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Review

A review study on sustainable development of ultra high-performance concrete

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Abstract: A systematic literature review was undertaken in this report to illustrate the development concepts and properties of ultra-high performance concrete (UHPC). UHPC's affluent development relies on its compositional content, water–binder (w/b) ratio, and design mix approach, which contributes to denser and comparatively more homogeneous packaging of particles. Numerous research studies from around the world were used to compile a database on UHPC mechanical and durability properties. Moreover, the results of this study reveal that the curing conditions, aggregates, fibre dosage and characteristics, and curing time are the most important elements in determining the mechanical and durability qualities of UHPC. Furthermore, due to its ultra-high-strength features, superior fatigue behavior, and extremely low porosity, UHPC is considered a practical and long-term alternative for improved sustainable building, resulting in increased resilience to hostile environments. Besides that, attempts are being taken to resolve existing challenges (such as high initial costs, a lack of skills, and a lack of design code) and their solutions to their widespread economic use. This study aims to help architects, builders, and other construction stakeholders better grasp UHPC's basic features and capacities, which will help to understand this durable and long-lasting building material.

Keywords: sustainable materials; ultra-high performance concrete; mechanical properties; durability; particle packing; water/binder ratio

1. Introduction

1.1. Background

Significant advancements in the field of concrete production have, however, been made over the course of the last several decades. Starting in the early 1930s, a concerted effort was made to increase the compressive strength of concrete. Concrete technology evolved slowly during the 1960s, with maximum compressive strengths ranging from 15 to 20 MPa. Over a ten-year period, the concrete compressive strength increased, from 45 to 60 MPa. Because of the technological obstacle of the present water reducer, concrete strength approaches a peak about 60 MPa in the early 1970s [1].

The granular skeleton's grain size distribution was chosen to attain a compressive strength of at least 280 MPa. To improve ultimate strength and durability, researchers developed a material with a limited number of flaws, such as interwoven pore gaps and micro cracks. A composite with a compressive strength of 240 MPa and a w/b ratio of 0.2 was developed in 180 days in the 1970s, whereas today's composites take years to develop [2].

Because of a growing demand for high-strength concrete in the construction industry, the development of ultra-high performance concrete (UHPC), also known as reactive powder concrete, was encouraged [3–8]. One of the most significant breakthroughs in civil engineering history was the invention of UHPC [9]. Richard and Cheyrezy [3] defined ultra-high-performance concrete (UHPC) as a new building material with improved mechanical and durability properties that can lead to cost-effective construction by reducing cross-sections of structural members, resulting in material savings and lower installation and labour costs [10].

UHPC is noted for its excellent material ductility and high strength when reinforced with steel fibres. Currently, thorough examination of raw ingredients, as well as specialised mixing and curing procedures, are necessary to attain these material qualities [11]. To increase strength, coarse aggregate is removed to improve homogeneity; high amounts of superplasticizer or water reducing agents are used to achieve low w/b ratios; and specially graded sands, silica fume, and glass powders are used to reduce porosity, improve particle-packing density, and ultimately increase strength.

It has a very low permeability to maximize strength, which improves the material's resistance to oxidation and corrosion, which is common in reinforced concrete and steel structures [12]. UHPC is suitable for base and column construction because it can achieve higher compressive strength due to material use minimization and strength optimization. It is also suitable for the construction of beams due to its improved flexure, shear, and torsion resistance. Furthermore, because of its high impact resistance, high strength, improved ductility, increased corrosion, and chemical resistance, UHPC is ideal for blasting efficiency, seismic and environmental protection [12,13]. These excellent UHPC properties result in structural weight reduction, which allows for the construction of slender structures. It also outperforms conventional concrete when exposed to blast, impact, and seismic loads [14].

1.2. Environmental impact

Cement manufacturing has increased dramatically in recent years, and it is now the third-largest source of human carbon dioxide emissions, after fossil fuels and land-use change. For the next few decades, one of the most pressing sustainability issues will be the design and manufacture of concrete that uses less clinker and emits less CO_2, while also providing the same level of reliability and durability [15]. The ultra-high performance fiber reinforced concrete (UHPFRC) gives the promising success of its application for several rehabilitation work for existing structures like bridges, culverts, since 1999, and has appeared as one of the contestants for reducing the global warming impact.

Efforts to introduce UHPC have been made all over the world with great success. However, there are still roadblocks in the way of its implementation. Continuous study and research activities fill holes to undertake creative, accessible, viable, feasible, and economical UHPCs in the future, as they will have a huge effect on increasing acceptance. The primary goal of this paper is to summarize recent developments to provide insight into this ultra-beneficial material by providing a general introduction to UHPC, as well as current information on its concept, applications, growth, and challenges.

2. Principle of development of UHPC

It is a cementitious material that is relatively new in terms of strength, ductility, and durability [3]. Fiber-reinforced UHPC, as explained from [16], is a hybrid of three technologies: fibre reinforced concrete (FRC), high-performance concrete (HPC) and self-compacting concrete (SCC). The following ideas have been generalized from the concepts demonstrated by the authors in [16], which are as illustrated in Figure 1. According to the recommendations from the Interim French President [17], UHPC is a concrete with at least 150 MPa compressive strength and steel fibre reinforcement to ensure ductility under tension.

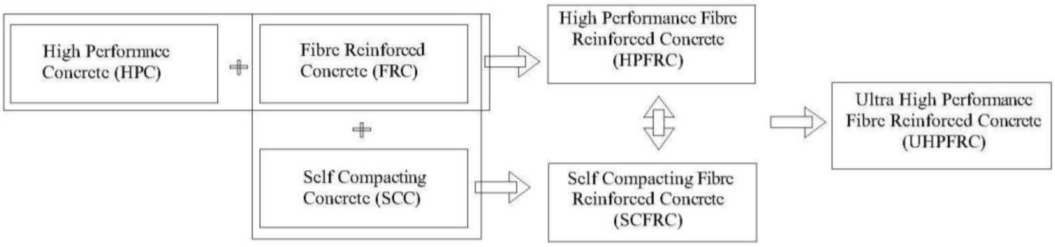

Figure 1. Development of UHPFRC accomplished through the combination of special concrete.

