Case Studies in Construction Materials 17 (2022) e01290

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Ultra-high-performance fiber-reinforced concrete. Part I: Developments, principles, raw materials

Mahmoud H. Akeed [a,*], Shaker Qaidi [b], Hemn U. ↱Ahmed [c], Rabar H. Faraj [d], Ahmed S. Mohammed [c], Wael Emad [e], Bassam A. Tayeh [f], Afonso R.G. Azevedo [g]

[a] School of Civil and Environmental Engineering, University of Technology Sydney (UTS), Sydney, Australia
[b] Department of Civil Engineering, College of Engineering, University of Duhok, Duhok, Kurdistan Region, Iraq
[c] Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimaniyah, ↱Kurdistan Region, Iraq
[d] Civil Engineering Department, University of Halabja, Halabja, Kurdistan Region, Iraq
[e] Department of Civil Engineering, Komar University of Science and Technology, Kurdistan-Region, Iraq
[f] Civil Engineering Department, faculty of Engineering, Islamic University of Gaza, Gaza Strip, ↱↱↱↱Palestine
[g] Advanced Materials Laboratory, State University of the Northern Rio de Janeiro – UENF, Av. Alberto Lamego 2000, Campos dos Goytacazes, RJ 28013–602, Brazil

ARTICLE INFO

Keywords:
Ultra-high-performance fiber-reinforced concrete
Developments, Principles
Raw materials

ABSTRACTS

Recently, Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) has offered notable advantages over other types of concrete. Therefore, a comprehensive investigation of the latest developments in Ultra-High-Performance Concrete (UHPC) is necessary to provide essential information for materials testing requirements and procedures and to expand its practical applications. The present work is a comprehensive four-part review of the UHPFRC. The current first part of the review focuses attention on the developments, principles, and raw materials of the UHPFRC. Part II covers the hydration and microstructure of the UHPFRC. Part III reviewed the fresh and hardened properties of the UHPFRC. Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. This review is expected to advance the fundamental knowledge of UHPC and promote further research and applications of UHPC.

1. Introduction

Concrete technology has "advanced in a new way to overcome conventional concrete limitations such as High-Performance Concrete (HPC) [1–4]. HPC is distinguished not only by its greater strength, but also by its better durability, resistance to various external agents, and rapid hardening rate. Brittleness, low tensile strength, and poor resistance to crack opening and propagation are the key disadvantages [1,2,5–8]. The concept of fiber-reinforced concrete (FRC) was invented to reinforce the brittle cement-based paste with various fibers such as steel fiber, glass fiber, synthetic fiber, polyethylene fiber, carbon fibers" [9–12].

Concrete casting can be "challenging in some reinforced concrete (RC) elements due to a lack of reinforcement rebars and/or stirrups. These challenges may have an impact on the vibration quality, lowering the quality of the concrete. Self-Compacting Concrete (SCC) was developed to address these issues by providing benefits like reduced noise on building sites, faster casting, particularly in rapidly changing surroundings, and certain high mechanical characteristics [13]. According to Fig. 1 [14], it is conceivable to develop

* Corresponding author.
E-mail address: mahmoud.akeed@uts.edu.au (M.H. Akeed).

https://doi.org/10.1016/j.cscm.2022.e01290
Received 11 May 2022; Received in revised form 22 June 2022; Accepted 28 June 2022
Available online 30 June 2022
2214-5095/

a new type of concrete known as UHPC based on the previous concrete's common mechanical and" rheological characteristics [14–19].

French engineers invented UHPC, "which has high compressive strength, high tensile strength, and ductility under tensile loading. “Because of the high ductility characteristics and the use of fine aggregate in the skeleton of this concrete, it can be employed in thin members in bending without the use of conventional reinforcement. Fig. 2 depicts the volume proportion of cementitious paste in several types of concrete. It can be seen that the amount of powder in UHPC is greater than in SCC and HPC," implying a greater number of fine gradients in the concrete skeleton [20–23].

2. Development of UHPC

Concrete is the most “widely used synthetic substance on the planet, and it will remain in high demand for the near future. It is estimated that global concrete output is over 6 billion cubic meters per year, with China now utilizing approximately 40% of global concrete production [25–31]. Concrete's superior properties, such as its strength and durability, capacity to be laid in a variety of forms, and low cost have made it the most well-known and vital material in the building industry. Concrete is generally employed because of its high compressive strength [32–41]. Over the previous few decades, considerable progress has been made in the field of concrete development. Intensive scientific attempts to improve concrete compressive strength began in the 1930 s Fig. 3 depicts significant concrete technological accomplishments during the previous 40" years [42].

The graph shows that concrete technology advanced slowly during the 1960 s, “with maximum compressive strengths ranging from 15 MPa to 20 MPa. Over around ten years, the compressive strength of concrete increased from 45 MPa to 60 MPa. Concrete strength peaks at around 60 MPa in the early 1970 s, owing to the technological barrier of the existing water reducer. At the time, the existing water reducer was unable to further reduce the water to binder ratio (W/ B) [43–48]. During the 1980 s, it was discovered that high-range water reducers known as superplasticizers (SP) could be employed to gradually reduce W/B down to 0.30. Reducing the W/B below this was thought illegal until Bache [49] showed that it was feasible to reduce the W/B below 0.16 with high doses of SP and silica fume (SF). By controlling the grain size distribution of the granular skeleton, concrete compressive strength of up to 280 MPa was attained using compacted granular materials. As a result, a material with a minimum number of imperfections, such as micro cracks and interconnecting pore spaces," was created to achieve ultimate strength and durability increase.

These technological advances, together “with basic knowledge of low-porous materials, have resulted in the development of ultra-high-performance Portland cement-based materials with extraordinary mechanical characteristics. In general, the evolution of UHPC can be divided into four stages: before the 1980 s, 1980 s, 1990 s," and after 2000.

Before the 1980 s, due to a lack of modern technology, UHPC “production was limited to the lab and required unique processes like vacuum mixing and heat curing. During the period, researchers experimented with several technologies to generate denser and more compact concrete to increase its strength. It has been reported that vacuum mixing combined with temperature curing can increase the compressive strength of concrete to 510 MPa [50–57]. Although the high compressive strength of concrete was reached," the preparation was time-consuming and energy intensive.

Micro defect-free cement (MDF) was invented in the early 1980 s [58]. “Polymers are used in the MDF technique to fill the pores and erase all imperfections in the cement paste. This procedure necessitates specific manufacturing conditions, such as the material being laminated by passing it through rollers. The compressive strength of MDF concrete can reach 200 MPa. However, its uses have been limited due to the prohibitive cost of raw materials, the difficult preparation method, substantial creep, and brittleness [58]. Bache [49] developed dense silica particle cement (DSP) after the introduction of MDF. Unlike MDF, DSP does not require harsh

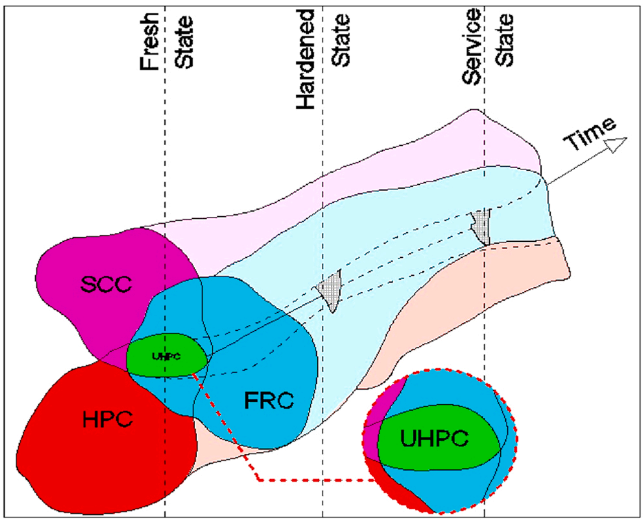

Fig. 1. Concrete classification: SCC (Self-Compacting Concrete), HPC (High-Performance Concrete), FRC (fiber-reinforced concrete), UHPC (Ultra-High-Performance Concrete) [14].

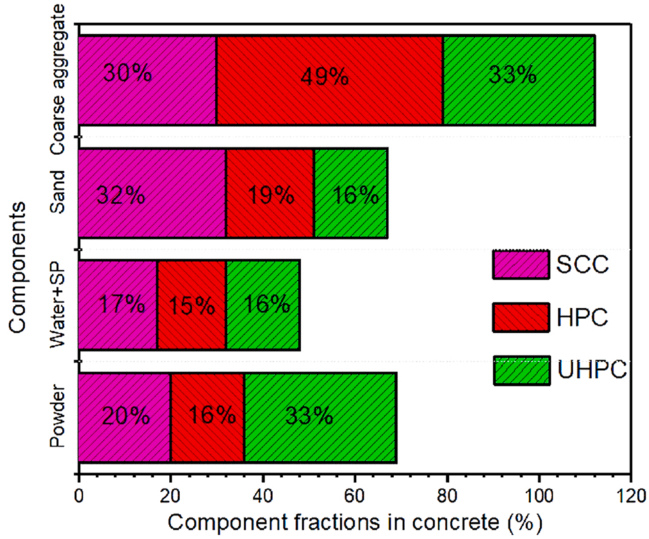

Fig. 2. Component volume fraction in several types of concrete. HPC (High-Performance Concrete), SCC (Self-Compacting Concrete) and UHPC (Ultra-High-Performance Concrete). Note the given percentages are estimated and depend on many other factors.
Adapted from Fehling, Schmidt and Stürwald [24].

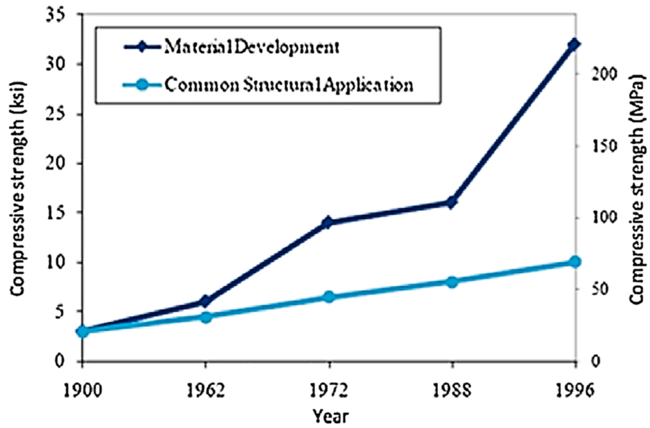

Fig. 3. The development of concrete compressive strength for over 100 years [42].

production conditions to be prepared. Improving particle packing density removed DSP flaws. DSP concrete comprises a high concentration of SP and SF and is cured using heat and pressure. DSP's maximum compressive strength can reach 345 MPa. Despite the increase in ultra-high strength, these materials become more brittle. Steel fibers were added in the 1980 s to help improve the brittleness of DSP concretes. This sort of steel fiber augmented concrete is a very novel material. It has a highly thick microstructure,

Table 1
UHPC mechanical characteristics and typical composition [50].

