Ultra High Performance Concrete Preparation Technologies and Factors Affecting the Mechanical Properties: A Review

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Abstract. Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a superior type of concrete. It has ultra-high strength, ductility and durability. Despite the large number of researches that have been performed to study it, no perfect approach has been determined yet to identify the proportion of materials involved in its composition, nor ideal curing methods after casting with the possibility of performing effectively. Also, there is no uniform technique for pouring concrete to ensure that fibres are spread properly. This paper focuses on the review of techniques carried out to choose the quality and quantity of materials used for UHPFRC with the analysis and comparison of the researchers’ findings to identify optimal proportions, pouring and treatment regimens to attain the best results of mechanical properties of UHPFRC. The optimum packing density resulting from high cement content, using silica fume, fine aggregate, low w/cm ratio and high dosage of HRWRAs are the key factors to reach ultra-high strength. Incorporation of short steel fibres leads to improving ductility, tensile strength and enhance strain hardening of UHPFRC. Heat treatment or steam curing stimulates the reaction between SiO$_2$ in cementitious materials and Ca(OH)$_2$ produced on cement hydration which results in rising strength.

1. Introduction

The use of cement alone as a binder for other conventional concrete components was proved to give about 50 MPa compressive strength. Also, the presence of coarse aggregate would prohibit strength enhancement due to the weakness of interfacial transition zone [1]. The Ca(OH)$_2$ produced from cement hydration occupies fairly large space of concrete microstructure, leading to limit access to high strength. Therefore, high compressive strength needs more than cement and low w/c. It needs other materials having the ability to react with the Ca(OH)$_2$ to award fine compounds of C-S-H, which reduce the porosity, enhance the strength and develop the durability. On the other hand, lowering the w/cm ratio results in diminishing the workability of fresh concrete, so that High Range Water Reducing Admixtures (HRWRAs) are used at high dosage to overcome this issue. Another drawback takes place upon reaching high strength concrete, which is an abrupt brittle failure. Fehling et al, Yoo and Yoon and De Larrard [2, 6, 11] found that the incorporation of fine high strength steel fibres in a concrete mixture can reduce this drawback. Steel fibres act as a micro-reinforcement inside the concrete microstructure to contribute effectively in increasing tensile...
strength, ductility, and post-cracking strains. According to these facts, UHPFRC can be produced. Hence, UHPFRC consists mainly of high cement content to replace the omission of coarse aggregate; other cementitious materials having a slightly high percentage of SiO$_2$ with ultrafine particle sizes to react with Ca(OH)$_2$ produced from cement hydration such as silica fume, fly ash, metakaolin, and slag; low w/cm ratio; high dosage of HRWRAs; steel fibres as illustrated in figure 1.

Figure 1. Common composition of UHPFRC

### 2. Historical Development of High Strength Concrete

The first trial to reach ultra-high-strength for a cementitious material matrix was performed by Roy et al [3] in 1972 who achieved 510 MPa compressive strength, 44 MPa indirect tensile strength, and 81.5 MPa shear strength for cement paste. The researchers used a special curing manner by heating to 250 °C and using a pressure of (172-345) MPa on conventionally prepared cement paste with 0.21w/c ratio, the paste was approached zero porosity. At the same time, in 1972, another trial by Yudenfreund et al [4] was performed to reach 240 MPa compressive strength of cement paste with ordinary curing at 25 °C at 180 days. The authors used a special treatment to cement by grinding to get a surface area (Blaine) from (600-900) m$^2$/kg and low w/c ratio of 0.20.

In 1981, Bache [5] developed a new class of cement paste that had ultra-high-strength and low porosity by using fine particle constituents. That class called densified small particles (DSPs) concrete through using pozzolanic additives and HRWRA which afforded 120-270 MPa compressive strength. Brichall et al in 1981[7], also developed another class of cement paste that had a compressive strength greater than 200 MPa and flexural strength of 60-70 MPa without fibers or high pressure. The researchers used the methodology of densified small particles (DSPs) also. The methodology of DSPs depended on minimizing the spaces between particles in the mixture by using fine materials to give high packing, using a low w/c ratio, and a high quantity of HRWRA [7].