2.1. UHPC production principles

Several researchers have worked together to get UHPC to a point where it is ready for use after 15 years of phenomenal progress. Compressive strength for a built UHPC could exceed 200 MPa. In the 1980s, it has already been proposed to make concrete with a high strength potential and dense microstructure [18].

The practical milestone was achieved following the invention of efficient SP, which allows for the production of high-percentage easy-flowing concrete from optimally packed ultra-fine particles with extremely low w/b ratio to reduce composite porosity. Several researchers like Schmidt and Fehling [19], Richard and Cheyrezy [3] and Rossi [20] have recognize the basic concept of UHPC architecture, which can be summarized as follows:

- Heat treatment improves the microstructure;

- Increased ductility by adding small steel fibres;
- Improved homogeneity by eliminating coarse aggregate;
- Optimized granular mixture by a large distribution of powder size groups and lowering the w/b ratio.

Steel fibers are added to increase tensile strength and ductility and applying these four concepts results in exceptionally high compressive strength [3]. In the recognition of UHPC microstructure important component are quartz powder, hydration materials (such as calcium silicate hydrate gel) and unhydrated cement clinker [21]. UHPC's interfacial transition zone (ITZ) is less porous, light weight and distinctively dense in comparison to traditional concrete. Buttignol et al. [22], on the other hand, describes ITZ as a weak region with a higher w/b ratio and substantial amount of CH crystals across the aggregates, making it extremely porous. Maximum CH crystals are converted into thick CSH gels due to low w/b and pozzolanic reactions between CH and reaction admixtures [23]. Because of the close packaging of solid particles and the improved ITZ, UHPC has an innovative microstructure. The second theory required for the development of UHPC is to increase homogeneity. A paste matrix and aggregates in conventional concrete have varying mechanical and thermal properties as well as varied tensile and shear stresses which causes a micro-level crack in the ITZ. However, these cracks are proportional to aggregate size, so while reducing the aggregate size in UHPC, size of the crack reduces. This demonstrates the increased homogeneity of the UHPC mixes.

The reduction of porosity is the third critical concept. Lowering the w/b ratio of concrete, which can also be achieved by using SP, fine admixtures, or very similar packaging of the raw materials, can minimize porosity and result in a stronger matrix [24].

The final concept notes that UHPC must be extremely durable, i.e., the material must be able to withstand energy absorption without fracturing. Concrete is naturally brittle and has poor tensile strength and crack resistance [25]. As a result, fibers are the most important factor in UHPC's excellent impact resistance and longevity, which is inserted in the concrete system to prevent and track the initiation and progression of cracks. Table 1 shows the variations between conventional concrete and UHPC.

Table 1. Distinction between conventional concrete and UHPC [26–28].

Properties	Normal traditional concrete	UHPC
Compressive strength (MPa)	22–40	100–200
Tensile strength (MPa)	<5	Upto 22
Flexural strength (MPa)	<6	45
Ductility	Nil	Highly ductile
Impact loading	<UHPC	Tough
Abrasion resistance	<UHPC	Tough like a rock
Impermeability	Steady carbonation, chloride penetration	Nil

2.2. UHPC mixture compositions

The primary objective of UHPC manufacturing is to improve mixture ingredient properties (i.e. macro and micro) to ensure homogeneity, optimum particle packing density, and minimum fault size [7,16,19,29]. The preferred UHPC structure is decided by the material's required physical and chemical qualities, as well as the relative proportions of different grain sizes. The initial cost of UHPC is significantly higher than that of standard concrete, however significant efforts have been made to reduce material prices while maintaining UHPC's beneficial features. The spectrum of UHPC constituents used in active UHPC efficiency evaluations is shown in Table 2.

Table 2. Typical composition adopted by various author for UHPC [27,30–32].

S.N.	UHPC constituents		Range (% by weight)
1	Cementitious material	Cement	25–40
		Silica fume	5–12
		Quartz powder	8–14
2	Sand		32–45
3	Super plasticizer (SP)		0.6–3
4	Water content		5–10
5	Steel fiber		0–7

2.2.1. Binder

In comparison to conventional strength concrete and high performance concrete, UHPC contains a higher proportion of cement [19,33]. Increased cement content has been shown to increase UHPC compressive strength; however, compressive strength tends to decrease outside of the maximum cement content due to restricted aggregate participation [30]. Because of the reduced water demand, cement with a moderate specific surface area and a C_3A content of less than 6% is recommended [7]. In the production of UHPC, special micro-fine cements are used which is having particle sizes smaller than normal [34].

However, since silica fume particles are thinner than cement particles, they are a stronger filler material for growing the packing density of the concrete matrix [35]. As it interacts with calcium hydroxide, it generates a denser CSH gel with greater strength and lower porosity (CH). Furthermore, some research recommended using a silica fume dose of 20–30% of the total binder content in UHPC to promote denser particle packing and pozzolanic reactions [23]. A dosage of 25% low carbon cement (0.5%) silica fume has been suggested as an acceptable dosage for UHPC, for example [7].

Several studies indicated the use of binder/recycled materials, fly ash (FA) is considered as one of the salient pozzolanic materials which has the tendency to increase the compressive strength at later ages of concrete and aids in increasing fresh concrete flow capacity, setting time, permeability on cement [36]. MK, GGBFS, RHA, nanoparticles etc. are some of the cement substitutes that contribute significantly to the improvement of the properties of UHPC mixes. As a cement substitute, MK can increase flexural strength, decrease autogenous shrinkage but marginally reduce compressive strength [37]. In contrast to silica fume, RHA has no effect on UHPC compressive strength; additionally, increasing RHA reduces shrinkage [38]. GGBFS or slag powder is also a by-product of iron and steel plants, including alumina, silica, lime, magnesia, and iron oxide. It improves structure stability by providing greater resistance to sulphate attack and chloride penetration, as well as lowering the risk of damage from alkali-silica reactions [39].