Ingredient in the manufacture (kg/m^3)	RPC 200	RPC 800
Portland cement	955	1000
Fine sand (150–600 mm)	1051	500
Silica fume	239	230
Ground quartz (d_{50} = 10 mm)	–	390
Steel fibers	168	630
Total water	162	190
Superplasticizer (Polyacrylate)	15	19
Heat treatment	20 C/90 C	250–400 C
Pre-setting pressurization	–	–
Compressive strength (MPa)	170 – 230	490 – 680
Flexural strength (MPa)	25 – 60	45 – 102

extremely high strength, superior durability, and great ductility. Compact reinforced composites (CRC) and slurry infiltrated fiber concrete (SIFCON) are two notable examples of what happened shortly after DSP. CRC and SIFCON both have exceptional mechanical qualities and durability. However, because of a lack of effective SP, both CRC and SIFCON have workability concerns that impede in-situ" applications [59].

Richard and Cheyrezy [50] employed "components with enhanced fineness and reactivity to develop RPC by thermal treatment in the 1990 s. RPC is a significant step forward in the evolution of UHPC. Its concept was based on the arrangement of several particles in a very dense manner. RPC is the most popular type of UHPC utilized in laboratory and field trials, with high binder content, extremely high cement content, exceptionally low W/C, and the usage of SF, fine quartz powder, quartz sand, SP, and steel fibers [50,60–64]. Steel fibers are typically 12.5 mm long and 180 mm in diameter [50]. The coarse particles are removed to improve the matrix's homogeneity. RPC has compressive strengths ranging from 200 MPa to 800 MPa. Table 1 shows the usual composition and mechanical properties of RPC as proposed by Richard and Cheyrezy [50]. Unlike its predecessors, RPC has particularly good usability. This workability feature is a benefit and the most important criterion for large-scale cement-based material applications. The first UHPC created using RPC technology was sold in the late 1990 s with the name Ductal+ . The world's first RPC structure, seen in Fig. 4, was created for a pedestrian bridge in Sherbrooke, Canada, in 1997 [65]. It was the first time RPC had been utilized to construct the entire framework. Despite the success of RPC structures," applications are still limited due to the prohibitive cost of materials and production.

Much progress has "been achieved in the development of UHPC since the year 2000. Engineers understood that advanced concrete should have additional useful properties than high strength as concrete technology improved, which resulted in the terms UHPC and UHPFRC [66]. A wide variety of innovative concrete formulas have been created to address a growing number of uses. Currently, different researchers are proposing sustainable UHPC formulations intending to lower both material and starting costs [67]. Supplementary cementitious materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), SF and among others [68–70] are utilized to replace some of the cement in the production of sustainable UHPC and to reduce its existing cement usage. It has also been stated that UHPC can be made using standard temperature curing without sacrificing its characteristics. Because of the emergence of environmentally benign UHPC at a reasonable cost, UHPC applications are gaining popularity. Several countries have been involved in various UHPC applications since the 2000 s. Many constructions in France, like bridges, facades, and slabs, have been created with UHPC [71]. UHPC is also finding increasing use in the maintenance and improvement of US roadway infrastructure [72]. Significant activities on UHPC development for bridge constructions have been conducted in Australia [73]. In Switzerland, UHPC has mostly been used for in-situ structural reinforcement [74]. Bridges made of UHPC have been built in the Netherlands and Spain [75]. UHPC has been used for bridge structures in Malaysia as part of a sustainable bridge construction strategy. Since 2010, a total of 113 UHPC bridges have been built or are under development in" Malaysia [76].

3. UHPC production principles

Many researchers have "evolved UHPC to the point where they are ready for applications throughout the last 15 years of concrete impressive progress. The compressive strength of the UHPC could be as high as 200 MPa. The basic concept of manufacturing concrete with extremely high strength and thick microstructure was first proposed in the 1980 s [49]. The practical breakthrough, however, came after the introduction of efficient SP, which permitted the fabrication of easy-flowing concrete with a large fraction of optimally packed ultra-fine particles to limit composite porosity while utilizing exceptionally low" w/b.

Several scientists [16,50,67,77,78] "have identified the fundamental design idea of UHPC, which can be described as follows: (i) Reducing w/b and minimizing composite porosity by optimizing the granular mixture through a wide variation of powder size classes. (ii) Microstructure enhancement using post-set heat treatment to accelerate the pozzolanic reaction of SF and increase mechanical characteristics. (iii) Increased homogeneity by removing coarse aggregate, resulting in a reduction in the mechanical impacts of heterogeneity. (iv) Improve ductility by including a sufficient volume fraction of small steel" fibers.

The first four principles result in "concrete with an extremely high compressive strength, and the addition of steel fibers improves

Fig. 4. Canada's Sherbrooke pedestrian bridge [66].

both the tensile strength and the ductility of the" concrete [50].

4. Raw materials

Cementitious components, "quartz powder, quartz sand, Polycarboxylate ether, superplasticizer (PCE), admixtures, water, and fibers are among the constituents of UHPC dosage. Quartz sand has the largest granular elements in the UHPC skeleton, while quartz powder is used as a filler due to its fine dimensions. It has been observed that the higher constituents of UHPC, which account for more than half of the total weight of fine materials and binder, have become a key factor [79], with values ranging between 1100 kg/m^3 and 1300 kg/m^3 as illustrated" in Fig. 5-a.

The main aspect of making UHPC "is to optimize the micro and macro characteristics of its mixed materials to ensure mechanical homogeneity, maximum particle packing density, and small fault size [2,80]. The selection of UHPC compositions should not be limited to the relative proportions of different grain sizes but should also include a suitable selection of materials with adequate physical and chemical characteristics. Table 2 shows some commercially available UHPC blends. According to the data, UHPC typically uses a high volume of cement content, SF, and sand. Although the initial cost of UHPC is significantly higher than that of conventional concrete, enormous efforts have been made to reduce material costs without losing UHPC's" desirable characteristics.

4.1. Cementitious components

4.1.1. Portland cement

Types of cement used in "traditional concrete include Type I to V and white cement, which can all be used to build the UHPC depending on the environmental conditions and applications [89]. Because of their high C3S content and Blaine fineness, type III and white cement are the most commonly used types because they provide fast setting and strength development [90,91]. If high early strength is not required but a low shrinkage is desired, Type I cement is a choice because of its low cost and reactivity. Fig. 5-a shows a relative frequency diagram of" the cement content.

4.1.2. Silica fume (SF)

SF could mention "pozzolanic properties as an important constituent for UHPC production. SF is derived from the manufacturing of ferrocenium alloys and is essentially an industrial derivative [92], which has resulted in an improved interfacial transition zone (ITZ) between the paste and aggregate [93]. It has been found that when SF was not used in the production of UHPC, the cement hydration reaction was accelerated. This can cause porosity to occur in the cement matrix, lowering the hardened mechanical characteristics [94]. The optimal SF content was greatly reliant on W/C, which reduced the workability and stability of UHPFRC in its fresh condition [95]. The optimal SF concentration has been reported to range between 20% and 30% of Portland cement weight [96]. According to Chan and Chu [96], increased fury has a direct association with increasing compressive strength. In Fig. 5-b, a radar chart was created to demonstrate the amount of SF over cement" weight.

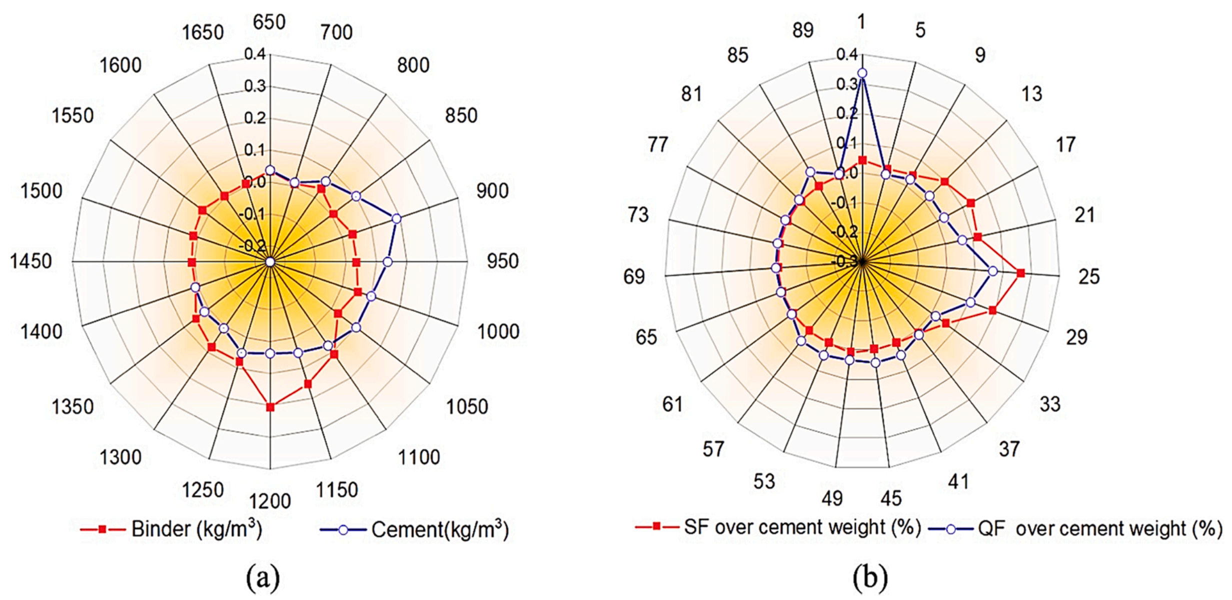

Fig. 5. Relative frequency radar chart for UHPC components: (a) binder and cement (kg/m^3), (b) SF and QF (Quartz Flour) cement weight ratio (%) [88].

Table 2
Commercial UHPC compositions.

Mixtures (kg/m^3)								Steel fibers	Compressive strength (MPa)	Slump flow (mm)	Refs
	Cement	FA	SF	Sand	QP	Water	SP				
Cor-Tuf®	758	–	497	733	295	158	13	140	200	–	[81]
CEMTEC®	1050	–	268	514	–	180	44	470	205	–	[58]
Shen	640	160	176	1000	–	150	32	156	162	165	[82]
BSI®	1114	–	169	1072	–	209	40	234	175	640	[83]
Kang	800	–	200	880	200	200	9.6	–	140	255	[84]
Ductal®	712	–	231	1020	211	109	31	156	149	180 ± 20	[85]
Ganesh	960	–	144	1017	115	163	34	156	116	183	[86]
Meng	712	221	231	1020	–	164	6.5	156	135	275	[87]

4.1.3. Rice husk ash (RHA)

RHA is an agricultural waste "produced by the combustion of rice husk. When the husk is burned under regulated conditions, it contains 90–96% amorphous silica and is a highly active pozzolan. The average particle size of RHA usually varies from 5 to 10 lm with an extremely high specific surface area (even more than 250 m^2/g). This huge surface area arises from the angular and porous nature of RHA. According to Van Tuan, Ye, Van Breugel, Fraaij and Dai Bui [97], UHPC combined with RHA with mean sizes ranging from 3.6 to 9 lm exhibited compressive strength above 150 MPa under a standard curing regime, as shown in Fig. 6. At 28 and 91 days, specimens with a mean particle size of 3.6 lm reached 180 and 210 MPa," respectively.

