

The successful use of "porous sand as an internal curing agent in UHPC dramatically reduced autogenous shrinkage. Fan, Meng, Teng and Khayat [104] investigated the effects of porous sand on the corrosion of steel reinforcing bars embedded in UHPC and the matrix's resistance [105]. The findings indicated that excessive use of porous sand could affect steel bar corrosion resistance and result in current shortcuts via chopped steel fibers in UHPC. This is due to the fact that as the porous sand content surpasses the optimal amount, the total porosity of UHPC increases dramatically. To counteract the negative effect, the porous sand replacement ratio should be limited to the optimum value. When the value is less than, the addition of pre-saturated porous sand enhances the hydration process, and the hydration products fill the pores, helping to compensate for the porosity provided by the sand, as illustrated in Fig. 4. Similarly, the incorporation of other porous materials into UHPC should be carefully planned and tuned in order to preserve or improve the" microstructure.

2.7.2. Control crack width for corrosion resistance

Steel reinforcement within "UHPC can be successfully protected by the greater impermeability of intact UHPC. Concrete constructions, on the other hand, are prone to cracking. Cracks provide short routes for hostile ions (such as chloride ions and sulfate ions) to touch the steel. Cracks are frequently followed by debonding between steel and UHPC, which can harm the passive coating on the steel surface and speed up corrosion [106]. In this regard, self-healing cracks in UHPC are important for long-term durability. The low degree of cement hydration is attributable to UHPC self-healing [107]. Unhydrated particles in UHPC are exposed to moisture and air after being fractured, resulting in hydration products from hydraulic and/or pozzolanic processes and the precipitation of calcium carbonate and C–S–H, as seen in Fig. 5. It is worth noting that the fracture width is crucial for self-healing because broad cracks cannot be filled, and it is usually preferable to keep the crack width between 100 μm [108]. The use of synthetic fibers in UHPC appears to be promising for controlling fracture width. With the addition of synthetic fibers, the cracking behaviors of UHPC have shifted toward multi-micro-cracking patterns rather than localized main cracking patterns. As a result, the number of cracks increases but the width of each crack decreases. Furthermore, any strategies that limit autogenous shrinkage and improve UHPC tensile strength are promising for improving crack" resistance and controlling crack width.

2.8. Chemical attacks

Chemical attacks, including chlorides and sulfates, cause spalling and corrosion in UHPC components exposed to maritime conditions. Because of its highly dense structure, UHPC takes awhile to develop obvious chemical attack indications. Franke, Schmidt and Deckelmann [44] compared the behaviors of UHPC species to those of CC when exposed to lactic acid, sulphuric acid, salt solutions, and ammonium nitrate. The corrosion depth of UHPC exposed to sulphuric acid with a pH of 3 was found to be the same as that of the reference mortar in sulphuric acid with a pH of 4. It was also reported that when UHPC was submerged in different concentrations of sulphuric acid solution, sodium chloride solution, and sulfate solution for 60 days, there was no significant change in mass and compressive strength. El-Dieb [109] discovered a 12% loss in compressive strength after 12 months of immersion in high sulfate environments. Tang, Xie and Long [110] discovered that the imitative UHPC has an extremely shallow depth of invasion and an anti-erosion factor greater than 1.1 after 120 days of sulphate leaching attack. Dils, Boel and De Schutter [111] discovered that after 180 days of immersion in tap water and artificial saltwater, the compressive and flexural strengths of UHPC specimens were larger than the initial strengths. As a result, UHPC is an excellent choice for use in severe maritime conditions.

3. Cost assessment

Cost reductions were "less essential in the initial stages of UHPC development when compared to the reliable development of UHPC for field applications. According to the researchers, the smaller quantity of concrete contained, the lower quantity of reinforcement, less formwork, and improved floor space areas due to thin sections can offset the expense of UHPC. As a result, savings in construction supplies, labor, transportation expenses, and less use of lifting and moving equipment on the construction site will lower overall costs [112]. However, throughout a decade of research, a considerable amount of data on the evolution of UHPC has been acquired. Despite its better qualities, the greater production cost of UHPC limits its use in public works departments (PWDs). Increased cement and silica fume (SF) requirements are primarily responsible for UHPC's higher production costs [113]. The addition of fibers raises the cost to the point where it is virtually expensive" for local suppliers.

Furthermore, "the expense of establishing a batching factory for large-scale UHPC manufacturing cannot be overlooked. A batching plant is required for the production of a large quantity of UHPC, which differs from a standard concrete batching plant in terms of additional storage bins for steel fibers, additional supplementary material storage bins, a larger batching plant area to accommodate

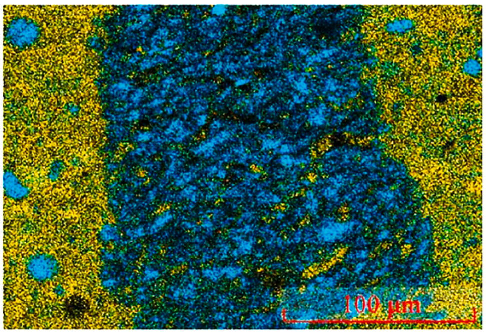

Fig. 4. Interface EDS mapping between Lightweight Sand (LWS) and matrix [105]. Take note that the blue hue represents Si, and the yellow tint represents Ca.