Nanoparticles i.e., nano-silica, nano-iron, etc. have the highest ratio of surface to volume of any cement component, according to Sobolev and Gutierrez [40] (Figure 2). They may also act as a filler material to increase density of the microstructure and promote further cement hydration by acting as a cement phase nucleus due to their high reactivity. Compressive and flexural strength are greatly increased when these nanomaterials are used in UHPC. Since nano-silica is so thin, it fills the gaps between the SF and the cement particles, resulting in a very thick matrix. As a result, the mechanical and reliability properties of UHPC would be greatly improved [35,41]. Because of the decrease in porosity, the density and homogeneity of the microstructure have improved. Wu et al. [41,42] recorded an improvement in the bond intensity and pull-out energy of fiber enhanced UHPC after the incorporation of nano-silica and nano-$CaCO_3$. However, this improvement in microstructure was only seen before hitting the optimum dose, which was 3.2% for nano-$CaCO_3$ and 1% for nano-silica. As a result of agglomeration concerns, these nanomaterials increased porosity, resulting in reduced UHPC efficiency.

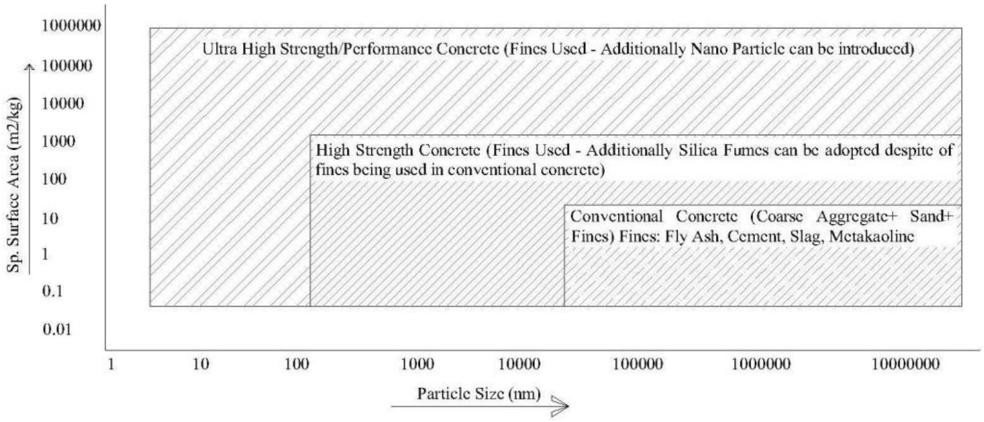

Figure 2. Comparative study between different concrete materials.

Due to the low w/b ratio, UHPC's reduced operability can be overcome by adding strong super plasticizers (SP). The amount of SP required is determined by the consistency of the mixture's ingredients as well as the form of SP used. Lowering the SP dosage can result from improved compatibility. Going to delay the inclusion of SP (rather than doing so all at once) improves the workability of UHPC mixtures by improving the dispersing action [43]. The Super plasticizer selection is influenced by the type of binder used in the manufacturing of UHPC [44]. Table 3 defined the variation of w/b ratio, Super plasticizer and specific surface area denoted by various authors.

Table 3. Typical variation of w/b ratio, SP and specific surface area [9,33,37,45,46].

Binder material used in UHPC composition	W/B ratio	SP (kg/m^3)
Nano silica (160 m^2/g)*	0.24–0.26	17–18
Silica fumes (18–26 m^2/g)*	0.16–0.27	18–27
GGBS (0.670 m^2/g)*	0.16–0.236	11–13
MK (15–30 m^2/g)*	0.22–0.27	22–27
Fly ash (21–22 m^2/g)*	0.22–0.25	35–40
RHA (50–52 m^2/g)*	0.18–0.236	10–17

*Specific surface area.

2.2.2. Aggregates

Aggregates are called an inert substance that is important in determining the dimensional stability of concrete. The failure of traditional concrete, including its elastic and thermal properties, is normally caused by internal damage that occurs between the cementitious matrixes and aggregates at the interfacial transfer zone (ITZ) [47]. The removal of coarse aggregates in UHPC, on the other hand, eliminates the weaknesses created by such ITZs. Furthermore, reducing ITZ defects reduces overall matrix porosity and improves mechanical strength [48].

The best aggregates for UHPC mix have high mechanical strength, well-graded distribution and are free of contaminants such as clay, silt, chemicals, and other contaminants, so the strength, porosity, density and hydration process of the concrete are not affected.

Natural sand, recycled glass cullet, Silica sand, quartz sand, iron ore tailings and crushed basalt, are among some of the aggregates currently used in UHPC production [15]. The fine aggregate, like quartz powder, determines the thickness of the paste (MPT). Iron ore tailing is a non-combustible substance with a particle size bigger than that of cement. As a result, it can be employed as a fine aggregate in the production of UHPCs [49].

2.2.3. Fibers

UHPC is very brittle because of high strength and homogeneity; but its ductility can be improved by addition of fibers [50,51]. Inside the concrete matrix, the added fibres provide greater resistance to crack generation and propagation. Fibres may be graded as defined in Table 4, according to the ACI 544.1R-96 [52].

Table 4. Typical properties of fibres as reported by several authors [15,52].

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

3. Mix design approaches

A thorough investigation of the mixing duration, speed, temperature, and mixing sequence in UHPC is required in order to provide optimal attributes in this system. In addition to creating a dense matrix structure, lower porosity, internal microstructure growth, and better mechanical and durability characteristics, the UHPC mixture design should be cost-effective and sustainable [31]. The main parameters that are initially considered for design to achieve enhanced homogeneous, microstructure with dense and ductile characteristics are optimization of granular mixtures, eliminate coarse aggregate, and proper integration of fibers [53]. The aim of the UHPC mix design is to eliminate pore spaces and defects in the final matrix of the micro cracks. Table 5 shows various model approaches widely used in the design of the UHPC mix.