Van Tuan, Ye, Van Breugel, Fraaij and Dai Bui [97] also "found that UHPC with 10% RHA and 10% SF had higher compressive strength than UHPC without RHA or with other combinations. The author attributed this to RHA's physical filling and water well effects since its particle size is between cement and silica fume particles, and its porous structure may absorb a certain quantity of water for subsequent cement" hydration.

4.1.4. Nanoparticles

UHPC has "been enhanced with nanoparticles such as nano-silica (nano-SiO_2), nano-$CaCO_3$, nano-titanium oxide (nano-TiO_2), and nano-iron (nano-Fe_2O_3), among others. They have a higher surface area to volume ratio than other concrete materials, as illustrated in Fig. 7. Meanwhile, due to their high reactivity, they can serve as nuclei for cement phases, further boosting cement hydration, and as nano-reinforcement and/or filler, densifying the microstructure and the ITZ, resulting in reduced" porosity [98].

Furthermore, as demonstrated in "Fig. 8-a, NCs have been observed to enhance yield stress and apparent viscosity. This is because NC nanoparticles can fill the spaces between cement particles or paste agglomerates, and the increased physical contact sites can improve UHPC rheology [99]. However, when using a fixed dispersion approach, an excess of nano-fillers may create agglomeration due to inter-particle adhesion via weak forces [100], introducing flaws with increased porosity, as seen in Fig. 8-b [101]. For uniform dispersion, two main methods have been used: (1) conduct ultrasonic cavitation, which generates high shear forces that break particle agglomerates into single dispersed particles [102], and (2) add surfactants, which convert the hydrophobic surface of nanomaterials into a hydrophilic surface for better dispersion in the" aqueous phase [103].

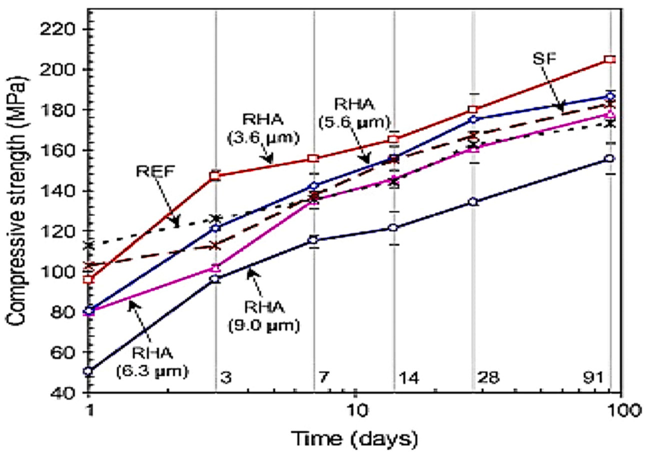

Fig. 6. Compressive strength of UHPC with 20% RHA of various particle sizes versus time, w/b ratio = 0.18 [97].

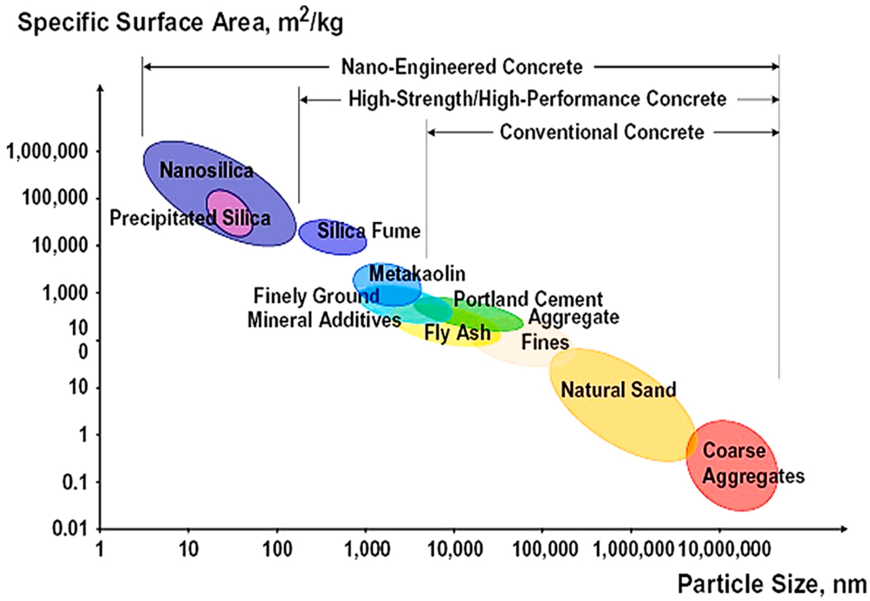

Fig. 7. Concrete particle size and specific surface area [104].

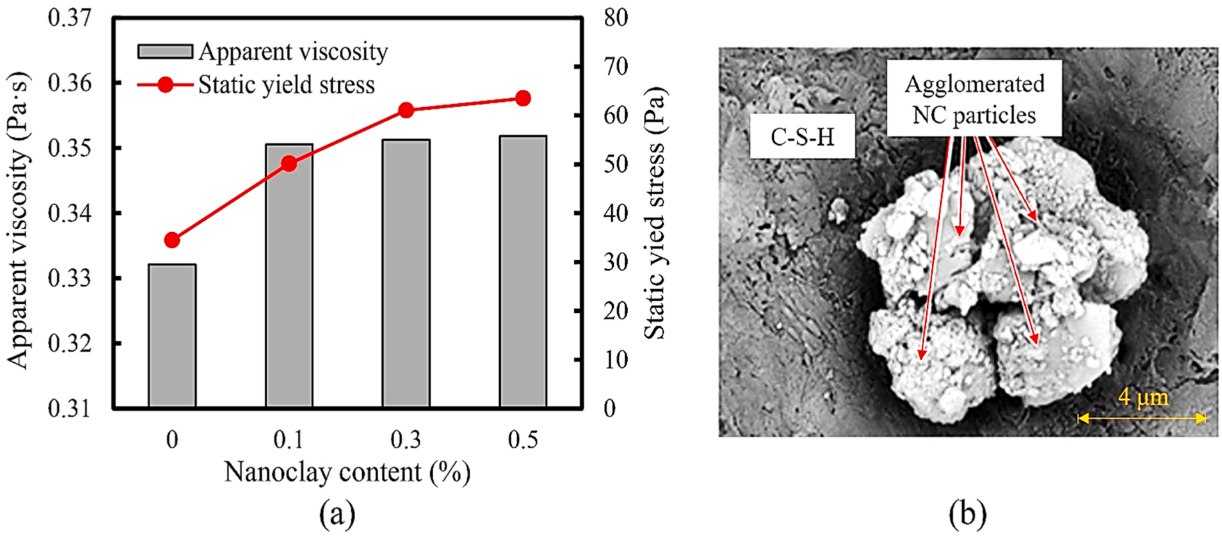

Fig. 8. UHPC with nano-scale fillers: (a) the effect of NC particles on the rheology of cement pastes [105]; and (b) the agglomerated NC particles [106].

4.2. Aggregates

4.2.1. Coarse aggregates

Richard and Cheyrezy [50] proposed "basic concepts for producing UHPC, in which coarse aggregates (i.e., larger than 4.75 mm) are generally avoided. This is due to the negative effects of coarse aggregates: (1) the angularity of coarse aggregates reduces the initial packing density of UHPC [107]; (2) the stress concentration at the contact between aggregates leads to weakness in the UHPC matrix [108]; and (3) the ITZ between coarse aggregate and UHPC matrix is weaker than the ITZ between sand and UHPC matrix," as shown in Fig. 9 [109].

However, the following advantages of "utilizing coarse aggregates in UHPC have been reported: (1) decreasing the volume of cementitious paste, which raises the elastic modulus and lowers shrinkage, as demonstrated in Fig. 10-a [110]; and (2) improving penetration impact resistance [111]. Basalt and limestone have been used because of their inexpensive cost, high elastic modulus, and inert properties [109]. However, when the aggregate's maximum particle size was increased from 3 mm to 16 mm, the 28-day compressive and tensile strengths were reduced by 10% and 15%, respectively [107], as shown in Fig." 10-b.

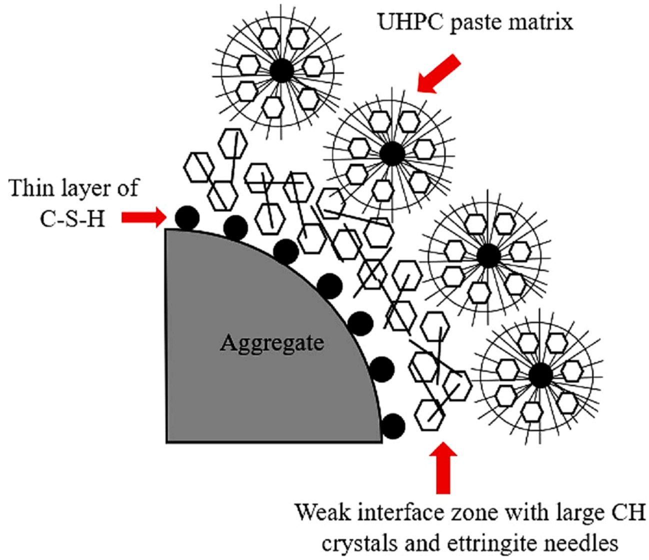

Fig. 9. Diagram of the ITZ between coarse aggregate and UHPC matrix [109].

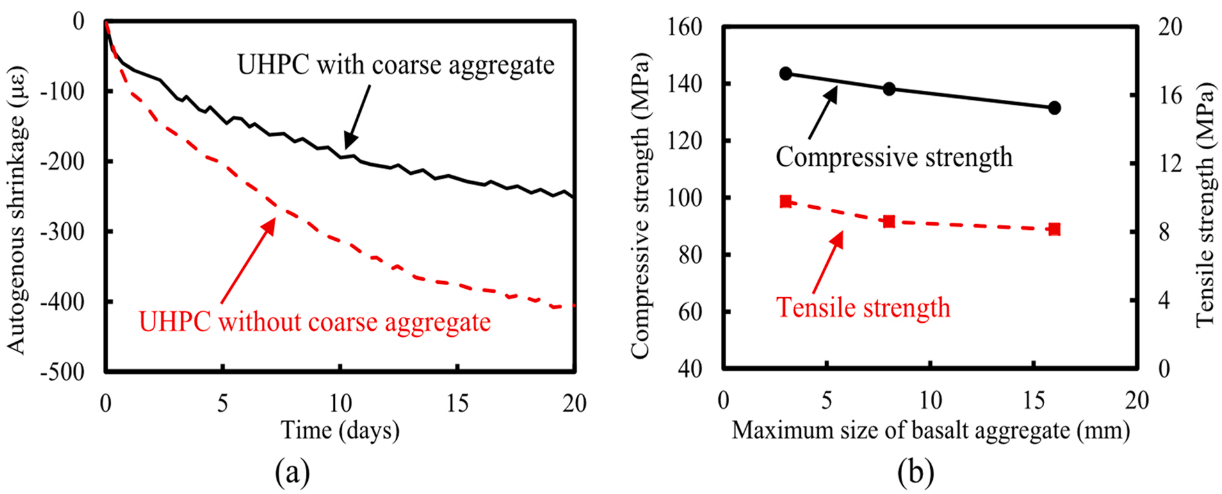

Fig. 10. Effects of coarse aggregate on the performance of a UHPC: (a) the autogenous shrinkage [110]; and (b) the compressive and tensile strengths [107].