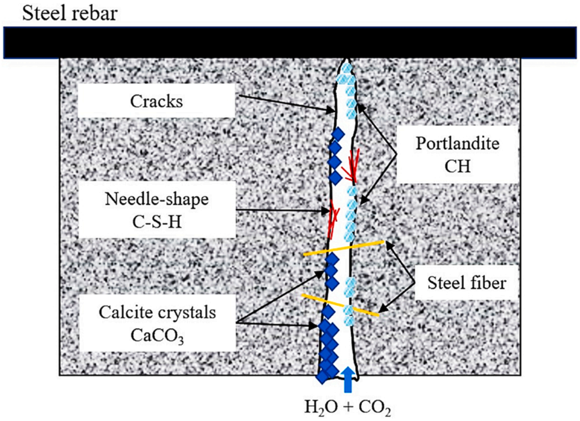

Fig. 5. Diagram illustrating the self-healing phenomenon and processes in UHPC [108].

the raw materials, and skilled workforce to operate" the machinery to mix the steel-fiber-containing UHPC. All of these issues raise the costs associated with establishing a UHPC batching plant.

Table 3 displays the various mixed designs described in some of the most current published literature. The maximum cement concentration is 900 kg/m^3, with a matching 28-day compressive strength of 194 MPa. Ding, Yu, Feng, Wang, Zhou, Shui, Gao, He and Chen [114] reported 550 kg/m^3 of cement to achieve 100 MPa, which is 48.45% lower than the strength reported by Mohammed [115].

The high material and "processing costs, as well as the energy implications of UHPC, can be attributed in part to the usage of massive amounts of cement, which functions as an expensive filler. Thus, improved binder phase packing through the use of cement substitute materials and fine fillers is a better method of boosting strength than increasing cement quantity. Many existing UHPC studies use a set of binding materials based on either reactivity or economy/sustainability without considering the physical space-filling aspect and rheology. Arora, Aguayo, Hansen, Castro, Federspiel, Mobasher and Neithalath [116] recently described a methodology for designing economical and efficient UHP binders that incorporate only conventional cement replacement materials (at an overall replacement level of up to 30%), achieving a high degree of microstructural packing and desirable rheology for flowable concrete. Similarly, the significance of aggregate packing in ensuring desirable concrete characteristics is widely documented. In addition to delivering improved performance, a well-designed aggregate component in UHPC mixtures helps to reduce costs and improve volumetric stability. Packing procedures for selected aggregate sizes have been published to create UHPC mixes [34,117], but a coordinated approach to designing aggregate blends from available coarse and fine aggregate sources to achieve maximum space-filling is" lacking.

Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] used a fundamental materials science-based "design method to demonstrate that UHPC combinations may be proportioned for a fraction of the cost of proprietary mixtures. To develop strong and economical UHPC mixtures, the authors describe an aggregate (size and amounts) selection method based on the compressible packing model [119], which is implemented alongside the binder selection method based on microstructural packing and rheology described in the Arora, Aguayo, Hansen, Castro, Federspiel, Mobasher and Neithalath [116] study. The binder component is intended to be sustainable and cost-effective, with fly ash, silica fume, metakaolin, and limestone powder replacing up to 50% of the Portland cement (mass-based) component. In contrast to typical UHPC combinations that comprise only fine aggregates, the material design presented in the study by Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] includes coarse particles (passing 9.5 mm sieve). The effect of fibers on aggregate packing is also considered. The designed UHPC mixes' mechanical (compressive and flexural strengths) and durability (moisture and ion transport resistance) performance, as well as their material cost, are also described. The methodology is built-in such a way that it can be implemented in a computer program to optimize UHPC mixtures in terms of both performance and" cost.

The earlier analysis by Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] only considers the material cost, which was acquired from published literature [76] as well as manufacturers/suppliers. The cost of UHPC mixes is equivalent to or somewhat cheaper when compared to previous "investigations on non-proprietary UHPC mixture formulations published in Graybeal [120] and Graybeal [121]. Table 4 shows the mixture proportions for the concrete mixtures studied by Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118]. Table 5 compares the cost per m^3 and strength-normalized cost (cost normalized by the 28-day compressive strength) of the selected UHPC combinations in the Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] study" to the Berry, Snidarich and Wood [33] study.

The mix designs in "Graybeal's Federal Highway Administration (FHWA) study [121] have a high concentration of silica fume, which is the primary cause of the higher costs. Simultaneously, non-proprietary, non-fiber-reinforced UHPC mixtures in [121] have been reported to cost between \$605 and \$850 per m^3, which is comparable to the cost of fiber-reinforced mixtures in the Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] study. Graybeal [121] reported that non-proprietary fiber-reinforced UHPC costs around \$1110 per m^3. Furthermore, Graybeal [122] and Graybeal [121] research utilize a maximum aggregate size of 1.2 mm, but Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] study uses 4.75 mm. As a result, while proprietary UHPC

Table 3
UHPC/UHPFRC mix design detail.