In 1994, Richard and Cheyrezy [8] launched the concept of reactive powder concrete (RPC) by using ultra-fine particles and powders in the mixture with ignoring the use of coarse aggregate to reach ultra-high strength at range (200-800) MPa at low w/c ratio and heat treatment at 90-400 °C. The Densified Small Particles and RPC are considered the basic concepts of a novel generation of concrete which is called UHPFRC. From year 2000 onwards, great progress had been performed to develop UHPFRC.

### 3. Composition, Mix Proportion of UHPFRC

The preliminary developments to achieve high strength concrete initiated with the use of superplasticizer as a high range water reducing admixture that permitted to lower w/cm ratio to a very low value. In this context, Laskar and Talukdar [9] investigated the flowability of concrete of high performance using different dosages of HRWRA. They used two parameters related to yield stress and plastic viscosity of fresh concrete through some charts to predict the compressive strength in a new method of mix design of HPC.

Azmee and Shafiq [10] suggested that UHPC can be treated as a combination of three concrete types that are SCC, FRC, and HPC. Several researchers indicated that UHPC is not concrete because the coarse aggregate does not present in the mixture, Larrad and Sedran [11,12] considered it as a mortar, not concrete. However, the expression “concrete” remained in use rather than mortar to express UHPFRC since it can be used in structural members [10].
Over the past two decades, UHPFRC had been investigated by many researchers and used as a superior structural material in many constructions in several countries, but till now there is no idealized method for the proper mix design or proportioning of its ingredients. Only the main principles for designing UHPFRC had authorized by many researchers, which can be summarized as follows [2,11,12]:

1. Using of high range of fine and ultrafine particles leads to optimize the granular packing, to improve dense composition and to lower porosity. This also can have pursued by lowering the w/cm ratio.
2. Improvement of microstructure by heat treatment to accelerate the pozzolanic reactions of silica fume with the hydration products of cement can enhance the mechanical properties.
3. Excluding coarse aggregate leads to improve the homogeneity and reduce pore sizes.
4. Incorporating short high strength steel fibres as a micro-reinforcement can increase the ductile behaviour, tensile and flexural strengths.

The design process of UHPFRC mixture directs toward achieving a high density and compacted mixture having good workability and a high strength [10]. The numerous possible constituents that can be used in UHPFRC, make the hardened phase more complex. Also, the participation of each component in the fresh properties and mechanical properties of UHPFRC, makes the selection proportions to be more difficult. However, the main principles for selecting materials and significant in the performance of UHPFRC are illustrated in figure 2.

![Figure 2. Main principles for Design of UHPFRC.](image)

4. Available Mix Design Manners of UHPFRC
Several manners had been introduced to design UHPFRC mixtures. Table 1 describes some of these manners. All of them depend on improving packing density, which is the ratio of the solid volume to the total volume of the composite [12]. The water demand of a concrete mixture depends on the granular specific surface as well as packing density, but the fine powders (at the cement particle size and lower), can be mainly influenced by packing density only [17].

Fine materials and superplasticizers are considered as the main ingredients to attain UHPC mixtures which are characterized by their flowability. This concept catalysed Lohas and Ramge [16] to study the effects of fines and the percentage of superplasticizer on the packing density and then on
the strength of concrete. Their results showed that the additional fine particles were important to modify the flowability of the mixtures, while the increment of coarser particles required a higher amount of liquid to reach the flowing state and might be causing segregation of the mixture when the further liquid was added. The researchers suggested a new method for the proportioning of robust UHPC mixtures depending on the fluid to solid volume ratio and including superplasticizer when determining the water demand for the mixture.