4.2.2. Fine aggregates

River sand is the "most commonly utilized fine aggregate to replace quartz sand [59]. River sand, on the other hand, has particle sizes ranging from 0 mm to 4.75 mm, with the maximum particle size being 5–8 times that of fine quartz sand. As a result, completely replacing fine quartz sand with river sand can reduce particle packing density. Finer and more evenly sized masonry sand (size range: 0–2 mm) was used to improve particle packing [87]. Masonry sand, on the other hand, is generated by crushing and grinding coarse aggregates, resulting in more angular particles than the river sand, which reduces the workability of UHPC [112]. Furthermore, when compared to quartz sand, the greater average particle size of river sand and construction sand results in a weaker ITZ between sand and the UHPC matrix [87]. To minimize the ITZ, the particle packing should be" optimized.

Limestone "sand is inexpensive, has a homogeneous composition, has huge reserves, and is available worldwide [113]. Yang, Yu, Shui, Gao, Xiao, Fan, Chen, Cai, Li and He [114] proved the possibility of preparing UHPC with recycled rock dust instead of fine quartz sand. According to Yang, Yu, Shui, Gao, Xiao, Fan, Chen, Cai, Li and He [114], the raw cost per unit volume of UHPC was decreased by 40% without affecting workability or mechanical performance.

Recently, lightweight porous sand, such as lightweight sand [115] and volcanic rock sand [116], has been used to make UHPC. This sand's porous nature enables internal curing in the UHPC. Pre-saturated internal curing agents (i.e., porous sand), as illustrated in Fig. 11, hold the curing water during concrete mixing and release it during concrete hydration. By increasing the IRH, the cement hydration degree is increased while the self-desiccation effect is reduced [117]. Internal moisture curing can be more successful than

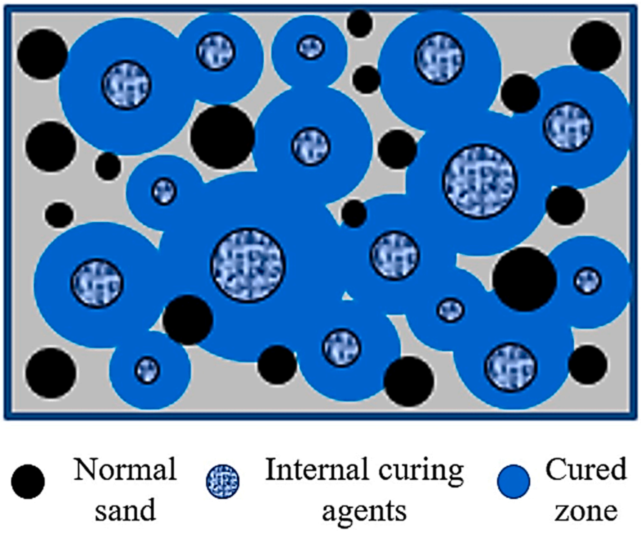

Fig. 11. Diagram showing the mechanism of internal curing agents used in UHPC [115].

external moisture curing in developing UHPC with low shrinkage and high mechanical" characteristics [115].

4.3. Superplasticizer (SP)

The typical w/c "in UHPC is in the 0.14–0.20 range. The most effective SP for UHPC was polycarboxylates (PCs) [118]. The length of the side chain was found to have the greatest influence on retardation time, while the density of the side chain was shown to have the greatest effect on workability [119]. Hirschi and Wombacher [120] studied the fresh and hardened properties of UHPC using eight diverse types of PC-based superplasticizers, as illustrated in Fig. 12. The setting time varied greatly, which is a good indicator of early strength development. Mixtures containing P5 and P11 with long side chain lengths outperformed those with medium side chain lengths in terms of early strength. The compressive strength matched the flexural strength perfectly. Courtial, de Noirfontaine, Dunstetter, Signes-Frehel, Mounanga, Cherkaoui and Khelidj [121] investigated the effect of PC dosages ranging from 0.5% to 2.0% on the microstructure of UHPC and discovered that the belite phase content decreased significantly when the PC dosage ranged from 1.8 to 1.2" percent.

The PCE head "with a negative charge is absorbed on the surface of cement particles, as illustrated in Fig. 13-a, and the steric barrier between the side chains of the absorbed PCE HRWR disperses the cement particles [122]. It is chosen to absorb and disperse silica fume particles due to the stereochemistry of the allyl ether based HRWR. However, as demonstrated in Fig. 13-b, the absorbed HRWR on cementitious particles slows the hydration reaction, which prolongs the setting time and reduces mechanical strengths at early" ages.

4.4. Fibers

As previously stated, "the superior ductility and impact resistance of UHPC is due to the choice of appropriate fibers. The parameters of the most extensively used fibers in concrete are shown in Table 3. Table 4 presents the physical and mechanical properties of the fibers utilized in the manufacturing of UHPFRC. Because of their better tensile strengths, steel and carbon fibers are typically employed in UHPC" matrices.

Steel fibers considerably "improved mechanical characteristics, according to Shu-hua, Li-hua and Jian-wen [124], whereas polypropylene and glass fibers did not due to their low strengths. The tensile strength of UHPFRC rose linearly as the fiber volume ratio grew from 0% to 5% [125]. At 14 days of heat treatment, including 2% steel fibers by volume reduced autogenous shrinkage by 42% [126]. The increased amount of fibers enhanced the interaction of fibers with each other during mixing, resulting in balling and a decrease in the workability of the mixture, as well as the mechanical" performances [127].

Combinations of two or three various fibers "in a UHPC matrix were used to decrease fiber amounts while achieving desired performance [128]. Park, Kim, Ryu and Koh [129] discovered that UHPC containing 1.0% macro steel fibers, and more than 0.5% micro steel fibers can generate tensile strain hardening, as illustrated in Fig. 14. UHPFRC with twisted macro-fibers had the best tensile performance, with post-cracking strength, strain capacity, and multiple micro-cracking behaviors of 18.6 MPa, 0.64%, and 3.8 mm, respectively, whereas UHPFRC with long smooth fibers had the poorest. Kim, Park, Ryu and Koh [130] investigated the impacts of micro and macro fiber combinations on the flexural performance of UHPFRC and discovered the following order of flexural performance: Hooked B (HB) fiber > twisted (T) fiber > long smooth (LS) fiber > hooked A (HA) fiber The deflection capacity δ_{MOR} and energy absorption capacity T_{MOR} of UHPFRC with 1.0% micro and 1.0% macro fiber combinations were 45.4–75.9% and 48.7–67.9% higher, respectively than those with 2.0% microfibers. The distribution and orientation of the fibers had a significant impact on the

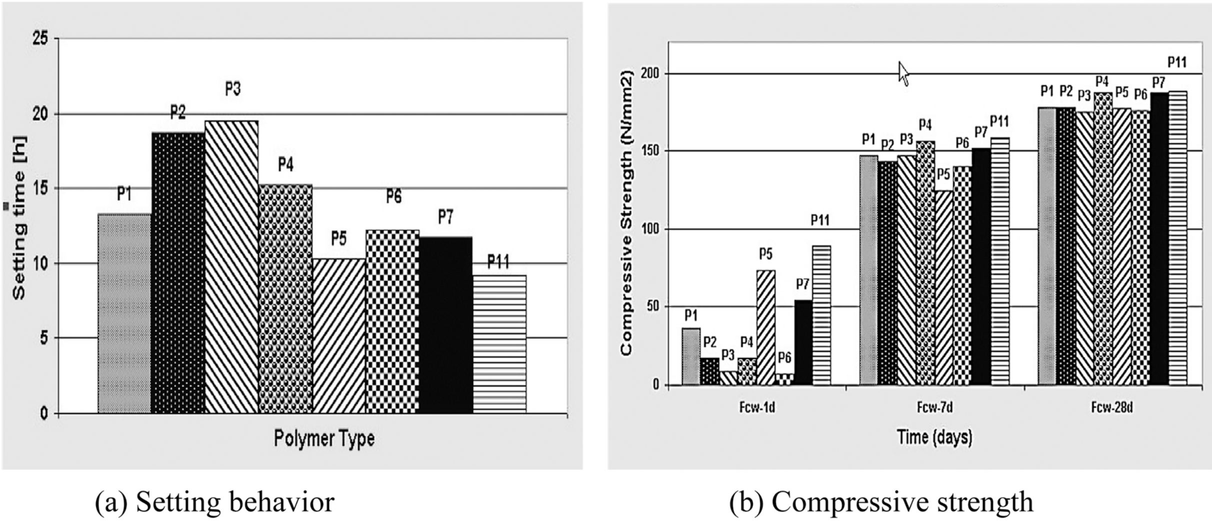

Fig. 12. The effect of various superplasticizers on the fresh and hardening characteristics of UHPC [120].

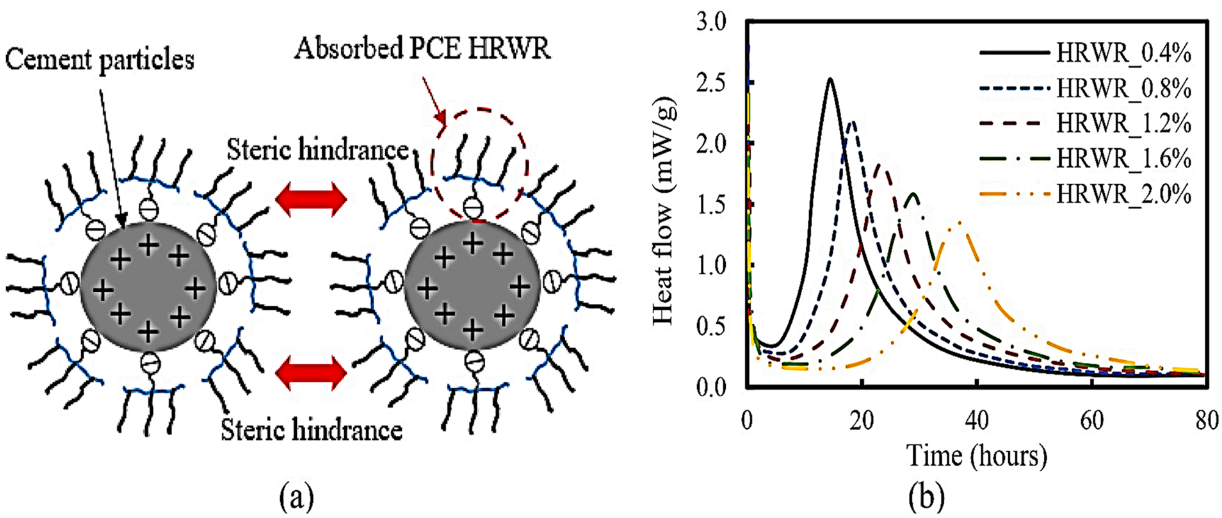

Fig. 13. Effects of PCE HRWR on UHPC: (a) fundamental mechanism of steric repulsion effect [122]; and (b) retarded hydration [123].