Table 5. Various model techniques for mix design of UHPC.

Model	Important observations
Linear packing density model [54]	It is based on linear nature of model
Solid suspension model [54]	It depends on virtual density theory
Modified andreasen and andersen model [8]	Ingredients of the mix optimized by different distribution modules
Locally produced UHPC mixture [55]	This mixture module based on the shape, size and density of particles
Ecological UHPC mixture [56]	It depends on the method of particle packing density which in turn reduces cement content by 50%
Lohas & ramge model [57]	It depends on a SP to achieve the optimal paste workability depending on the w/b ratio
Modified andreasen & andersen particle packing model [8]	UHPC has been produced with less cement content (675 kg/m^3)
Statistical mixture design model [33]	To optimise the model of the UHPC mixture
Artificial neural network models [33]	Developed to predict UHPC performance under various curing conditions
Polynomial regression model [33]	Appropriate to predict the desirable properties of UHPC mix
The D-optimal design model [58]	A good correlation with experimental results was reported

To get a suitable mix design of UHPC, there are following parameters which are helpful to obtain an optimized mix design of UHPC.

3.1. Packing density

It is nowadays very clear that the single most important parameter influencing the performance of concrete is the packing density of the aggregate. The packing density of a given aggregate, or a given lump of solid particles is the ratio of the volume of solids to the bulk volume of the solid particles. Since the bulk volume is equal to the volume of solids plus the volume of voids, a higher packing density means a smaller volume of voids to be filled and vice versa. Packing density of aggregate and cementitious particle can be effectively improved by distribution of size, shape, and texture [59]. Furthermore, the improvement in ingredient packaging and lower w/b ratio will result in increased strength and lower UHPC bleeding, porosity, permeability, segregation, and shrinkage [59,60]. As a result, by enhancing its hardened and reliability characteristics as well as optimizing the packing density, the overall UHPC performance will be improved.

Furthermore, the principles of particle packing can be used to improve the density and flow ability of a mix by incorporating specially graded components [54].

3.2. Water–binder (w/b) ratio

It is a significant consideration when evaluating the fresh and hardened qualities of a material. In the case of UHPC concrete, the water–binder ratio is less than that of conventional concrete. As the w/b ratio drops, the distance between adjacent binder particles reduces, implying that the hydrates of one particle must shrink to reach the hydrates of surrounding particles. It also improves the hydration of the product and densifies the microstructure of the UHPC, resulting in increased mechanical strength and durability of the product [61]. A concrete mix's packing density is also inversely proportional to its w/b ratio. However, as the w/b ratio decreases, the voids between the particles decrease in result increase the packing density and implying greater strength and decreased permeability (Figure 3) [26].

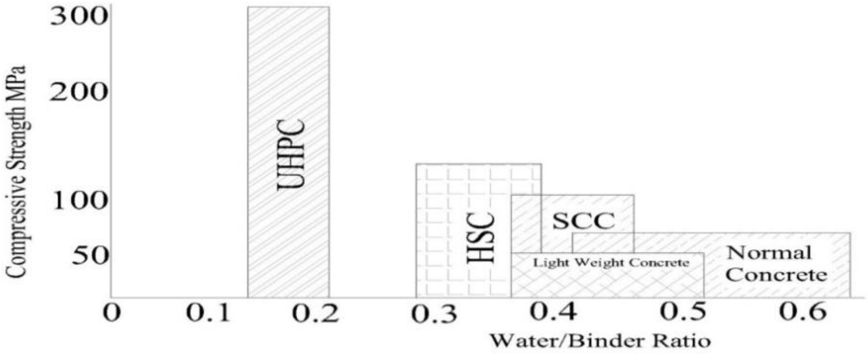

Figure 3. Compressive strength and water–binder relationship for different concretes.

According to Richard and Cheyrezy [3], the w/b ratio was 0.08. This ratio, on the other hand, did not result in tight particle packing. Many researcher's studies suggested that the w/b ratio should be in the 0.13–0.20 range [3,15,54]. However, author like Wille et al. [7], adopted a w/b ratio of 0.25 to reach compressive strength greater than 150 MPa. Therefore, w/b is not the only factor affecting the strength parameter.

3.3. Curing condition

Additionally, specialised mixing and curing techniques can improve material properties, such as:

(a) Fine particle dispersion and admixture blending can be improved by using a high-intensity mixer [62].

(b) Multi-stage curing techniques, such as steam curing, can boost strength and speed up the strength gain process.

(c) Applying pressure during the setting process can help to reduce porosity while increasing strength [63,64].

While UHPC with strengths more than 200 MPa [65] and 500 MPa [63,64] can be produced utilizing very sophisticated materials, mixing, and curing procedures, the greater complexity and hence cost of creating UHPC limits its general use.

If we talk about curing conditions and types like heat curing, regular curing, and autoclave curing are the three standard methods for manufacturing UHPC [15]. Normal curing at room temperature imparts the average duration of the CSH chain for pozzolanic reactions and hydration [28]. In comparison to other options, it is the most environmentally and economically viable. Furthermore, the results revealed that traditional curing is more effective than steam curing, while autoclave curing yielded intermediate results [66]. When compared to other methods of enhancing strength, autoclave curing is by far the most efficient method available. Even though it can attain compressive strength of 200 MPa in just eight hours of steam curing at high temperature and pressure, it reduces the UHPC flexural strength of the material [67].