Particulars(kg/m^3)	[131]				[115]	[132]	[133]						[134]	[135]	[114]		[136]
Cement	863	863	863	863	900	833.3	430.9	450.8	426.1	478.9	625.7	341.5	771.2	588	600	550	750
Fine sand	–	–	–	–	1125	–	287.2	300.5	284.1	319.3	–	455.3	–	839.9	990	990	990
River sand	1079	1001	923	845	–	1041.6	–	–	–	–	–	–	–	–	–	–	–
micro silica	–	–	–	–	–	–	28.7	30.1	28.4	31.9	41.7	22.8	–	39.2	–	–	–
Silica fume	216	216	216	216	135	208.3	–	–	–	–	–	–	154.2	–	200	200	144
Steel fiber	0	78	156	234	160	152.9	–	–	–	–	–	–	235.5	46.8	–	–	–
Fly ash	–	–	–	–	–	–	–	–	–	–	–	–	77.1	–	–	–	–
Water	194.22	194.22	194.22	194.22	207	193.7	123.5	129.2	122.1	137.3	166.9	109.3	180.45	157	198	313.5	105–180
Superplasticizer	4.3	6.5	8.6	9.7	54	31.3	9.8	10.2	9.7	10.9	10.8	9.1	20.1	7	33	33	35
Quartz powder	–	–	–	–	–	–	–	–	–	–	–	–	154.2	–	–	–	–
Quart sand	–	–	–	–	–	–	–	–	–	–	–	–	848.4	–	–	–	–
Limestone powder	–	–	–	–	–	–	114.9	120.2	113.6	127.7	166.9	91.1	–	156.8	300	550	200
Basalt aggregate (dia. 5–8 mm)	–	–	–	–	–	–	–	–	–	–	–	–	–	232.3	–	–	–
Basalt aggregate (dia. 2–5 mm)	–	–	–	–	–	–	–	–	–	–	–	–	–	413.2	–	–	–
Basalt aggregate (8–25)	–	–	–	–	–	–	1715	1582	1514	1563	1514	1514	–	–	–	–	–
Total binder (kg)	1079	1079	1079	1079	1035	1041.6	459.6	480.9	454.5	510.8	667.4	364.3	1002.5	627.2	800	750	894
Density (kg/m^3)	2356.52	2358.72	2360.82	2361.92	2581	2461.1	2710	2623	2498	2669	2526	2543.1	2441.15	2480.2	2321	2636.5	2119
% Of binder	45.79	45.75	45.70	45.68	40.10	42.32	16.96	18.33	18.19	19.14	26.42	14.33	41.07	25.29	34.47	28.45	42.19
28 days compressive strength (MPa)	115.3	124.8	142.2	152.4	194	27.61	142.1	131	116.2	121.8	113	121.1	145	146.7	109	100	118

Table 4
Concrete mixture proportions. Except for the fiber content, all starting material contents are relative masses to the OPC [118].

Mixture components	F17.5M7.5L5	F17.5M7.5L5-f	M20L30	M20L30-f
OPC	1.0	1.0	1.0	1.0
Limestone (LS)	0.05	0.05	0.30	0.30
Silica Fume (SF)	0.075	0.075	0.20	0.20
Fly Ash (FA)	0.175	0.175	–	–
Steel Fibers (% by volume)	–	1.0	–	1.0
Superplasticizer	0.0125	0.0125	0.0127	0.0127
Aggregate/Binder	0.7	0.7	0.7	0.7
w/b (mass-based)	0.165	0.168	0.180	0.185

Table 5
Material costs for each mixture [118].

Mixture ID	Cost ($) per m^3	Cost ($) per MPa per m^3
Proprietary UHPC [33]	2616	15.85
$M_{20}L_{30}$-f	868	6.53
$^{M}20^{L}30$	618	4.72
$^{F}17.5^{M}7.5^{L}5^{-f}$	788	5.32
$^{F}17.5^{M}7.5^{L}5$	545	3.56

mixtures are reported to cost between $1500 and $3000 per m^3, UHPC mixtures designed as part of the Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118] study can be proportioned at a fraction of the cost, making it a viable alternative for transportation and infrastructure agencies interested in high-strength and high-performance mixtures. The fiber-reinforced combinations appear" less appealing in terms of compressive strength-normalized cost, but realistically, they should be compared based on ductility or post-cracking tensile strength-normalized cost to ensure fair comparisons.

Fig. 6(a) depicts the cost of raw materials used to proportion the selected UHPC mixtures, with and without fibers, whereas Fig. 6(b) depicts the relative cost of each mixture element as a fraction of the total cost of the mixture. In conjunction with the material design strategy described in the study by Arora, Almujaddidi, Kianmofrad, Mobasher and Neithalath [118], an understanding of "material costs, local availability, and energy-and-emission implications can be used to conduct life cycle cost and impact analyses that assist

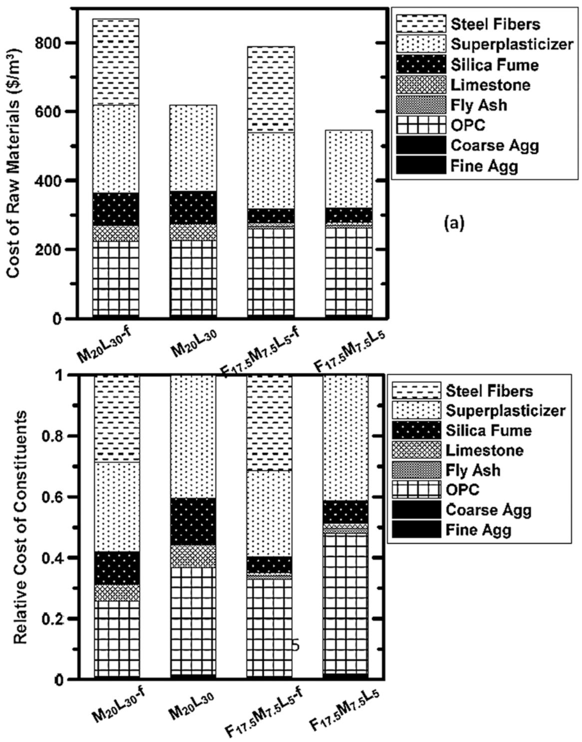

Fig. 6. (a) Cost of raw materials per m^3 of selected UHPC mixtures, and (b) relative cost of the individual components in the UHPC mixtures [118].

decision-makers in selecting the appropriate material combinations for respective UHPC applications. It should be noted that this approach does not consider the capital investment required for equipment upgrades to crush, sort, and proportion huge volumes of aggregates. These numbers clearly show that, in terms of cost, superplasticizers and fibers account for the majority of the cost of UHPC, followed by OPC. It should be noted that in mixes where the paste percentage has not been tuned, the OPC cost can be even higher. A larger OPC concentration causes various environmental effects related to such combinations, emphasizing the significance of a mixture" selection technique.