Tai and El-Tawil [18] studied the influence of replacing part of cement by slag cement (25% of cement weight) with less percentage of silica fume and w/cm of 0.22. The authors depended on particle size distribution to reach the best packing density. Ragalwar et al [19] also considered particle packing models to reach dense particle packing through determination of the constituents of UHPC mixture.

Since a low w/cm ratio with high cement content used in UHPFRC leads to hydrate only a portion of cement, the other portion of cement acts as a filler. The replacement of part of cement by other constituents to act as fillers such as silica fume, fly ash, metakaolin, and glass powder, can help to reduce the total cost and may maintain the same properties of UHPFRC. These concepts adopted by Arora et al [17] who studied a microstructural stochastic packing model which is described in Table 1.

The omission of coarse aggregate increases the cost of UHPFRC. Hence, another development to design an economic UHPC mixture was done by Arora et al [20] through using a coarse aggregate of 6.25 mm, 4.75 mm, and 2.35 mm sizes besides 0.6 and 0.2 mm fine aggregate in the mixture. The researchers used microstructural packing and rheological considerations through a separation of the optimization process of binder and aggregate phases to produce UHPC with a compressive strength greater than 150 MPa and 10 MPa flexural strength at w/b ratio between 0.165-0.2.

Fladr et al [21], also used coarse basalt aggregate with two sizes (4-8) mm and (8-18) mm at 25 % of concrete volume, ordinary sand (0-4) mm and micro-silica at 15% of cement content. The basalt aggregate has good mechanical properties; therefore, 140 MPa compressive strength and 16 MPa flexural strength were obtained from this mixture. This ultrahigh strength may be obtained due to the use of high strength basalt aggregate.

The Germany Guideline for UHPC (DAfStb) [23], focused on class and quality assurance of cement, mineral additions, superplasticizers, optimization of packing density of the finest grains up to 0.25 mm, in preparation and producing the UHPC mixtures. The Guideline limited the maximum size of grain used, to be between (0.5-16) mm.

Alsalman et al [22] observed that raise of cement content up to 1700 kg/m$^3$ leads to raising the compressive strength, while increment cement content above 1700 kg/m$^3$ causes lowering strength. Attributing this to that UHPC does not reach the optimum packing density. Also, they deduced that the use of extra fine aggregate can be the main factor in yielding UHPC, for its role in improving the packing density of the mixture, where a denser matrix can be achieved by filling the interior microspaces, hence, compressive strength can be increased. They achieved highest strength of 169 MPa when fly ash used as fine material.

5. Mixing Regimens and Mixing Time of UHPFRC

It was found that not only mix proportion is significant for mechanical properties of UHPFRC, but also mixing regimen has an important effect to attain the flowability of the mixture, which in turn influences the later age mechanical properties. De Larrad and Sedran [11] proposed mixing of silica fume with water and part of superplasticizer firstly, followed by adding cement with another part of superplasticizer, then blend sand with the remainder superplasticizer and mixing with high speed. On the other hand, Tai and El-Tawil [18], ACI 239R-18 [24], Yu et al [25], and Alsalman et al [22] suggested another mixing process, consisted of mixing dry constituents of cement, slag, silica fume and sand in dry condition firstly. Then water with superplasticizer is added and mixing up to form a thick slurry. The fibres are incorporated finally, and mixing further to distribute fibres regularly. In all methods, the fibres are incorporated in a slow way to assure uniform distribution without segregation or accumulation. The period of mixing differs according to mixer energy and type, where pan mixer is
used, shorter time required than the use of drum mixer. Also, the batches prepared by the pan mixer gave higher strengths as compared with the drum mixer. The content of admixtures was increased in batches mixed by drum mixer as compared with the one mixed by pan mixer [22].