Since this UHPC mixes has a 160 MPa compressive strength at 20 ºC in 90 days, steam and wet curing are more efficient, while both wet (20 ºC in 90 days) and steam (90 ºC in 90 days) have a 200 MPa compressive strength [68]. In a similar way, Wu et al. [41] found that steam curing and hot water had higher flexural and compressive properties than regular curing with an optimum content of 40% GGBFS or 20% FA than regular curing. Autoclave curing (@200ºC) is the foremost method for achieving full matrix bonding strength, according to Zhang et al. [28], whereas water curing (@20ºC) is the least preferred method. The bond strength achieved during stream curing is comparable to that achieved during water curing but slightly lower than that obtained during autoclave curing. It is common to perform thermal treatment on UHPC because it avoids shrinkage and creep, accelerates the rate of strength expansion, and boosts the overall durability of the treatment process [16]. Despite these advantages, the high cost and energy consumption habits of the technology prevent wider use [69].

4. Fresh properties

4.1. Air content

The total air content of the UHPC mix will increase with increasing w/b and SP doses. Similarly, the overall air content is heavily influenced by the form of mix employed [70]. Depending on the form of mixture, the declared air content in UHPC combinations ranged from 0.3% to 5.4% by volume of blend. Laboratory mixers with a greater blending speed, for example, increase the air content in the paste, making it stickier (normally 4.3%). For improved spread flow and features of UHPC mixtures, a threshold value of 2% air content by mix volume has been proposed as a starting point [7]. In comparison, ring-type mixers apply high shear forces in precast plants, resulting in a nearly lower air content (around 3.2%) with comparable mixture structure and extents. A vacuum accessory able to achieve less than 1% air content in UHPC was reported to have a pressure of 50 mbar. The process of laying concrete has a huge effect on air quality. For example, spiral pumping concrete into formwork reduced air content from 2.9% to 1.3% [71]. Delaying the addition of SP lowered the viscosity of the UHPC mixture, and the air concentration was reduced from 2.5% to 1% [43].

4.2. Setting time

Graybeal [50] recorded an initial setting time of 3.45 MPa penetration resistance 15 hours after casting and a final setting time of 27.60 MPa penetration resistance 18–20 hours after casting. Depending on the type of the mixture, UHPC's observed setting time ranged from 6 to 12 hours [3,70,72]. However, due to the fixed retarding impact of the high SP dose, a few studies have revealed that the UHPC setup time can be delayed by up to 30–40 hours [5,73]. Furthermore, it was discovered that a new batch of UHPC surface covering postponed its setting time [72].

4.3. Workability

UHPC handling is a big difficulty during casting due to its low w/b and poor workability. Steel fibres have a detrimental impact on UHPC's workability. According to research, mixtures containing fibres with a lower aspect ratio are more workable than mixtures containing fibres with a higher aspect ratio. The workability of steel fibres can be improved by using shorter steel fibres with 0.15 mm diameter and longer steel fibres with 0.15 mm diameter. Steel fibres with 12 mm and 0.15 mm diameter can be used with up to 3% of the total mixture volume without affecting the workability. Steel fibres with 0.15 mm diameter and a length of 6 mm can be used with up to 10% of the total mixture volume without impacting the workability [7,74]. Furthermore, for lightweight UHPC without fibres, Wille et al. [7] suggested a flow diameter spread of 200–350 mm. Furthermore, using nano-particle materials will improve the spread flow. For example, adding 1% cement weight of nano-silica resulted in a 16% increase in spread flow [75].

5. Mechanical properties

5.1. Compressive strength

UHPC has a compressive strength of around 150 MPa or even higher than standard concrete. Under compressive loading, the UHPC and UHPFRC are thought to behave very differently. Fibres do not play a significant role in improving compressive strength, but they do give concrete a ductile quality due to their restraining and confining effect [76]. In addition, the sample size has a substantial impact on the estimated compressive strength of UHPC, which was measured in this study. Skazlic et al. [77] discovered a 21% improvement in cylinder compressive strength for a specimen with dimensions of 70 mm × 140 mm when compared to a specimen with dimensions of 100 mm × 200 mm. Furthermore, due to the strong confinement effect of the testing machine platens, cube specimens outperformed cylindrical specimens in terms of overall strength [6,71]. Additionally, Alsalman et al. [32] stated that compressive strength of specimen is increased by 4–8% while addition of 3% steel fibres. The inclusion of fine added materials in the mix design can result in an increase in the compressive strength of the concrete. Copper slag (CS) will cure in 28 days and produce an ultra-high-performance concrete (UHPC) with a compressive strength of 150 MPa as a waste material [78]. Using 5% SF as a binder material will also result in a compressive strength of 155 MPa after 90 days when utilized as a binder material. SF greater than 10%, on the other hand, shows no discernible increases in compressive strength, yielding strength equivalent to a 5% SF addition [32]. FA and coal bottom ash (CBA) are two other industrial by-products that can help with strength growth. Due to its highly amorphous structure and pozzolanic reaction, coal bottom ash can provide increased compressive strength after 28 days [39]. Several other admixtures like glass powder (GP) used by Soliman and Hamou [79] with the view to make an environmentally sustainable UHPC, producing 20% and 50% GP as the best cement alternative in terms of compressive strength and flow ability, respectively.

5.2. Tensile strength

The flexural characteristics of UHPC have been demonstrated to be significantly influenced by fibres [70,80]. The flexural properties of UHPC were found to be greatly affected by fibres [81]. In comparison to regular beams without fibres, an improvement of 2.5% in the mixtures of additional steel fibres resulted in a 144% increase in flexural strength [80]. Fibre's main function is to prevent micro cracks from forming by absorbing tensile stress [82]. The tensile strength of the UHPC matrix with additional fibres is normally between 15–20 MPa, depending on the properties of the matrix. In most instances, it costs twice as much as UHPC without fiber. Energy absorption capacity, ultimate cracking rate, and strain limit are all highly tensile parameters which must be extensively explored to assess ductility.

On the other hand, Nguyen et al. [83] investigated the influence of geometry and scale on the tensile properties of UHPC. The findings show that increasing the volume, the length of the gauge, and the section area of the specimen reduces ultimate cracking power, energy absorption potential and strain capability.

The flexural capacity of UHPC beam samples tested under high frictional support was 30–60% higher than equivalent beam specimens, depending on the fibre dose [84].