Despite this, the enormous amount of data allows the researchers to find aspects of UHPC cost reduction. Until present, four techniques for decreasing UHPFRC prices have been reported: (1) use less high-strength "steel fiber without reducing hardened characteristics [123,124], (2) combine coarse aggregate to minimize powder [125,126], and (3) eliminate heat treatments or high-pressure compaction operations [127,128]. Another technique (4) is to encourage the use of low-cost locally available materials [128–130]. To achieve compatibility between the 28-day compressive strength and the lowest cement content, more consistent efforts must be made in the future to minimize the cost of UHPC" for infrastructure construction.

4. Applications

With an expanding "number of applications in recent years, UHPC's exceptional performance opens up new options for infrastructure work, building construction, and numerous niche markets. According to Grand View Research (GVR) market research, the global UHPC market was valued at USD$ 892 million in 2016 and is predicted to expand by 8.6% to USD$ 1867.3 million in 2025. With commercialization available in several countries, including Australia and New Zealand [137], Austria [138], Canada [139], US [140],

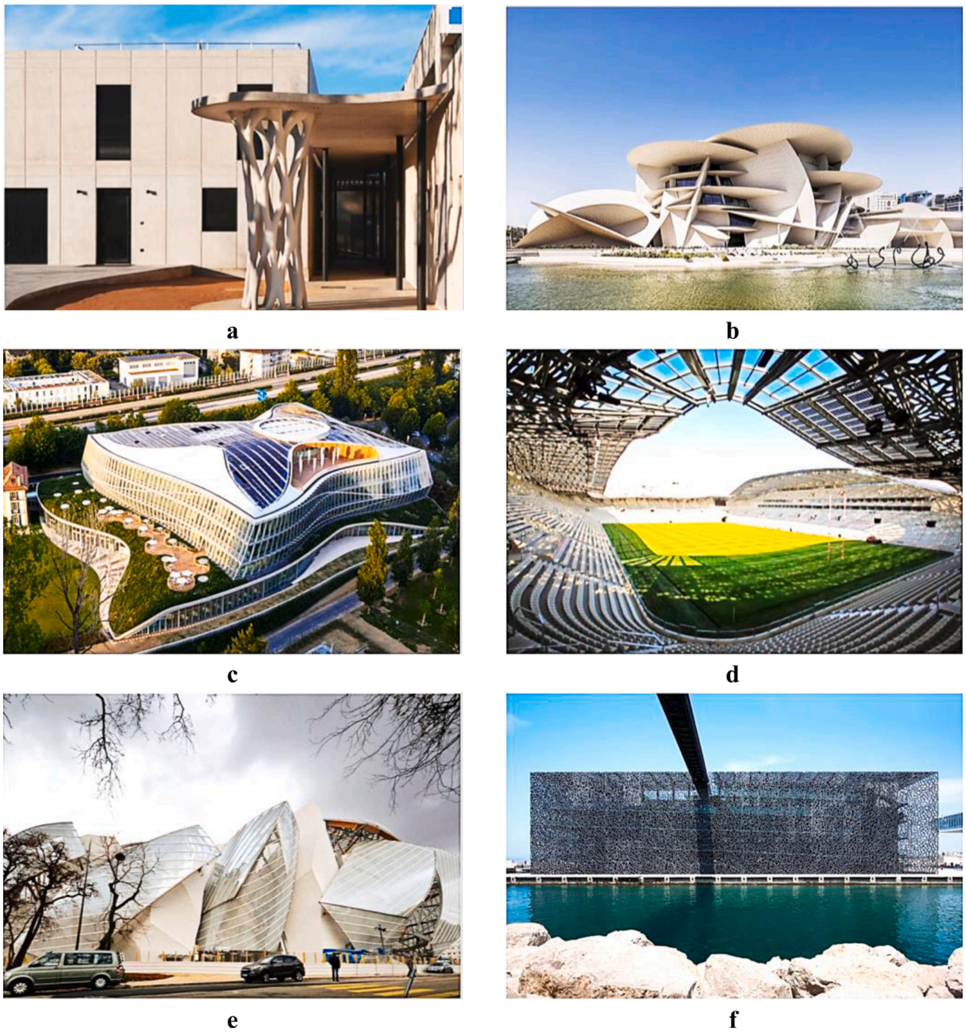

Fig. 7. Representative applications of UHPC in buildings: (a) a 4-m-high pillar fabricated via 3D printing [161]; (b) Qatar National Museum [160]; (c) Olympic Museum in Lausanne [159]; (d) Jean Bouin Stadium [158]; (e) Foundation Louis Vuitton pour la Creation [157]; and (f) Museum of European and Mediterranean Civilizations [156].

Germany [141], France [142], Italy [143], Japan [144], Malaysia [145], Netherlands [146], and Slovenia [147], UHPC has gained worldwide interest. Over the last two decades, scholars and engineers around the world have conducted extensive research initiatives in an attempt to industrialize UHPC technology as the future sustainable construction material [148]. A thorough search of the literature yielded over 200 finished bridges that used UHPC in one or more of their components [8]. Other UHPC uses include building, structural strengthening, retrofitting, precast elements, and other unique applications [23,142]. Both business and public sectors are focusing their efforts and resources on exploiting UHPC as the future sustainable" construction material [149–155].

4.1. Buildings

As demonstrated in Fig. 7, "the exceptional mechanical properties of UHPC enable the design and manufacture of slim, light, and aesthetically pleasing architectural components. For example, the Museum of European and Mediterranean Civilizations in Marseille, France, was the first structure in the world to use UHPC substantially. UHPC was used to create the tree-like façade, perimeter footbridge brackets and decks, façade and roof lattices, and protective covers for the prestressing anchorage points [156]. The Foundation Louis Vuitton pour la création, which boasts significant geometric intricacy, was built-in Paris, France, in 2014. The claddings were made out of 19,000 custom-made UHPC panels [157]. UHPC was also used to build the roof of the Jean Bouin Stadium in Paris [158], the Olympic Museum in Lausanne [159], and the Qatar National Museum [160]. In addition, a 4-m-high freeform pillar was built with UHPC in Provence," France [161].