Table 3
Typical characteristics of commonly used fibers in concrete [133].

Type	Diameter (μm)	Relative density (gcm^{-3})	Elongation (%)	Young modulus (GPa)	Tensile strength (MPa)
Steel	250–1000	7.80	0.5–4.0	200–250	280–2800
Acrylic	5–17	1.18	9–11	16–23	800–950
Asbestos	< 0.5	2.75	0.3–0.6	84–140	500–980
Polyethylene	800–1000	0.96	3–4	5–6	200–300
Polyester	10–80	1.38	11–15	6–18	735–1200
Polypropylene	20–70	0.91	15–25	3.5–11	300–770
PVA	1.30	1.30	6–17	5–50	600–2500
Nylon	23	1.16	18–20	4.2–5.2	900–960
Rock wool	2.7	2.7	0.6	70–119	490–770
Aramid	10–12	1.44	2.1–4.5	60–120	2500–3100
Wood	25–400	1.40	–	15–40	50–1000
Glass	10–16	2.74	2.5–3.5	70–80	1400–2500
Carbon	7–18	1.75	1.2–1.6	200–480	1800–4000

Table 4
Physical and mechanical properties of UHPFRC fibers.

Type	Form	Length (μm)	Diameter (μm)	Aspect ratio	Specific density (kg/m^3)	Tensile strength (MPa)	Ref.
Steel	Straight Hooked	6000	160	37.5	7850	2000	[134]
Steel		30,000	380	78.9	7850	3000	
Steel	Straight	12,700	200	63.5	7850	–	[135]
Steel	Straight	13,000	200	65	7800	–	[136]
Wollastonite	–	152	8	19	–	–	[137]
Wollastonite	–	50–2000	– 40	3–20 15	–	2700–4100	[138]
		600	12	13			
		156					
Steel	Straight	13,000	200	65	7800	–	[136]
Steel	Straight Hooked	6000	160	37.5	7800	–	
Steel		35,000	550	63.7	7800	–	
Steel	Straight	13,000	200	65	–	2500	[139]
Steel	Crimped	30,000	450	66	–	800	[140]
Polypropylene	–	12,000	38	316	–	550–600	
Steel	Straight Hooked	13,000	160	81	–	2500	[141]
		60,000	750	80	–	1225	
Steel	Straight	13,000	200	65	7500	2500	[142]
Steel	Twisted	14,000	500	28	–	2450	[143]
	Twisted	14,000	500	28	–	2450	
	Straight	12,500	175	72	–	2200	
Steel	Straight	6000	200	30	–	2800	[144]
		13,000	200	65		2800	
Polypropylene bar chip modified macro	–	6000	20	300	920	600–700	[145]
polypropylene Steel	Straight Hooked	50,000	70	58	910	700–800	
		35,000	600		7850	800–1000	
Steel	Long	35,000	700	50	–	1800	[146]
	Short Long	30,000	700	43	–	1000	
	ultra-fine	19,000	200	95	–	2800	
	Short ultra-fine	13,000	200	65	–	1500	
	Flattened end	30,000	700	43	–	1200	

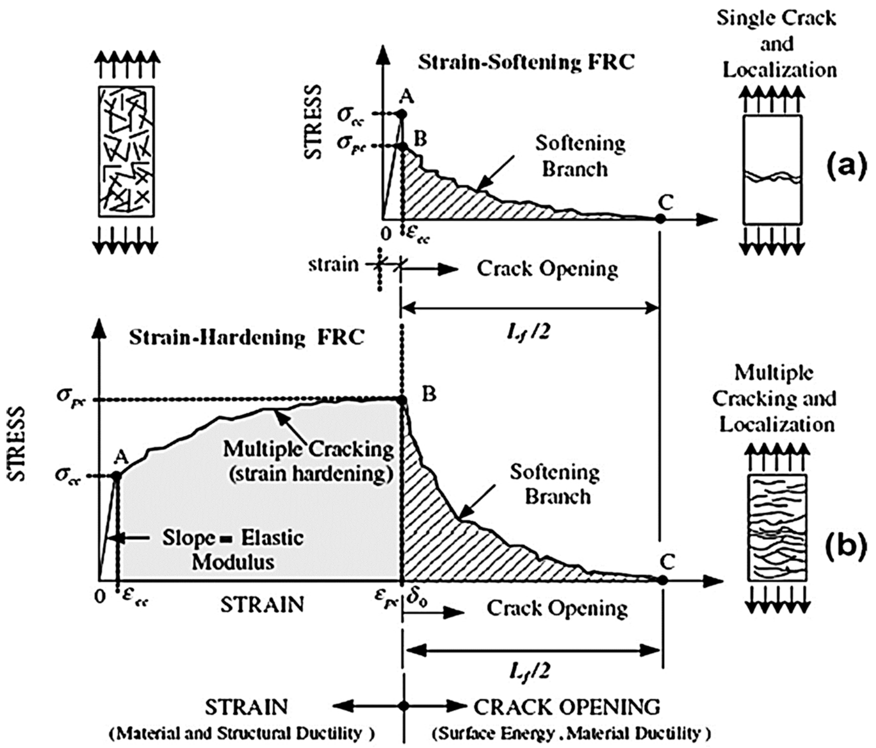

Fig. 14. FRC softening and hardening under tensile strain Park, Kim, Ryu and Koh [129].

mechanical characteristics of UHPFRC [131]. The early cracking and ultimate flexural strengths of UHPC placed parallel to the longitudinal direction were 5.5% and 61% higher, respectively, than those placed" transversely [132].

Despite UHPC's excellent characteristics, "it is extremely difficult to manufacture very ductile and high strength UHPFRC with a tensile strain capacity greater than 0.5%, tensile strength greater than 16 MPa, and compressive strength greater than 150 MPa [129]. To attain these required concrete characteristics, several researchers have attempted to use several types of fibers in terms of material, shape, and aspect ratio, as well as a variety of mineral admixtures, as illustrated in Fig. 15. Table 4 depicts the distinct types of fibers used to construct UHPFRC, as well as their physical and mechanical properties. Park, Kim, Ryu and Koh [129] showed that the addition of hybrid fibers to concrete might result in tensile strength of UHPFRC in the range of 18–20 MPa and tensile strain capacity in the range of 0.64" percent–1.06%.

5. Conclusions

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

1. The amount "of powder used in various concrete types was reported to be 33% (UHPC), 16% (HPC), and 20% (SCC). As a result, for UHPC, a considerable amount of cement (800–1300 kg/m^3) was reported in the literature. Partially substituting cement appears to have certain advantages in terms of ultimate cost and chosen mechanical characteristics such as higher compressive strength and less" shrinkage.

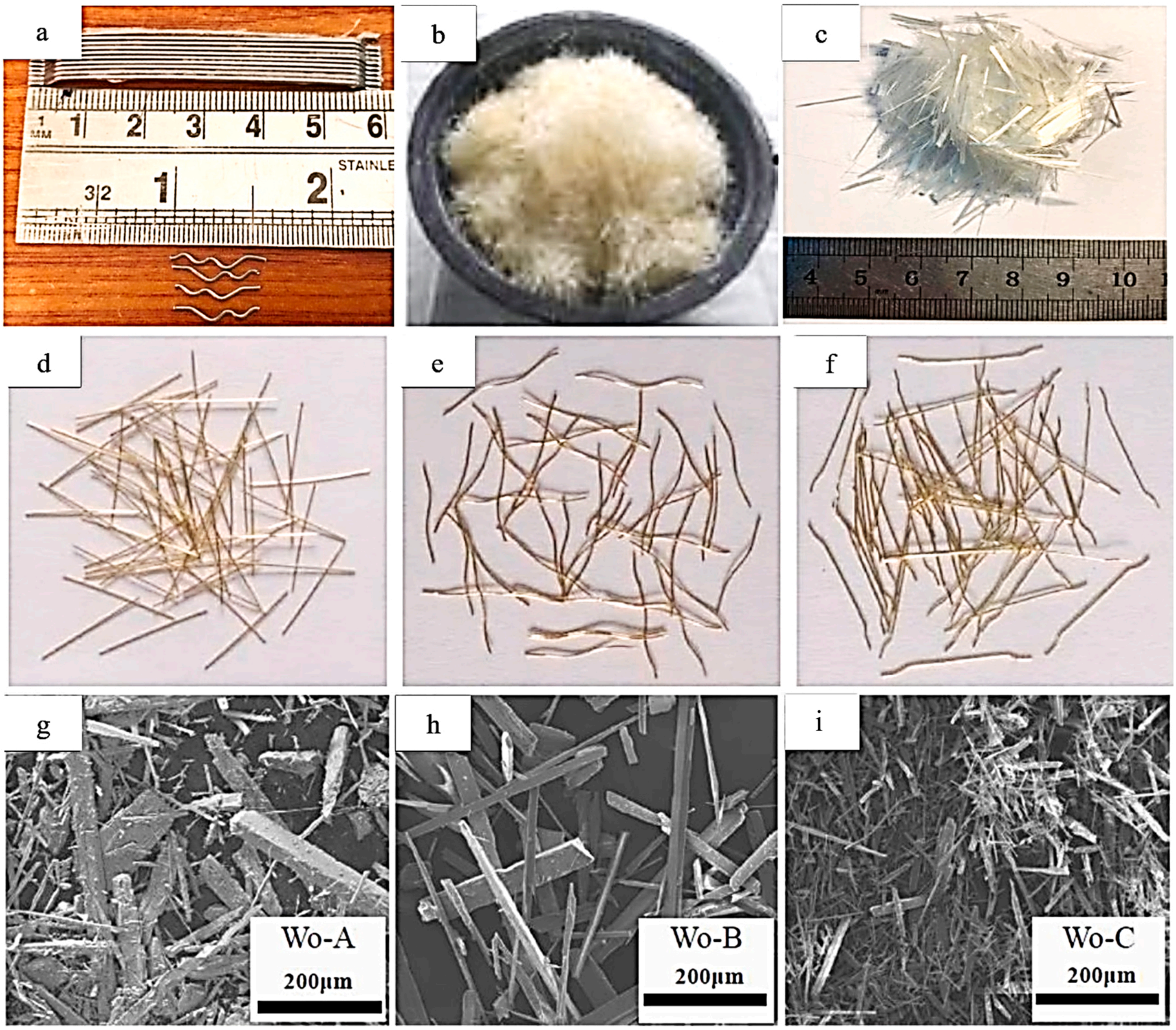

Fig. 15. Various types of fiber used for developing the UHPC/UHPFRC and UHPFRC: (a) crimped and hooked fiber [147], (b) sisal fiber [148] and (c) polyvinyl alcohol (PVA) fiber [149], (d) straight fiber [150], (e) corrugated fiber [150], (f) hooked fiber [150], (g) wollastonite -A (aspect ratio 3–20) [138], (h) wollastonite -B (aspect ratio 15) [138], (i) wollastonite -C (aspect ratio 156) [138].