5.3. Shear strength

The ability of a material to withstand structural failure or shear yield is referred to as shear strength. UHPC beats both conventional and high strength concrete in terms of shear resistance. Hussein and Amleh [85] studied UHPC structural behaviors and concluded that UHPC have higher ultimate shear strength than NSC/HSC. Under shear loading, UHPC normally exhibits a very complex behavior. Shearing forces and bending moments are the main causes of the systems shear failure. Shear length is related to the ratio of shear width to shear resistance, and shear resistance is proportional to fibre volume [86].

5.4. Toughness and flexural strength

In UHPC, flexural strength is frequently more significant than compressive strength. Aggregate types, fibers and casting methods are just a few key elements that influence the UHPC's flexural strength. Because of their stronger bond with hardened paste, fine aggregates such as quartz sand, barite sand and nanomaterials have greater flexural strength [87]. Nano-silica content of up to 2% increases the concrete matrix's ITZ, while overdose which can be 2–5% causes agglomeration. As a result, while addition of nano silica increases flexural strength of UHPC only up to 2% addition then after it will decrease.

The type of fibres, bridging power, homogeneous distribution, and matrix orientation all influence the performance of the fibres under flexural loading. Even if the fibre has a higher mechanical strength, if it is not evenly distributed and properly aligned, its output will suffer under load. As a result, numerous research on the contribution of fibres to the enhancement of UHPC's flexural properties have shown contradictory results. According to Yoo et al. [88], twisted fibres enhanced flexural strength by 167% as compared to straight fibres. Other results by Yoo et al. [88]

show that the beams integrated with straight fibres have the required strength and flexural strength as compared to the twisted ones.

The casting process influences flexural strength because it affects the orientation of the fibres. Increasing the casting speed in the uniaxial beam casting process will improve UHPC performance under flexural strength [88].

The specimen thickness has the opposite impact; as the thickness grows, all the parameters dramatically increase. The flexural strength of the UHPC decreases as the specimen size grows greater. A sample size of 700 × 150 × 150 mm demonstrated a 33% drop in flexural strength when compared to a similar specimen with a scale of 160 × 40 × 40 mm [89].

5.5. Elastic modulus

The addition of fibres to the UHPC had no effect on the elastic modulus of the material [65]. Furthermore, UHPC's elastic modulus is affected by thermal treatment as reported by few researchers [3,5,50]. When specimens were exposed to 250 ℃ for two days, the elastic modulus increased by almost 25% [3].

5.6. Impact resistance

In comparison to normal conventional concrete, UHPC must be more impact and earthquake resistant. It has a more energy dissipation under impact loading and a significantly higher post-loading performance. The size of the specimen, the fibre (type, dosage, duration, direction), and the mineral combinations are all important factors in UHPC's resistance to sway loads [90].

Furthermore, the addition has steadily improved UHPC's efficiency under seismic and blast loads. According to Wu et al. [42], the incorporation of SCMs and fibres into UHPC increased its impact resistance potential due to an improvement in its microstructure, ductility, and ductility properties. Furthermore, according to Astarlioglu and Krauthammer [91], under blast loadings, UHPC columns showed a 30% reduction in displacement as compared to traditional concrete columns.

As a result, UHPC has a promising range in seismic zone structures that require high explosion resistance and seismic load. A high dose of long straight steel fibre is needed for a significant increase in energy absorption and residual moment capability, as well as a notable increase in ultimate residual deflection capacity [88].

However, a summarized description on mechanical properties of UHPC has been highlighted in Table 6.

Table 6. Summary of studies on UHPC mechanical characteristics.

Authors	Major conclusions
Maca et al. [92]	• When fibre content is increased by more than 2%, compressive strength and modulus of elasticity are decreases • The composition of the constituents, the mixing process, particle dispersion, casting method, and curing condition all influence mechanical properties • Including fibres improved impact tolerance, but there was no meaningful effect beyond 1%
Nguyen et al. [93]	• The UHPC's bending power, durability, and flexural strength are all inversely proportional to its scale • On UHPC specimens with higher tensile stress capability, the size of the specimen has a minor effect
Ambily et al. [78]	• Copper Slag provide a 150 MPa compressive strength at 28 days • Fiber gives 5–7 times greater resistance to fracture • Reinforcement of fibers achieves twice the flexural strength
Hussein and Amleh [85]	• Fibers increase flexural strength by 50–90% • The ultimate shear strength of composite beams is greater than that of NSC/HSC beams • NSC/HSC beams have lower ductility than that of composite beams
Jankovic et al. [87]	• Aggregate has more impact on flexural strength • Up to 2% Nano-silica increases compressive and flexural strength but decreases further
Kang et al. [81]	• Compressive strength, tensile strain capacity, ultimate tensile strength, and initial cracking were all higher for steel reinforcement than for hybrid reinforcement.
Xu et al. [94]	• UHPFRC is highly resistant to compressive, flexural, and explosive blast loading shock waves due to its strengthened microstructure.
Yoo et al. [88]	• Despite using similar fibre volume and positioning methods, smaller beams had better fibre orientation as compared to larger ones • As compared to weak beams, better fibre orientation increases flexural strength, deflection strength, durability, and impact resistance
Li et al. [95]	• The mechanical strength of coarse basalt aggregates used in UHPC, such as compressive and tensile strength, is reduced • In UHPC, coarser aggregates should be used with lower powder content • Compressive strength rises in direct proportion to concrete age and fibre volume • Because UHPC has a higher fibre dosage, it has a higher residual power
Ren et al. [96]	• Steel fibre inclusion has a greater impact on tensile strength than compressive strength; yet flexural strength and deflection potential are proportional to the material of steel fibres
Wu et al. [97]	• Increment in steel fibre have improved the compressive and flexural strengths of UHPC • Compressive and flexural strengths were raised by 8–32 % and 22–72%, respectively, when 1–3% straight steel fibres were used • As compared to a reference mixture made without fibre, the optimal steel fibre content was found to be 2%, with a further increase to 3% having no effect on strength and strength