4.2. Bridges

Precast bridge elements are "particularly effective for facilitating the expedited construction timetables that are frequently required for highway projects. The reliance on the performance of field-cast connectors is one issue that comes from the usage of prefabricated bridge components. These types of connections frequently cause problems with constructability, durability, and structural performance. Because of its greater durability and strength, which has been found to improve bond strength, the inclusion" of UHPC in these field-cast connections may improve their performance.

Yuan and Graybeal [162] investigated the "bond of reinforcing steel within UHPC concrete and discovered that UHPC had improved bond performance when compared to conventional high-strength concretes. However, neither compressive strength (*f'c*) nor $f'c^{1/was}$ found to be useful in forecasting bond strength in UHPC. The University of Michigan [163] also conducted a comprehensive investigation on bond length on the UHPC mix generated during their research. This UHPC blend required much less bond length than conventional concrete; nonetheless, the authors recommend further research because their specific results differ from those published by Yuan and Graybeal [118] stated" above.

El-Tawil, Alkaysi, Naaman, Hansen and Liu [163] conducted field-cast joint testing between two precast bridge deck sections utilizing "UHPC and determined that a 6-inch joint length could be sufficient for load transfer between the two elements. Graybeal [114] investigated field-cast connections and discovered that using UHPC in such connections can alleviate some of their potential problems. According to Graybeal [164] research, full development of reinforcing steel can be accomplished in a substantially shorter duration when compared to typical concrete and grout combinations. This enables designers to define shorter lap splices and connection details, reducing construction complexity and costs. UHPC's tensile strength and ability to attach extraordinarily well to previously cast concrete have also aided in the creation of simpler connecting details. Because of the improved characteristics of UHPC, precast bridge deck closing pours of 6 in. or less in length can be successfully constructed as thin shear keys. Full-scale structural testing has proven that field-cast UHPC deck connections can outperform monolithically cast bridge decks. This study further demonstrated that, even under extreme loading conditions, reinforcement in both transverse and longitudinal" UHPC-filled connections does not debone from UHPC.

4.2.1. Example of bridging applications

Around 1985, the first "research and development aimed toward the implementation of UHPC in construction began [1]. Since then, several technical solutions and UHPC formulations have been developed to fulfill the specific needs of distinct designs, structures, and architectural approaches. Breakthroughs in UHPC application include the first pre-stressed hybrid pedestrian bridge over the Magog River in Sherbrooke, Canada, built-in 1997 [165], the replacement of corroded steel beams in the aggressive environment of France's Cattenom and Civaux nuclear cooling towers [166], and the Bourg-les-Valence bridge built for cars and trucks in 2001 [167]. Because of UHPC's superior mechanical characteristics and endurance, standard design methods for many typical bridge components can be reconsidered. Many studies on the optimal designs incorporating UHPC elements had been undertaken, culminating in the creation, and building of UHPC bridges all over the world. The Seonyu footbridge in South Korea, with a primary span of 120 m, was built using UHPC in 2002 and completed in 2004 [168]. The Seonyu footbridge structure, the world's longest span bridge constructed utilizing UHPC, needed almost half the material amount that would have been used in standard concrete construction while providing equal strength attributes [169]. In Japan, the Sakata-Mirai footbridge with a span of 50 m was constructed in 2003. The bridge illustrated how a perforated web in a UHPC superstructure can reduce weight while still being aesthetically beautiful [170]. Following the success of these projects, UHPC pedestrian bridges have been built-in Europe, North America (the US and Canada), Asia, and Australia" [171].

According to a 2013 FHWA "report, 55 bridges using UHPC have been built or are being built-in the United States and Canada. There are approximately 22 UHPC bridges in Europe and 27 UHPC bridges in Asia and Australia [172]. UHPC can be employed in various applications such as beams, girders, deck panels, protective layers, field-cast joints between different components, and so on

[173–175]. In comparison to standard reinforced concrete bridges, most bridges designed using UHPC components or joints have a slim appearance, a significant reduction in volume and self-weight, simplified implementation, and improved durability [176]. Most UHPC structures require only half the section depth of typical reinforced or pre-stressed concrete components, resulting in weight savings of up to 70% [177]. UHPC structures' lighter weight construction and material efficiency result" in a more sustainable structure with fewer carbon footprints [178].

4.3. Infrastructures

The Monaco subterranean "train station's acoustic panels were made from UHPC. Small holes were cast into the thin and light UHPC panels to help with their acoustic characteristics. The non-flammable panels are impact-resistant and provide passengers with a visually pleasant and bright atmosphere. Due to their resilience to car pollution and deicing salts, acoustic panels have also been utilized along a roadway in Châtellerault, France. Other UHPC application possibilities include security infrastructure employed as barrier protection systems or as fundamental components of essential infrastructure. Extensive research on the mechanical properties of UHPC subjected to high strain loading rate [179,180], blast resistance [181,182] and penetration resistance" [183].

4.4. Non-structural products

UHPC has been widely utilized as "an overlay to repair existing concrete structures due to its superior characteristics, boosting mechanical and durability properties for less maintenance work [184,185]. The first UHPC overlay application was reported on a bridge over the La Morge River in Switzerland [186]. UHPC was used to replace the severely damaged bridge deck and curbing. After one year of use, no cracks were found on the prefabricated UHPC curb. Because these materials were successful in repair and rehabilitation applications, they paved the path for similar technology to be employed on deteriorating bridges. UHPC was used to repair and rehab hydraulic structures at the Hosokawa River Tunnel in Japan [187], as well as the Caderousse and Beaucaire Dams in" France [188].