2. The use of “readily available supplemental cementitious materials such as fly ash and slag to substitute cement and silica fume could greatly reduce the material cost of UHPC. Simultaneously, following normal curing, UHPC with the appropriate amount of those extra cementitious materials could achieve a compressive strength of 150–200” MPa.
3. The superplasticizer “dosage of polycarboxylates had a considerable impact on the reactivity of the two calcium silicates. Using PC in the range of 1.8–2% of the cement weight greatly decreased the cement’s” belittle phase.
4. Porosity was reported “to be reduced by up to 19% in UHPC specimens with glass powder replacements of up to 90% or nano-silica replacements of up to 1% when compared to those with no nano-silica. Glass powder and nano-silica are also observed to lower the peak intensities of C2S and C3S, which further converts CH to C–S–H. Finally, metakaolin, which is employed as a cement replacement in UHPCs, is claimed to convert more CH to C–S–H, whereas C2ASH8 is created with up to 20%” substitutions.
5. The fundamental concepts for UHPC design are decreased porosity, improved microstructure, increased homogeneity, and increased toughness. The characteristics of UHPC are significantly influenced by raw materials, preparation technique, and curing regimens.
6. Because UHPC “is a sort of customized concrete, the types, morphologies, and amounts of mineral admixtures, as well as the fibers utilized, have extremely sensitive effects on the material’s performance. An optimal amount of a mineral admixture is beneficial for densifying the matrix at the microstructure level. However, an excess percentage of a mineral admixture is left unreactive in the matrix, which is not beneficial for performance” enhancement.

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.

References

[1] B.A. Tayeh, B.A. Bakar, M. Johari, Mechanical properties of old concrete-UHPFC interface, Int. Conf. Concr. Repair, Rehabil. Retrofit. (2012) 02–05.
[2] B.A. Tayeh, B.A. Bakar, M.M. Johari, Y.L. Voo, Mechanical and permeability properties of the interface between normal concrete substrate and ultra high performance fiber concrete overlay, Constr. Build. Mater. 36 (2012) 538–548.
[3] B.A. Tayeh, B.H. Abu Bakar, M. Johari, Characterization of the interfacial bond between old concrete substrate and ultra high performance fiber concrete repair composite, Mater. Struct. 46 (5) (2013) 743–753.
[4] B.A. Tayeh, B.A. Bakar, M.M. Johari, M.M. Ratnam, The relationship between substrate roughness parameters and bond strength of ultra high-performance fiber concrete, J. Adhes. Sci. Technol. 27 (16) (2013) 1790–1810.
[5] Y.I.A. Aisheh, D.S. Atrushi, M.H. Akeed, S. Qaidi, B.A. Tayeh, Influence of steel fibers and microsilica on the mechanical properties of ultra-high-performance geopolymer concrete (UHP-GPC), Case Stud. Constr. Mater. 17 (2022), e01245.
[6] F. Aslam, O. Zaid, F. Althoey, S.H. Alyami, S.M.A. Qaidi, J. de Prado Gil, R. Martínez-García, Evaluating the influence of fly ash and waste glass on the characteristics of coconut fibers reinforced concrete, Structural Concrete n/a(n/a).
[7] Y.I.A. Aisheh, D.S. Atrushi, M.H. Akeed, S. Qaidi, B.A. Tayeh, Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete, Case Stud. Constr. Mater. (2022), e01234.
[8] S.M.A. Qaidi, A.S. Mohammed, H.U. Ahmed, R.H. Faraj, W. Emad, B.A. Tayeh, F. Althoey, O. Zaid, N.H. Sor, Rubberized geopolymer composites: A comprehensive review, Ceramics International (2022).
[9] E. Najaf, H. Abbasi, S.M. Zahrai, Effect of waste glass powder, microsilica and polypropylene fibers on ductility, flexural and impact strengths of lightweight concrete, International Journal of Structural Integrity (ahead-of-print) (2022).
[10] M. Orouji, S.M. Zahrai, E. Najaf, Effect of glass powder & polypropylene fibers on compressive and flexural strengths, toughness and ductility of concrete: An environmental approach. Structures, Elsevier, 2021, pp. 4616–4628.
[11] E. Najaf, M. Orouji, S.M. Zahrai, Improving nonlinear behavior and tensile and compressive strengths of sustainable lightweight concrete using waste glass powder, nanosilica, and recycled polypropylene fiber, Nonlinear Eng. 11 (1) (2022) 58–70.
[12] S.M. Zahrai, M.H. Mortezagholi, E. Najaf, Using AP2RC & P1RB micro-silica gels to improve concrete strength and study of resulting contamination, Adv. Concr. Constr. 4 (3) (2016) 195.
[13] A. el Mahdi Safhi, P. Rivard, A. Yahia, M. Benzerzour, K.H. Khayat, Valorization of dredged sediments in self-consolidating concrete: Fresh, hardened, and microstructural properties, J. Clean. Prod. 263 (2020), 121472.
[14] N. Gupta, R. Siddique, R. Belarbi, Sustainable and greener self-compacting concrete incorporating industrial by-products: a review, J. Clean. Prod. 284 (2021), 124803.
[15] B.A. Tayeh, B.A. Bakar, M.M. Johari, Y.L. Voo, Evaluation of bond strength between normal concrete substrate and ultra high performance fiber concrete as a repair material, Procedia Eng. 54 (2013) 554–563.
[16] B.A. Tayeh, B.A. Bakar, M.M. Johari, Y.L. Voo, Utilization of ultra-high performance fibre concrete (UHPFC) for rehabilitation–a review, Procedia Eng. 54 (2013) 525–538.
[17] B.A. Tayeh, B.H.A. Bakar, M.A. Megat Johari, A. Zeyad, Flexural strength behavior of composite UHPFC-existing concrete, Advanced Materials Research, Trans. Tech. Publ. (2013) 32–36.
[18] L.K. Askar, B.A. Tayeh, B.H. Abu Bakar, Effect of different curing conditions on the mechanical properties of UHPFC, Iran. J. Energy Environ. 4 (3) (2013).
[19] B.A. Tayeh, B.H. Abu Bakar, M. Megat Johari, A.M. Zeyad, Microstructural analysis of the adhesion mechanism between old concrete substrate and UHPFC, J. Adhes. Sci. Technol. 28 (18) (2014) 1846–1864.
[20] M. Elsayed, F. Althoey, B.A. Tayeh, N. Ahmed, A. Abd El-Azim, Behavior of Eccentrically Loaded Hybrid Fiber-Reinforced High Strength Concrete Columns Exposed to Elevated, Temp., J. Mater. Res. Technol. (2022).
[21] I.Y. Hakeem, M. Amin, B.A. Abdelsalam, B.A. Tayeh, F. Althoey, I.S. Agwa, Effects of nano-silica and micro-steel fiber on the engineering properties of ultra-high performance concrete, Struct. Eng. Mech. 82 (3) (2022) 295–312.
[22] M.A. Hosen, M.I. Shammas, S.K. Shill, M.Z. Jumaat, U.J. Alengaram, R. Ahmmad, F. Althoey, A.S. Islam, Y. Lin, Investigation of structural characteristics of palm oil clinker based high-strength lightweight concrete comprising steel fibers, J. Mater. Res. Technol. 15 (2021) 6736–6746.