6. Durability properties

6.1. Water absorption and porosity

The concrete’s ability to absorb water represents its long-term durability. Concrete’s durability improves as the absorbing potential of water decreases. UHPC has a water absorption potential is approximately 10 times lower than HPC as well as 60 times lower than NSC [20,98]. UHPC has excellent durability due to reduction of pores [99]. Heat treatment and w/b have been found to have a significant impact on total porosity. The concrete’s water absorption ability can easily provide information on the porosity and quantity of permeable pores, as well as their interconnectivity [100]. The ability to absorb water is greatly reduced when pore connectivity is restricted, and porosity is low. The microstructure of UHPC is highly homogeneous with the addition of mineral admixture, and the ITZ thickness is significantly reduced. By partially blocking the water transport pathway, this reduces the UHPC’s water absorption capacity [101]. Essentially, mineral admixture has a greater impact on the water’s final absorption capacity (72 hours) than on its initial absorption capacity (30 minutes) [100].

6.2. Chloride penetration

One of the most critical factors in concrete strength is chloride ion penetration resistance. Concrete with a higher chloride tolerance has a higher ductility. The w/b ratio, exposure condition, curing regime and the exposure duration are the main determinants of chloride penetration [102]. The addition of cemented components and thermal treatment considerably improves the resistance of concrete to chloride penetration. Thermally treated UHPC has a much lower coefficient of chloride diffusion (2×10^{-14} m^2/s) than high-performance concrete (6×10^{-13} m^2/s) and ordinary concrete (1×10^{-12} m^2/s), according to Roux et al. [98]. Another way of defining the chloride penetration of the specimen is the electrical charge passed in coulombs as per ASTM C1202-10.

6.3. Freezing and thawing

The act of freezing and thawing is especially difficult for UHPC. It is a key factor to improved homogeneous microstructure, lower permeability, and reduced porosity [50]. Generally, 400–500 freezing-thawing cycles and 4500 wetting-drying cycles can be maintained without degradation [29]. Furthermore, Acker and Behloul [53] demonstrated that the UHPC microstructure is unaffected by the 300 freeze-thaw period. Internal micro cracks form because of many freeze-thaw cycles, and concrete deterioration begins because of their propagation. The addition of such mineral admixtures improves UHPC’s freeze thaw tolerance. UHPC’s resistance capacity is significantly improved by just 10% of Class C fly ash and silica fume [103]. All these results indicate that UHPC has a high freezing and thawing quality.

6.4. Fire resistance

Due to its reduced porosity, very compact microstructure, and low proportion of water binders, UHPC structure are more susceptible to elevated temperatures and fire, resulting in physical harm [104]. The concrete is exposed to high temperatures ranging from 1000 to 1200 ºC during the blast, causing physical and chemical changes in the concrete matrix. These transformations cause concrete structures to disintegrate, which is essentially dictated by the final temperature, rate of heating and the previous fire exposure [22]. The use of polypropylene (PP) fibres, on the other hand, will help to alleviate this issue. Adding 0.6% by mixture volume of PP fibres increased the fire resistance qualities (prevented spalling) of UHPC, according to Heinz and Ludwig [99], because melting of the PP fibres at high temperatures generates space to release the pressure build-up. Furthermore, Tai et al. [105] found that when UHPC specimens were heated up to 300 ºC, compressive strength increased; however, when the temperature was elevated above 300 ºC, compressive strength decreased. At high temperatures, the internal microstructure of UHPC weakened, resulting in a decrease in mechanical properties [106].

6.5. Shrinkage

Shrinkage of concrete results cracks which is happen due to the loss of water, whether due to evaporation, carbonation etc. Wu et al. [41] state that basic type of shrinkage in concrete are due to chemical, carbonation, drying, autogenous and thermal shrinkage. In addition to this UHPC's low porosity and the evaporation of internal water, drying shrinkage is minimized. However, Autogenous shrinkage is a problem in UHPC due to the large amount of cement consumption and low w/b ratio. Autogenous shrinkage is a decrease in the volume of cement components at the macroscopic level owing to cement hydration after the first environment [51,107]. The development of surface tension within the very fine concrete matrix capillaries is the primary cause of its occurrence, which is mainly caused by a lack of sufficient water for the binder material to fully hydrate [51,108]. Chemical shrinkage occurs because there are less hydration products created. Wherever thermal shrinkage occurs because of large temperature variations. Table 7 outlines several factors that influence the long-term durability of UHPC.

Table 7. Following is a summary of the research done on the durability properties of UHPC.

Authors	Major observations
Graybeal et al. [50]	• For greater freeze-thaw resistance and a homogeneous microstructure, lower permeability and porosity are needed
Garas et al. [109]	• In comparison to tensile strength, tensile creep is more affected by thermal treatment • Tensile creep is reduced by 57% and 63%, respectively, by thermal treatment at 600 ºC for 48 hours and 900 ºC for 72 hours
Ye et al. [110]	• Generation of maximum crack @300ºC and explosion @400 ºC • Up to 300ºC, the introduction of PP fibres (2 kg/m^3) induces marginal changes • PP fibres are the preferred reinforcement for fire resistance
Sabet et al. [100]	• Mineral admixtures have a greater influence on water absorption in the end (72 h) • Silica fume at a concentration of 10% and 20% decreased water absorption by 38.7% and 43%, respectively • In terms of water absorption, silica fume outperforms zeolite and fly ash