| Design Manner                  | Proposal Author (year) | Features depended                                      | Results                                      |
|-------------------------------|------------------------|--------------------------------------------------------|----------------------------------------------|
| Densified small particles (DSP) | Bache [5] (1981)       | Fine particle constituents (pozzolanic additives)      | Compressive strength = 120 - 270 MPa         |
|                               |                        | The use of HRWRA                                       |                                              |
| Densified small particles (DSP) | Brichall et al [7] (1981) | Minimizing the spaces between particles using fine materials | Compressive strength ≥ 200 MPa, Flexural strength = 60 - 70 MPa, without fibers |
| Linear packing density model (LPDM) | Larrad & Sedran (1994) [11] | Fine grain sizes, Specific packing density, Addition of superplasticizer | Good implementation to predict the mixture proportion, Linear model restricted its use |
| Solid suspension model (SSM)    | Larrad & Sedran (2002) [12] | Packing density, High viscosity reduces water demand, Analysis the gradation of each monosize of constituents, Making continuous gradation | Well packing density, Produced fluid mortar with very low w/c = 0.14, Compressive strength = 236 MPa, after 4-day of heat curing at 90 C |
| Compressive packing model       | Larrad Sedran [12] (2002) | Packing of monosize particles Compaction index for each solo particle | It can be used to design UHPC mixture |
| High packing density           | Fennise et al (2009) [15] | Replacing cement with other fillers to reach higher packing density and to reduce the cost, Decreasing water content, Reduces void spaces & decreases w/cm ratio | Improving the stiffness and strength, Reducing the effects of shrinkage and creep, Reducing the voids through fillers, Reducing water demand |
| Generic algorithm, practical swarm optimization | Lim et al [13] (2004), Rezae and Ahangar [14] (2012) | Reduce number of trials to reach a suitable mix proportion Random solution, The generic algorithm consists of 3 processes: selecting materials, crossover and alteration | 2-equation to define the functions of fc and slump, The equations are functions of w/b, water content, fine aggregate ratio, FA, SF, air entrainment and superplasticizer |
| Microstructural stochastic packing model | Arora et al [17] (2018) | Reduce cement content by replacing with other cementitious substances (SF, FA, MT, glass powder) | Replacing 30 % of cement by other cementitious materials or fillers can maintain the same workability |

Mazanec et al [26] showed that a long time was required for mixing UHPC. This time depended on the concrete constituents and mixer speed. Graybeal [27] stated that the mixture procedure used for traditional concrete can also be used for the mixing of UHPC. Baqersad et al [28] imposed that the
use of ice in mixing UHPC in lieu of water can prevent overheat of a mixture, justified that, high energy required in the mixing procedure may raise the heat.

6. Curing Regimens

Conventional curing by immersing the specimens in a water at room temperature was one of the curing methods used by several researchers [18,20,29]. Heat treatment immediately after demoulding the specimens or at later age was another method [2]. Alsalman et al [22] implemented eight curing regimes for their specimens, the best one was consisted of curing at 90 °C in a water bath for 28 days, which gave 12 % increase in compressive strength as compared with specimens that were cured in water at 60 °C for 2 days followed by curing at 90 °C. This can be attributed to the development of the hydration process during heat curing and acceleration of the pozzolanic reactions. Also, Alsalman et al appointed that standard curing method at 21 °C water for 28 days showed the lowest strength level. Another method included treatment of fresh UHPC mixture to reach higher strength, that was using autoclaving and compaction under high pressure, but this type of treatment is required some special techniques, which are difficult to use on large sizes members such as beams or slabs [11,12]. AFGC Recommendations [30], characterized two types of heat treatment, the first one can be performed for a short time after hardening of concrete to be at 65 °C with high moisture. The second type includes submerging in the water at 85-90 °C for one or two days. Generally, Table 2 shows some curing regimens that can be used for UHPFRC.

| No. | Curing regimen                              | Avg. compressive strength, MPa |
|-----|--------------------------------------------|-------------------------------|
| 1   | Air curing at room temperature             | 98 -102                       |
| 2   | Water curing at room temperature           | 102 – 118                     |
| 3   | Heat treatment at 90 °C water for 2-3 days | 120 – 150                     |
| 4   | Heat treatment at 90 °C for 28 days        | 140 - 230                     |
| 5   | Autoclaving and compaction under high pressure | ~ 240                        |