[23] F. Althoey, O. Zaid, J. de-Prado-Gil, C. Palencia, E. Ali, I. Hakeem, R. Martínez-García, Impact of sulfate activation of rice husk ash on the performance of high strength steel fiber reinforced recycled aggregate concrete, J. Build. Eng. 54 (2022), 104610.
[24] E. Fehling, M. Schmidt, S. Stürwald, Ultra High Performance Concrete:(UHPC); Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, March 05-07, kassel university press,, 2008, p. GmbH2008. March 05-07.
[25] O. Uche, Influence of recycled concrete aggregate (RCA) on compressive strength of plain concrete, Pan 8 (2) (2008) 0.17.
[26] A.N. Mohammed, M.A.M. Johari, A.M. Zeyad, B.A. Tayeh, M.O. Yusuf, Improving the engineering and fluid transport properties of ultra-high strength concrete utilizing ultrafine palm oil fuel ash, J. Adv. Concr. Technol. 12 (4) (2014) 127–137.
[27] L.K. Askar, B.A. Tayeh, B.H. Abu Bakar, A.M. Zeyad, Properties of ultra-high performance fiber concrete (UHPFC) under different curing regimes, Int. J. Civ. Eng. Technol. (IJCIET) 8 (4) (2017).
[28] B.A. Tayeh, A.S. Aadi, N.N. Hilal, B.A. Bakar, M.M. Al-Tayeb, W.N. Mansour, Properties of ultra-high-performance fiber-reinforced concrete (UHPFRC)—A review paper. AIP Conference Proceedings, AIP Publishing LLC,, 2019.
[29] M. Amin, B.A. Tayeh, I.S. Agwa, Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete, J. Clean. Prod. 273 (2020), 123073.
[30] W. Mansour, B.A. Tayeh, Shear behaviour of RC beams strengthened by various ultrahigh performance fibre-reinforced concrete systems, Advances in Civil Engineering 2020 (2020).
[31] N.K. Baharuddin, F. Mohamed Nazri, B.H. Abu Bakar, S. Beddu, B.A. Tayeh, Potential use of ultra high-performance fibre-reinforced concrete as a repair material for fire-damaged concrete in terms of bond strength, Int. J. Integr. Eng. 12 (9) (2020).
[32] E.F. O'Neil, B.D. Neeley, J.D. Cargile, Tensile properties of very-high-strength concrete for penetration-resistant structures, Shock Vib. 6 (5, 6) (1999) 237–245.
[33] S.M.A. Qaidi, Y.S.S. Al-Kamaki, State-of-the-art review: concrete made of recycled waste PET as fine aggregate, J. Duhok Univ. 23 (2) (2021) 412–429.
[34] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Challenges, 2022.
[35] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Applications, 2022.
[36] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Cost assessment, 2022.
[37] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Durability properties, 2022.
[38] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Hardened properties, 2022.
[39] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Fresh properties, 2022.
[40] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Hydration and microstructure, 2022.
[41] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Mixture design, 2022.
[42] A. Spasojevic, D. Redaelli, M. Fernández Ruiz, A. Muttoni, Influence of tensile properties of UHPFRC on size effect in bending, ultra high performance concrete (UHPC), Second Int. Symp. . Ultra High. Perform. Concr., Ultra High. Perform. Concr. (UHPC), Second Int. Symp. . … (2008) 303–310.
[43] P.-C. Aïtcin, Cements of yesterday and today: concrete of tomorrow, Cem. Concr. Res. 30 (9) (2000) 1349–1359.
[44] H.U. Ahmed, A.S. Mohammed, S.M.A. Qaidi, R.H. Faraj, N. Hamah Sor, A.A. Mohammed, Compressive strength of geopolymer concrete composites: a systematic comprehensive review, analysis and modeling, European, J. Environ. Civ. Eng. (2022) 1–46.
[45] X. He, Z. Yuhua, S. Qaidi, H.F. Isleem, O. Zaid, F. Althoey, J. Ahmad, Mine tailings-based geopolymers: a comprehensive review, Ceram. Int. (2022).
[46] B.A.T. Shaker M.A. Qaidi, Abdullah M. Zeyad, Afonso R.G. de Azevedo, Hemn Unis Ahmed, Wael Emad, Recycling of mine tailings for the geopolymers production: A systematic review, Case Studies in Construction Materials (2022).
[47] B.A.T. Shaker M.A. Qaidi, Haytham F. Isleem, Afonso R.G. de Azevedo, Hemn Unis Ahmed, Wael Emad, Sustainable utilization of red mud waste (bauxite residue) and slag for the production of geopolymer composites: A review, Case Studies in Construction Materials (2022).
[48] S.M.A. Qaidi, Y.Z. Dinkha, J.H. Haido, M.H. Ali, B.A. Tayeh, Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: a review, J. Clean. Prod. (2021), 129251.
[49] H.H. Bache, Densified cement ultra-fine particle-based materials, (1981).
[50] P. Richard, M. Cheyrezy, Composition of reactive powder concretes, Cem. Concr. Res. 25 (7) (1995) 1501–1511.
[51] S.M.A. Qaidi, Ultra-high-performance fiber-reinforced concrete: Principles and raw materials, 2022.
[52] S.M.A. Qaidi, PET-concrete confinement with CFRP, 2021.
[53] S.M.A. Qaidi, PET-Concrete, 2021.
[54] S.M.A. Qaidi, Behavior of Concrete Made of Recycled PET Waste and Confined with CFRP Fabrics, College of Engineering, University of Duhok, 2021.
[55] A. Mansi, N.H. Sor, N. Hilal, S.M. Qaidi, The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review. IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022.
[56] F.A. Jawad Ahmad, Rebeca Martinez-Garcia, Jesús de-Prado-Gil, Shaker M.A. Qaidi, Ameni Brahmia, Effects of waste glass and waste marble on mechanical and durability performance of concrete, Sci. Rep. 11 (1) (2021) 21525.
[57] M.M.A.-T. Ibrahim Almeshal, Shaker M.A. Qaidi, B.H. Abu Bakar, Bassam A. Tayeh, Mechanical properties of eco-friendly cements-based glass powder in aggressive medium, Mater. Today.: Proc. 2214–7853 (2022).
[58] P. Rossi, A. Arca, E. Parant, P. Fakhri, Bending and compressive behaviours of a new cement composite, Cem. Concr. Res. 35 (1) (2005) 27–33.
[59] N. Soliman, A. Tagnit-Hamou, Development of ultra-high-performance concrete using glass powder–Towards ecofriendly concrete, Constr. Build. Mater. 125 (2016) 600–612.
[60] R.H. Faraj, H.U. Ahmed, S. Rafiq, N.H. Sor, D.F. Ibrahim, S.M.A. Qaidi, Performance of self-compacting mortars modified with nanoparticles: a systematic review and modeling, Clean. Mater. 2772–3976 (2022), 100086.
[61] R.H. Faraj, H.U. Ahmed, S. Rafiq, N.H. Sor, D.F. Ibrahim, S.M. Qaidi, Cleaner Materials.
[62] S.N. Ahmed, N.H. Sor, M.A. Ahmed, S.M.A. Qaidi, Thermal conductivity and hardened behavior of eco-friendly concrete incorporating waste polypropylene as fine aggregate, Materials Today: Proceedings (2022).
[63] H.U. Ahmed, A.S. Mohammed, R.H. Faraj, S.M.A. Qaidi, A.A. Mohammed, Compressive strength of geopolymer concrete modified with nano-silica: Experimental and modeling investigations, Case Studies in Construction, Materials 2 (2022), e01036.
[64] H.U. Ahmed, A.A. Mohammed, S. Rafiq, A.S. Mohammed, A. Mosavi, N.H. Sor, S.M.A. Qaidi, Compressive strength of sustainable geopolymer concrete composites: a state-of-the-art review, Sustainability 13 (24) (2021) 13502.
[65] S. Abbas, A.M. Soliman, M.L. Nehdi, Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages, Constr. Build. Mater. 75 (2015) 429–441.
[66] P. Acker, M. Behloul, Ductal® technology: a large spectrum of properties, a wide range of applications, Proc. Int. Symp. UHPC Kassel, Ger. (2004) 11–23.
[67] A. Hassan, S. Jones, G. Mahmud, Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC), Constr. Build. Mater. 37 (2012) 874–882.
[68] A. Safhi, Valorization of Dredged Sediments as Sustainable Construction Resources, 2022.
[69] J. Duchesne, Alternative supplementary cementitious materials for sustainable concrete structures: a review on characterization and properties, Waste Biomass-.-. Valoriz. 12 (3) (2021) 1219–1236.
[70] A. el Mahdi Safhi, Y. El Khesssaimi, Y. Taha, R. Hakkou, M. Benzaazoua, Calcined marls as compound of binary binder system: Preliminary study, Materials Today: Proceedings (2022).
[71] J. Resplendino, F. Toutlemonde, The UHPFRC revolution in structural design and construction, RILEM-Fib-AFGC int. symposium on ultra-high performance fibre-reinforced concrete, UHPFRC,, 2013, pp. 791–804.
[72] H.G. Russell, B.A. Graybeal, H.G. Russell, Ultra-high performance concrete: A state-of-the-art report for the bridge community, United States. Federal Highway Administration. Office of Infrastructure …, 2013.

[73] B. Cavill, G. Chirgwin, The world's first RPC road bridge at Shepherds Gully Creek, NSW, Austroads Bridge Conference, 5th, 2004, Hobart, Tasmania, Australia, 2004.
[74] E. Brühwiler, E. Denarié, Rehabilitation and strengthening of concrete structures using ultra-high performance fibre reinforced concrete, Struct. Eng. Int. 23 (4) (2013) 450–457.
[75] A.E. Naaman, K. Wille, The path to ultra-high performance fiber reinforced concrete (UHP-FRC): five decades of progress, Proc. Hipermat (2012) 3–15.
[76] M.K. Tadros, Y. Voo, Taking ultra-high-performance concrete to new heights, ASPIRE 10 (3) (2016) 36–38.
[77] M. Schmidt, E. Fehling, Ultra-high-performance concrete: research, development and application in, Eur., Acids Spec. Publ. 228 (4) (2005) 51–78.
[78] P. Rossi, Influence of fibre geometry and matrix maturity on the mechanical performance of ultra high-performance cement-based composites, Cement and Concrete, Composites 37 (2013) 246–248.
[79] E.C. Torregrosa, Dosage optimization and bolted connections for UHPFRC ties, Universitat Politècnica de Valéncia, 2013.
[80] Y. Voo, S. Foster, L. Pek, Ultra-high performance concrete—technology for present and future, Proc. High. Tech. Concr.: Where Technol. Eng. Meet., Maastricht, Neth. (2017) 12–14.
[81] E.M. Williams, S.S. Graham, P.A. Reed, T.S. Rushing, Laboratory characterization of Cor-Tuf concrete with and without steel fibers, ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS GEOTECHNICAL AND …, 2009.
[82] P. Shen, H. Zheng, D. Xuan, J.-X. Lu, C.S. Poon, Feasible use of municipal solid waste incineration bottom ash in ultra-high performance concrete, Cem. Concr. Compos. 114 (2020), 103814.
[83] E. Camacho, J.Á. López, P. Serna, Definition of three levels of performance for UHPFRC-VHPFRC with available materials, Proc. Hipermat (2012) 249–256.
[84] S.-H. Kang, S.-G. Hong, J. Moon, The use of rice husk ash as reactive filler in ultra-high performance concrete, Cem. Concr. Res. 115 (2019) 389–400.
[85] B.A. Graybeal, Compressive behavior of ultra-high-performance fiber-reinforced concrete, Acids Mater. J. 104 (2) (2007) 146.
[86] P. Ganesh, A.R. Murthy, Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material, Constr. Build. Mater. 197 (2019) 667–680.
[87] W. Meng, M. Valipour, K.H. Khayat, Optimization and performance of cost-effective ultra-high performance concrete, Mater. Struct. 50 (1) (2017) 1–16.
[88] H. Abdolpour, P. Niewiadomski, Ł. Sadowski, Recycling of steel fibres and spent equilibrium catalyst in ultra-high performance concrete: literature review, research gaps, and future development, Constr. Build. Mater. 309 (2021), 125147.
[89] A. ASTM, C150/C150M-20 Standard Specification for Portland Cement, ASTM,, West Conshohocken, PA, USA, 2020.
[90] H.F. Taylor, Cement chemistry, Thomas Telford London1997.
[91] N.M. Azmee, N. Shafiq, Ultra-high performance concrete: from fundamental to applications, Case Stud. Constr. Mater. 9 (2018), e00197.
[92] A. Wetzel, B. Middendorf, Influence of silica fume on properties of fresh and hardened ultra-high performance concrete based on alkali-activated slag, Cem. Concr. Compos. 100 (2019) 53–59.
[93] J.A. Rossignolo, Effect of silica fume and SBR latex on the pasteaggregate interfacial transition zone, Mater. Res. 10 (1) (2007) 83–86.
[94] C. Shi, S. Hu, Cementitious properties of ladle slag fines under autoclave curing conditions, Cem. Concr. Res. 33 (11) (2003) 1851–1856.
[95] P. Máca, R. Sovják, P. Konvalinka, Mix design of UHPFRC and its response to projectile impact, Int. J. Impact Eng. 63 (2014) 158–163.
[96] Y.-W. Chan, S.-H. Chu, Effect of silica fume on steel fiber bond characteristics in reactive powder concrete, Cem. Concr. Res. 34 (7) (2004) 1167–1172.
[97] N. Van Tuan, G. Ye, K. Van Breugel, A.L. Fraaij, D. Dai Bui, The study of using rice husk ash to produce ultra high performance concrete, Constr. Build. Mater. 25 (4) (2011) 2030–2035.
[98] F. Sanchez, K. Sobolev, Nanotechnology in concrete–a review, Constr. Build. Mater. 24 (11) (2010) 2060–2071.
[99] Y. Qian, Characterization of structural rebuilding and shear migration in cementitious materials in consideration of thixotropy, Columbia University2017.
[100] I. Gosens, J.A. Post, L.J. de la Fonteyne, E.H. Jansen, J.W. Geus, F.R. Cassee, W.H. de Jong, Impact of agglomeration state of nano-and submicron sized gold particles on pulmonary inflammation, Part. Fibre Toxicol. 7 (1) (2010) 1–11.
[101] Z. Wu, K.H. Khayat, C. Shi, B.F. Tutikian, Q. Chen, Mechanisms underlying the strength enhancement of UHPC modified with nano-SiO2 and nano-CaCO3, Cem. Concr. Compos. 119 (2021), 103992.
[102] M.S. Konsta-Gdoutos, Z.S. Metaxa, S.P. Shah, Highly dispersed carbon nanotube reinforced cement based materials, Cem. Concr. Res. 40 (7) (2010) 1052–1059.
[103] A. Peyvandi, P. Soroushian, N. Abdol, A.M. Balachandra, Surface-modified graphite nanomaterials for improved reinforcement efficiency in cementitious paste, Carbon 63 (2013) 175–186.
[104] K. Sobolev, M.F. Gutiérrez, How nanotechnology can change the concrete world: part two of a two-part series, Am. Ceram. Soc. Bull. 84 (11) (2005) 16–19.
[105] S. Ma, Y. Qian, S. Kawashima, Experimental and modeling study on the non-linear structural build-up of fresh cement pastes incorporating viscosity modifying admixtures, Cem. Concr. Res. 108 (2018) 1–9.
[106] N. Hamed, M. El-Feky, M. Kohail, E.-S.A. Nasr, Effect of nano-clay de-agglomeration on mechanical properties of concrete, Constr. Build. Mater. 205 (2019) 245–256.
[107] P. Li, Q. Yu, H. Brouwers, Effect of coarse basalt aggregates on the properties of Ultra-high Performance Concrete (UHPC), Constr. Build. Mater. 170 (2018) 649–659.
[108] M. Alkaysi, S. El-Tawil, Z. Liu, W. Hansen, Effects of silica powder and cement type on durability of ultra high performance concrete (UHPC), Cem. Concr. Compos. 66 (2016) 47–56.
[109] K.-Y. Liao, P.-K. Chang, Y.-N. Peng, C.-C. Yang, A study on characteristics of interfacial transition zone in concrete, Cem. Concr. Res. 34 (6) (2004) 977–989.
[110] J. Ma, M. Orgass, F. Dehn, D. Schmidt, N. Tue, Comparative investigations on ultra-high performance concrete with and without coarse aggregates, Int. Symp. . Ultra High. Perform. Concr., Kassel, Ger. (2004) 205–212.
[111] J. Fládr, P. Bílý, Specimen size effect on compressive and flexural strength of high-strength fibre-reinforced concrete containing coarse aggregate, Compos. Part B: Eng. 138 (2018) 77–86.
[112] S. Yang, S. Millard, M. Soutsos, S. Barnett, T.T. Le, Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC), Constr. Build. Mater. 23 (6) (2009) 2291–2298.
[113] D.P. Bentz, C.F. Ferraris, S.Z. Jones, D. Lootens, F. Zunino, Limestone and silica powder replacements for cement: early-age performance, Cem. Concr. Compos. 78 (2017) 43–56.
[114] R. Yang, R. Yu, Z. Shui, X. Gao, X. Xiao, D. Fan, Z. Chen, J. Cai, X. Li, Y. He, Feasibility analysis of treating recycled rock dust as an environmentally friendly alternative material in ultra-high performance concrete (UHPC), J. Clean. Prod. 258 (2020), 120673.
[115] W. Meng, K. Khayat, Effects of saturated lightweight sand content on key characteristics of ultra-high-performance concrete, Cem. Concr. Res. 101 (2017) 46–54.
[116] K. Liu, R. Yu, Z. Shui, X. Li, X. Ling, W. He, S. Yi, S. Wu, Effects of pumice-based porous material on hydration characteristics and persistent shrinkage of ultra-high performance concrete (UHPC), Materials 12 (1) (2018) 11.
[117] S.-D. Hwang, K.H. Khayat, D. Youssef, Effect of moist curing and use of lightweight sand on characteristics of high-performance concrete, Mater. Struct. 46 (1) (2013) 35–46.
[118] C. Schröfl, M. Gruber, J. Plank, Preferential adsorption of polycarboxylate superplasticizers on cement and silica fume in ultra-high performance concrete (UHPC), Cem. Concr. Res. 42 (11) (2012) 1401–1408.
[119] A. Feylessoufi, M. Crespin, P. Dion, F. Bergaya, H. Van Damme, P. Richard, Controlled rate thermal treatment of reactive powder concretes, Adv. Cem. Based Mater. 6 (1) (1997) 21–27.
[120] T. Hirschi, F. Wombacher, Influence of different superplasticizers on UHPC. Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel University Press,, Kassel, 2008, pp. 77–84.
[121] M. Courtial, M.-N. de Noirfontaine, F. Dunstetter, M. Signes-Frehel, P. Mounanga, K. Cherkaoui, A. Khelidj, Effect of polycarboxylate and crushed quartz in UHPC: Microstructural investigation, Constr. Build. Mater. 44 (2013) 699–705.