Because of its remarkable "properties of high flexural strength and dense microstructure, UHPC has the potential to be used in specific settings. According to reports, UHPC was utilized for cover plates along China's high-speed railroads [189] and for the retrofit of nuclear reactor containment walls in France [190]. UHPC has also been used in marine environments due to its high resistance to hostile chemicals. Several sea windmills have been successfully created, as previously reported by researchers [191,192], and the rejuvenation of marine signalization buildings using UHPC has also been shown to be highly effective [193]. In Japan, the Haneda Airport was expanded by building a massive UHPC slab over the sea [170]. To date, this is the largest UHPC project completed. UHPC's superior performance is responsible for its vast potential in a variety of applications; however, many have yet to be discovered to take use of its improved strength, durability, and flexural capacity. In places where CC struggles, UHPC offers cost-effective and innovative alternatives. UHPC is the future construction material; it is here to stay and will continue" to grow globally.

4.5. Other applications

In addition to buildings and "bridges, UHPC has the potential to be applied to tunnels, wind turbine towers, and nuclear power facilities. UHPC can develop more efficient tunnel systems with bigger usable spaces for tunnel applications by reducing tunnel element thickness [194]. UHPC components for wind turbine towers enable the construction of taller and more slender wind turbine towers, enhancing energy generation efficiency [195]. UHPC has greater radiation shielding properties and stronger blast endurance for nuclear power plants, which can improve the security of critical" infrastructure [196].

4.6. Proposed applications

4.6.1. Using UHPFRC for retrofitting purposes

Another use for the "proposed UHPFRC is for retrofitting existing RC constructions. Normally, time is vital for repairing and retrofitting existing structures since the elements must be overheated in order to bear the imposed loading. For that purpose, a prefabricated element can be more effective in terms of minimizing retrofitting time, improving element quality during fabrication in the laboratory and before sending for installation, and lowering labor expenses. As a result, in this study, a thin prefabricated element based on UHPFRC that is dimensioned according to the specifications can be proposed. CFRP material can be employed to increase the ductility of this system. CFRP can be employed as an attached sheet on the outer faces of prefabricated elements using Externally Bonded Fiber (EBR) techniques or as a Near Surface Mounted (NSM) technology employing a laminate inside the pre-sawn grooves on its face. The orientation of the CFRP sheets and/or laminates can be adjusted to meet the needs. This prefabricated element can be attached to the surface of RC elements using" adhesive bonding, anchorage bonding, or a combination of the two.

4.6.2. Using UHPFRC as shear reinforcement in RC beams

One of the weaknesses of "ordinary concrete is its low resistance to shear forces before reaching the ultimate flexural capacity of the elements. This failure is generally unexpected and unnoticed. Based on this, adding shear reinforcement as a shear stirrup is critical for hiding the weakness of concrete, increasing shear resistance, and so boosting the flexural behavior of the elements. However, after updating requirements, the amount of % shear stirrups increased to be used in a key zone where shear forces are higher than in other places. Using the number of shear stirrups increases the cost of final manufacturing in terms of labor and material costs. Even with some elements, such as thin-walled beams and hollow sections, executing the standards requirement is problematic. These shear stirrups are particularly accentuated in the area where the seismic danger is considerable, with a very condensed in some portions of the element. This shear stirrup condensate has occasionally caused complications with concrete vibration and achieving nonhomogeneous" concrete.

Based on these findings, "it will be effective to investigate the feasibility of utilizing UHPFRC as shear reinforcement in RC beams. The proposed material appears to be suitable for use as shear reinforcement in RC beam elements for minimizing the number of stirrups by boosting RC member" shear resistance and reducing the size of longitudinal rebars by increasing flexural capacity.

5. Challenges and future perspectives

5.1. UHPFRC mixes

When generating "sustainable UHPC with the same substitution, different or even opposing effects can be found due to differences in the physicochemical characteristics of source materials, particularly agricultural and industrial waste. As a result, the combination proportion described in some publications rarely provides direct and accurate guidance in-field application. As a result, most designers still find it difficult to build sustainable UHPC with optimal performance. To break down the barriers, it is more vital to tap into the design of sustainable UHPC (the foundation for yielding sustainable UHPC that matches specifiable features for a specific application) than to replicate" the old mixing proportions. However, research on the design of sustainable UHPC is limited.

Adoption of models "that meet design requirements remains difficult. To model the relationships between material composition and performance of sustainable UHPC, both response surface methodology (RSM) and artificial neural networks (ANN) can be applied. There are, however, numerous important distinctions between the two types of models. Furthermore, large function solution techniques exist for both RSM and ANN. Before selecting the ideal algorithm, designers must have a comprehensive understanding of the characteristics of each technique, as well as the relationship and difference" between methods.

Furthermore, "similar to the statistical method, the approach to resolving the packing theory-based model remains a barrier for designers lacking mathematical theory, despite the fact that numerous software has been developed to alleviate" the issue.

The major goal that "should be followed is to propose a mix design. Several parameters must be considered in this mix design, including (i) increasing the synergistic interaction between the number of constituent materials; (ii) satisfying some requirements related to safety, serviceability, durability, cost, and environmental impacts; (iii) acquiring adequate confidence in the admixture gradients properties and synergies to achieve an optimal mixture; and (iv) obtaining percentage of cement replacement by SCM and volume friction of steel fiber. Admixture components might be carefully chosen to achieve this goal based on the availability of local materials. As a result, the powder components used to produce the UHPFRC mortars can include conventional Portland cement, silica fume, fly ash, and quartz flour. A superplasticizer based on Polycarboxylate and steel fiber can also be" used.