Continued on next page

Authors	Major observations
Du et al. [101]	• Because of the refined pore size distribution, the rate of chloride penetration and water absorption has decreased • Water penetration depth has declined by 45% • The chloride migration coefficient has decreased by 28.7%
Yoo et al. [111]	• Free shrinkage strains showed higher values than retrained shrinkage strains • The resistance to shrinkage can be enhanced by increasing the concrete thickness
Li [112]	• The addition of SF or FA to cement causes drying shrinkage to increase, while the addition of MK causes drying shrinkage to decrease. Using MK, FA, and cement, as opposed to SF cement, resulted in lower drying shrinkage
Tafraoui et al. [37]	• Chloride ions diffusion is in the range of 10–15 m^2/s • Water absorption coefficient should be less than 0.6 kg/m^2
Li et al. [113]	• With increased temperature and heat curing time, the rate of shrinkage development increases and eventually stabilizes at 900 ºC after 10 hours of heat curing • The ultimate shrinkage obtained after 48 h was 450 mm. Higher reinforcement ratios are better able to prevent shrinkage development
Liang et al. [114]	• Explosive spalling depends primarily on the vapour pressure rather than the heating rate • In regulating explosive spalling, but not for complete removal, PP fibres proved worthwhile • Steel fibres can over-check spalling strength and increase the compatibility of binder paste and aggregates
Wu et al. [97]	• Steel fibre volume and form had a major impact on preventing UHPC shrinkage • The use of 2% steel fibres significantly lowered autogenous and drying shrinkage values • The hooked fibre was more effective at preventing shrinkage than the straight and corrugated fibres
Li et al. [115]	• Because of its low w/b ratio and compact structure, UHPC exhibits exceptional permeability resistance to water and chloride-ion penetration, carbonation, and other chemical attacks • Based on important factors such as mixture percent, curing regime, medium solution concentration, steel fibre volume, and testing age, it has been demonstrated that the chloride ion diffusion coefficient of UHPC is at least one order of magnitude lower than that of HPC
Li et al. [95]	• Due to its thick microstructure, control specimens experienced extreme explosive spalling • No protection against explosive spalling was provided by the addition of steel fibre alone, while the inclusion of 4 kg/m^3 of PP fibre suppressed UHPC explosive spalling in the current study • Even at low fibre dosages, the use of hybrid and steel fibres absolutely avoided explosive spalling due to a substantial increase in permeability

7. Sustainability and cost estimation of UHPC

UHPC has a greater initial material cost than Normal Strength Concrete (NSC) and High Strength Concrete (HSC) due to its higher cement content and steel fibre inclusion. Because of the potential for improved economic, social, and environmental effects, the implementation of UHPC would result in more sustainable construction. The cross-sectional measurements of structural components have a direct relationship with the overall cost of the structures. The use of structural members from UHPC helps to minimize cross-sectional dimensions, which frees up more usable space in buildings. UHPC's high strength facilitates for the construction of slender structures, resulting in a reduction of the structure's self-weight due to the use of less materials. This can also lead to a decrease in demolition waste, resulting in less demand for transportation and, as a result, less environmental pressure [116]. Even though UHPC has a higher cement content, the material cost is lower than an NSC component with a wider cross section. Furthermore, even though no coarse aggregate is used in UHPC, the volume of fine aggregates can be reduced by 30% [56]. According to Racky [117], using UHPC instead of NSC would result in a material cost reduction of about 56%. Furthermore, UHPC is more sustainable because by-products such as fly ash/silica fume are used instead of cement. Since UHPC members have improved reliability characteristics, they need less maintenance and thus have lower life cycle costs, resulting in a longer lifespan [117,118]. UHPC has a smaller effect on the ozone layer, has a lower risk for environmental degradation, and emits less greenhouse gases. In short, due to its improved longevity, environmental considerations, economic benefits, and recyclability in different applications, UHPC can be a green material. To broaden and expand the use of UHPC, cost-effective manufacturing techniques utilizing readily available materials and industrial technology are required [11,37].

8. Conclusions

- The unique properties of UHPC offer several advantages over normal-strength concrete (NSC) due to its material constituents and composition. Important conclusions have been drawn based on a comprehensive review research conducted on the unique qualities of UHPC, which are given below: Improved microstructure, reduced porosity, increased homogeneity, improved hydration, and durability are all significant considerations in the production of UHPC. To meet these criteria, mixes must have a high binder content (ultra-fine powders), a low w/b ratio, addition of high range Superplasticizers, fiber consistency and an excellent mix design by obtaining an optimized particle packing, along with proper curing.
- One suggestion for promoting UHPC in construction is to investigate alternate materials to replace expensive UHPC composites and traditional concrete. Because of the following advantages, it was suggested that waste materials with cementitious qualities be used to replace Portland cement: (1) Lower the cost of production; (2) make concrete more ecologically friendly by eliminating waste materials and gas emissions from cement manufacturing; and (3) improve the uniformity and density of the concrete for greater strength and durability.
- UHPC required only fine aggregate like natural sand, Silica sand, recycled glass cullet, quartz sand etc. and eliminates coarse aggregate because it weakens the ITZ.
- Water–binder ratio is not the only factor that influences the strength parameter. However, a w/b ratio of 0.25 can be used to achieve compressive strength over 150 MPa.
- Previous studies have shown that hot water and steam curing produces better compressive and flexural qualities than normal concrete mix.
- It has been observed from different studies that the compressive strength parameter is least affected by the addition of fibre in UHPC mixes. However, the motive of adding fibres is just to improve the ductile properties of UHPC.
- Moreover, literature also reveals that the property like flexural strength is also affected by different pouring methods of concrete into the moulds. Results indicated that the UHPC mixtures incorporating fibres with higher aspect ratio had increased flexural capacity.

- UHPC has a higher energy dissipation under impact loading and a significantly higher post-loading performance, so it is good for structure have greater earthquake and impact resistance condition.
- As the following qualities, such as water absorption capacity and chloride penetration, rise, the durability of UHPC diminishes. On the contrary, when the freezing and thawing resistance increases, the durability has been discovered to be increasing. Mineral admixtures, correct heat treatment, and maintaining the water–cement ratio can all aid in producing UHPC with the desired characteristics.
- UHPC constructions are more vulnerable to fire and high temperatures, posing a risk of physical harm.

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Conflict of interest

The authors declare no conflict of interest.

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