[122] M. Ilg, J. Plank, Non-adsorbing small molecules as auxiliary dispersants for polycarboxylate superplasticizers, Colloids Surf. A: Physicochem. Eng. Asp. 587 (2020), 124307.
[123] P. Li, Q. Yu, H. Brouwers, Effect of PCE-type superplasticizer on early-age behaviour of ultra-high performance concrete (UHPC), Constr. Build. Mater. 153 (2017) 740–750.
[124] L. Shu-hua, L. Li-hua, F. Jian-wen, Study on mechanical properties of reactive powder concrete, J. Civ. Eng. Constr. 1 (1) (2012) 6–11.
[125] S.-T. Kang, Y. Lee, Y.-D. Park, J.-K. Kim, Tensile fracture properties of an ultra high performance fiber reinforced concrete (UHPFRC) with steel fiber, Compos. Struct. 92 (1) (2010) 61–71.
[126] V.Y.G. Yanni, Multi-scale investigation of tensile creep of ultra-high performance concrete for bridge applications, Georgia Institute of Technology2009.
[127] D. Dupont, L. Vandewalle, Distribution of steel fibres in rectangular sections, Cem. Concr. Compos. 27 (3) (2005) 391–398.
[128] C. Qian, P. Stroeven, Development of hybrid polypropylene-steel fibre-reinforced concrete, Cem. Concr. Res. 30 (1) (2000) 63–69.
[129] S.H. Park, D.J. Kim, G.S. Ryu, K.T. Koh, Tensile behavior of ultra high performance hybrid fiber reinforced concrete, Cem. Concr. Compos. 34 (2) (2012) 172–184.
[130] D.J. Kim, S.H. Park, G.S. Ryu, K.T. Koh, Comparative flexural behavior of hybrid ultra high performance fiber reinforced concrete with different macro fibers, Constr. Build. Mater. 25 (11) (2011) 4144–4155.
[131] S.T. Kang, B.Y. Lee, J.-K. Kim, Y.Y. Kim, The effect of fibre distribution characteristics on the flexural strength of steel fibre-reinforced ultra high strength concrete, Constr. Build. Mater. 25 (5) (2011) 2450–2457.
[132] S.J. Barnett, J.-F. Lataste, T. Parry, S.G. Millard, M.N. Soutsos, Assessment of fibre orientation in ultra high performance fibre reinforced concrete and its effect on flexural strength, Mater. Struct. 43 (7) (2010) 1009–1023.
[133] C. Shi, Z. Wu, J. Xiao, D. Wang, Z. Huang, Z. Fang, A review on ultra high performance concrete: Part I. Raw materials and mixture design, Constr. Build. Mater. 101 (2015) 741–751.
[134] S. Kwon, T. Nishiwaki, T. Kikuta, H. Mihashi, Development of ultra-high-performance hybrid fiber-reinforced cement-based composites, Acids Mater. J. 111 (3) (2014) 309.
[135] L. Sorelli, G. Constantinides, F.-J. Ulm, F. Toutlemonde, The nano-mechanical signature of ultra high performance concrete by statistical nanoindentation techniques, Cem. Concr. Res. 38 (12) (2008) 1447–1456.
[136] R. Yu, P. Spiesz, H. Brouwers, Development of ultra-high performance fibre reinforced concrete (UHPFRC): towards an efficient utilization of binders and fibres, Constr. Build. Mater. 79 (2015) 273–282.
[137] A. Soliman, M. Nehdi, Effects of shrinkage reducing admixture and wollastonite microfiber on early-age behavior of ultra-high performance concrete, Cem. Concr. Compos. 46 (2014) 81–89.
[138] S. Kwon, T. Nishiwaki, H. Choi, H. Mihashi, Effect of wollastonite microfiber on ultra-high-performance fiber-reinforced cement-based composites based on application of multi-scale fiber-reinforcement system, J. Adv. Concr. Technol. 13 (7) (2015) 332–344.
[139] D.-Y. Yoo, J.-H. Lee, Y.-S. Yoon, Effect of fiber content on mechanical and fracture properties of ultra high performance fiber reinforced cementitious composites, Compos. Struct. 106 (2013) 742–753.
[140] N. Ganesan, P. Indira, M. Sabeena, Behaviour of hybrid fibre reinforced concrete beam–column joints under reverse cyclic loads, Mater. Des. (1980-2015) 54 (2014) 686–693.
[141] K. Turker, U. Hasgul, T. Birol, A. Yavas, H. Yazici, Hybrid fiber use on flexural behavior of ultra high performance fiber reinforced concrete beams, Compos. Struct. 229 (2019), 111400.
[142] I. Yang, C. Joh, B. Kim, Flexural strength of ultra high strength concrete beams reinforced with steel fibers, Procedia Eng. 14 (2011) 793–796.
[143] P. Aghdasi, A.E. Heid, S.-H. Chao, Developing ultra-high-performance fiber-reinforced concrete for large-scale structural applications, Acids Mater. J. 113 (5) (2016).
[144] Z. Wu, C. Shi, W. He, D. Wang, Uniaxial compression behavior of ultra-high performance concrete with hybrid steel fiber, J. Mater. Civ. Eng. 28 (12) (2016), 06016017.
[145] H. Bahmani, D. Mostofinejad, S.A. Dadvar, Effects of synthetic fibers and different levels of partial cement replacement on mechanical properties of UHPFRC, J. Mater. Civ. Eng. 32 (12) (2020), 04020361.
[146] Y. Ye, S. Hu, B. Daio, S. Yang, Z. Liu, Mechanical behavior of ultra-high performance concrete reinforced with hybrid different shapes of steel fiber, CICTP 2012: Multimodal Transp. Syst., Safe, Cost. -Eff., Effic. (2012) 3017–3028.
[147] R. Sharma, P.P. Bansal, Efficacy of supplementary cementitious material and hybrid fiber to develop the ultra high performance hybrid fiber reinforced concrete, Adv. Concr. Constr. 8 (1) (2019) 21–31.
[148] G. Ren, B. Yao, H. Huang, X. Gao, Influence of sisal fibers on the mechanical performance of ultra-high performance concretes, Constr. Build. Mater. 286 (2021), 122958.
[149] K. Zhang, T. Ni, G. Sarego, M. Zaccariotto, Q. Zhu, U. Galvanetto, Experimental and numerical fracture analysis of the plain and polyvinyl alcohol fiber-reinforced ultra-high-performance concrete structures, Theor. Appl. Fract. Mech. 108 (2020), 102566.
[150] Z. Wu, C. Shi, K.H. Khayat, Investigation of mechanical properties and shrinkage of ultra-high performance concrete: influence of steel fiber content and shape, Compos. Part B: Eng. 174 (2019), 107021.