Mixture design is an "important phase in the manufacture of concrete. Future studies should explore the following aspects to promote the fabrication and utilization of UHPC: I SCMs like slag, fly ash, and silica fume play an essential role in the design of UHPC mixtures. However, due to the shift from coal to natural gas power plants, conventional SCMs are becoming scarce. As a result, research on alternative SCMs is in high demand; (ii) Considering the conflicting requirements of those UHPC performances, integration of two or more mixture design methods to exploit the advantages of each method by meeting multiple UHPC requirements, resulting in better UHPC mixture" proportion.

Some statistical methods, "such as central composite design, appear to be advantageous for getting effectively suitable mixing when creating mortar mixes. In conjunction with experimental data, mathematical empirical models can be developed to determine the impacts of mixture design parameters on fresh mortar qualities (workability, resistance, viscosity) and hardened mortar properties" (maximum flexural and compressive strength and toughness characters).

5.2. Rheology

To improve the strength, "rheology, and sustainability of UHPC with appropriate rheology, the binder concentration must be reduced even further. Particle packing over the entire particle size distribution with optimal use of adhesive and space-filling capabilities of hydrates is generally studied for UHPC optimization. However, developing a UHPC formulation with a certain range of characteristics, such as rheology, structural build-up, hardening kinetics, microstructure, mechanical properties, durability, and sustainability, might be difficult. To overcome this issue, computational modeling techniques can be employed to aid in the mixture design of UHPC for managing its rheological properties. This includes computational fluid dynamics (CFD), which analyzes concrete as a fluid and has limitations for modeling composite materials with fibers [197,198]. The discrete element method (DEM) can record the motion of individual particles to model flow characteristics such as blockage, segregation, and near boundary walls [199]. The flow of UHPC may be effectively modeled when DEM and CFD are combined [197]. Computational intelligence can also produce accurate predictions based on experimental or publicly available data, which is regarded as" the most promising way of addressing complicated problems [200,201].

5.3. Mechanical properties

Based on the review, the following are the challenges and prospects for mechanical properties:

1. UHPFRC “has steel fibers that are randomly arranged. To fully comprehend the mechanical properties of UHPFRC composites with numerous randomly oriented fibers at high loading rates, an examination of the dynamic pullout behavior of multiple inclined steel fibers embedded in UHPC should be” carried out.
2. The present “results on the effect of fiber type (twisted and straight) on the impact resistance of UHPFRC are in dispute. This disparity is due to differences in fiber characteristics and the use of different impact test machines,” hence the impacts of steel fiber type on the impact resistance of UHPFRC must be further researched.
3. Flexural, tensile, and thermal characteristics of UHPC specimens exposed to heating should also be studied. This is critical for core UHPC and fire safety design inputs.
4. The initial “cracking strength has a higher rate sensitivity than the post-cracking strength, which is related to fiber pullout behavior. As a result, a quantitative comparison of dynamic increase factor (DIF) and strain-rate curves for initial and post-cracking strengths is required in the” future.
5. To provide a scientific “theoretical basis for performance improvement, load–slip modeling in UHPC should consider the effects of fiber fracture, matrix damage at the anchorage end and along with the fiber, matrix compressive strength, and age, slip-hardening, incomplete straightening, and concrete” macro-properties.
6. Steel fibers in reinforced UHPC beams reduce ultimate deflection capacity before and after impact damage caused by steel bar rupture. As a result, a new method for preventing premature steel bar rupture in UHPFRC buildings must be developed.
7. The UHPC research “trend is now tied to nanotechnology. Experiments have been carried out to change its characteristics by employing nanoparticles such as nano-silica and nanofibers. Furthermore, several researchers have attempted to examine the structure of hydration products in UHPC at the nanoscale [202]. Nanotechnology may offer a solution to UHPC’s shortcomings, such as the shrinking issue, and hence may improve UHPC’s overall” performance.

5.4. Durability

UHPC’s strong “mechanical characteristics and durability make it an excellent alternative for infrastructure systems, particularly those exposed to adverse environmental conditions. However, because UHPC is being implemented directly into structural applications without suitable design codes, wasteful material utilization and functional exertion must be” considered.

To improve the durability of “UHPC structures even further, steel reinforcing should be reduced to allow for digital 3D printing fabrication and increased construction productivity [203]. In this situation, the autonomous building of complex shapes is viewed as a new opportunity rather than a problem. A large volume of fibers can be used to generate materials for non-reinforced structures. The correct rheological properties of UHPC will be critical in distributing fibers and improving the mechanical properties and durability of concrete structures. However, using fibers with a volume of more than 3.5% in UHPC will be an issue that must be addressed” in the future.

The corrosion of “fiber-reinforced concrete is caused by free and bonded chlorides. A thorough analysis of the chloride transport characteristics and chloride binding isotherms of UHPC subjected to external” chloride environments may provide useful information for service life prediction.

Binders are commonly “found in high concentrations in UHPC and can be utilized to trap recycled or ambient CO_2 while increasing the mechanical characteristics and durability of the UHPC. The UHPC is interested in developing CO_2 sequestration” technologies.

Material characterization of “UHPC specimens subjected to freeze-thaw cycling and loading conditions may offer light on the fracture recovery effect. Additional microstructural study of UHPC specimens treated with different curing regimes will also aid in the description of this phenomenon.

5.5. 3D-printing

The cementitious material must be suitable for 3D printing in terms of pumpability, extrudability, and buildability. They must, in particular, have a low viscosity and a high yield stress, and they must set quickly for continuous flows during the extrusion process, preventing material sagging after disposition and withstanding the weight of the subsequent layer deposited above [204,205]. Several academics recently released work demonstrating the viability of using UHPC/UHPFRC in 3D printing [206]. The creation of UHPFRC for 3D printing was reported by Arunothayan, Nematollahi, Ranade, Bong and Sanjayan [207]. The author claimed that using UHPFRC composites results in improved shape retention ability (SRA) compared to using normally cast UHPFRC. The UHPFRC composite matrix sample failed at 1.2 kg vertical load, whereas conventionally cast UHPFRC can withstand 0.7 kg vertical stress. The composite sample has a larger apparent porosity than traditionally manufactured UHPFRC. Because of the presence of fibers, the matrix can entrap air, resulting in a higher porosity of the composite. The direction of the fiber during extrusion is normally the printing direction, resulting in a 2D orientation. However, the fiber distribution in traditionally cast UHPFRC was 3D.

Despite the existing data on UHPC 3D printing, production is still based on specialized printing with certain printing configurations (e.g., nozzle type, flow rate, pumping specifications) and may not be suitable for diverse cementitious mixes and printing configurations [207]. As the creation of UHPC continues to be difficult for practitioners around the world, major efforts are needed to produce accessible knowledge on the usage of UHPFRC for the manufacturing of large-scale structural parts utilizing 3D printing technology.

5.6. Cost

In numerous countries during the last two decades, UHPC has been used for both structural and non-structural precast components.

However, due to its high initial prices and a lack of design codes, this remarkable technology has struggled to become a popular technology for everyday usage. Furthermore, the prohibitive cost of UHPC materials and high energy consumption make it difficult to compete with CC designs, limiting its use. Research on lowering the cost and enhancing the sustainability of UHPC is required to allow for its future widespread implementation. Several studies were conducted to adjust material mixes using local raw materials and waste products in order to reduce the amount of Portland cement, steel fiber, and SP [208]. With lower costs and environmental effects, UHPC will be much easier to adopt by the infrastructure market and will pique the interest of infrastructure owners. To achieve compatibility between the 28-day compressive strength and the lowest cement and fiber content, more consistent efforts must be made in the future to minimize the cost of UHPC for infrastructure construction.

6. Conclusions

Based on the review and discussions above, it can be summarized as follows:

1. Because of its low W/B and compact structure, UHPC displayed better permeability resistance to water and chloride ion penetration, carbonation, and other chemical assaults.
2. After 1–3 years of exposure, carbonation rarely occurs on UHPC, whether under conventional or heat curing. Newly produced carbonation products, on the other hand, can partially or fully fill microcracks in UHPC to restore mechanical strength.
3. Depending on critical criteria such as mixture proportion, curing regime, medium solution concentration, steel fiber volume, and testing age, the chloride ion diffusion coefficient of UHPC was determined to be at least one order of magnitude lower than that of CC or HPC.
4. Because of its low permeability, accelerated tests revealed that corrosion of steel reinforcement and alkali-silica reaction is not a concern for UHPC under any curing regime. After one year of exposure, no corrosion of steel reinforcement was discovered. Nanoparticles can significantly lower the corrosion rate of steel bars immersed in UHPC. The alkali-silica reaction (ASR) expansion value of UHPC with a high concentration of recycled glass sand was low.
5. The bond performance of UHPC was analyzed in terms of durability. Bonds are weakened by temperatures above 400 °C, but cryogenic temperatures (−170 °C) and fiber corrosion can improve bond characteristics. Future research should investigate the coupling effects of high and low temperature and mechanical load on steel fiber bonding in UHPCs because actual failure under harsh conditions typically has numerous coupling components.
6. Over hundreds of freeze-thaw cycles, up to 1000 cycles, UHPC gained mass, compressive strength, and relative dynamic modulus. This is due to absorbed water and/or continuing hydration in the presence of a high concentration of unhydrated cement particles.
7. During heating, UHPC went through three separate stages: 1) the first stabilizing and recovering stage from 150 to 350 C; 2) the strength loss stage from 350 400–800 C; 3) the overall strength loss stage beginning after 800 C. The addition of polypropylene fibers, thermally stable aggregates, and an increase in steel fiber content can reduce the explosive spalling of UHPC. Because of the enhanced permeability and greater connection of pores and channels associated with the melting of polypropylene fibers, fiber hybridization of steel and polypropylene fibers in UHPC is the most popular and successful method of preventing spalling. However, aggregates containing stored moisture should be utilized with caution to avoid severe violent spalling caused by the addition of additional water.
8. The utilization of traditional binder and filler materials, as well as elevated levels of OPC replacement by microstructural packing and rheological optimization, allows for material cost reduction. Furthermore, UHPC mixtures with optimized binder and aggregate combinations are expected to perform well in a life cycle cost and impact analysis, owing to the significant reduction in OPC content as well as the use of common cement replacement materials for production rather than those with higher economic and environmental impacts.
9. Throughout the world, achievements in the application of UHPC can be seen. UHPC, on the other hand, is moving slowly, with constraints restricting its uses. High starting costs, limited codes, design challenges, and complex production techniques, combined with limited available resources, impeded its commercial development and application in modern buildings, particularly in developing countries.
10. The majority of existing UHPC applications are accomplished by factory pre-fabrication and onsite assembly. Given the prohibitive cost and complexity of the curing process, standard materials, and common technology, such as conventional casting and room temperature curing, are the UHPC trends.
11. Recent advances in 3D printing technology may hasten the use of UHPC in infrastructure development. However, one problem with using UHPC for 3D printing is that material production is based on specialized printing with specific printing configurations, which means that UHPC may not be suitable for varied cementitious mixtures and printing configurations. During the extrusion operation, the nozzle's border aligns the fibers in one direction. As a result, during 3D printing, the mechanical properties of a cementitious mix decrease in the transverse direction, and gaps form between two layers. As a result, the manufacturing of UHPC employing 3D technology remains a challenge for practitioners worldwide.
12. The challenges to UHPC commercialization are the greater initial cost, the need for particularly skilled labor, and the lack of open talks on multiple UHPC standards accessible worldwide to agree on minimum strength achievements and test requirements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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