7. Raw Materials of UHPFRC

The composition of UHPFRC can be varied from one region to another, depending on the availability and cost of the constituents. The selection of the constituents is based on the particle size to obtain the optimum packing density, i.e., a continuous gradation of the particles to reduce voids and reach dense microstructure to enhance the mechanical properties [17,24]. However, the common constituents of UHPFRC are described as follows:

7.1. Cement

Cement is a main hydraulic binder for other constituents in the concrete mixture. The most important features of cement to use in UHPFRC are presented in Table 3. Tai and El-Tawil [18] showed that the type of cement to be used in the UHPFRC mixture should have a low content of alkali and low to medium fineness. The main components in cement that develop strength, are C\textsubscript{3}S and C\textsubscript{2}S; therefore, cement with a higher content of both C\textsubscript{3}S and C\textsubscript{2}S is preferred. In contrast, C\textsubscript{3}A gives rapid hydration which increases with the increase of specific surface area, hence, it increases water demand, while UHPC is required a low w/cm ratio [17,18].

Graybeal [27,34] stated that the average diameter of cement particles of 15 µm is being the second-largest particle after the fine sand. Therefore, cement has a significant role in packing density. ACI Committee 211.4R [31] stated that “there is an optimum cement content beyond which little or no additional increase in strength is achieved by increasing the cement content”, in this context, Al-Salman et al [22] found that raising of cement content rises the strength, but beyond a cement content of 1700 kg/m\textsuperscript{3} compressive strength resorts to decrease.
Table 3. The main features of cement to use in UHPFRC.

| Features | Significance or negative impact | Limitation |
|----------|--------------------------------|------------|
| Surface area | The finer the cement, the faster the chemical reactions | ≥ 400 m²/kg (Blaine) [18] |
| C₃S, C₂S | High content enhances strength gaining | |
| C₃A | Causes rapid hydration, increase water demand [17,18] | ≤ 8 % |
| Content | High content raises strength | 1700 kg/m³ [22] |

7.2. Silica Fume (SF)
SF has high percentage of pozzolanic materials; therefore, it can be used with concrete to enhance the mechanical properties of hardened concrete [32] as a solo material or replace a portion of cement content. The characteristic properties of SF are illustrated in Table 4.
At the beginning of the use, silica fume was used to replace a portion of cement and was limited to less than 10% of cement content [20], while recently usage is a supplementary ingredient, to produce high-performance concrete. To obtain the best performance of using silica fume in the mixture, the concrete should be heated at (80-90) °C. Heat treatment can accelerate the reaction between Ca(OH)₂ produced during cement hydration and SiO₂ in silica fume. However, traditional curing of concrete in water exhibits lower compressive strength by (10-20) % as compared to heat-treated concrete strength. In the latter case, silica fume acts as a filler material only [2,22]. The effect of SF on strength gaining can be interpreted by chemical and physical aspects. Chemically, silica fume starts to act when Ca(OH)₂ presents to react with it, forming additional compounds of calcium silicate hydrates. Physically, the ultrafine size of SF particles contributes effectively to optimize the packing density of the composite [35]. Some studies found that the perfect percentage of silica fume to be used in UHPC mixtures was at a range between (15-30) % of cement content depending on the other constituents [7,11,18,27,34,35,36,37]. Figure 3 summarizes the influence of SF on UHPC properties.

Table 4. The Main Features of SF to Use in UHPFRC.

| Features | Significance or negative impact | Limitation |
|----------|--------------------------------|------------|
| Very fine, non-crystalline structure | Enhance packing density | 0.1-0.2 μm [32,33] |
| High content of SiO₂ | High reactivity with Ca(OH)₂ | ≥ 85 % |
| Content, SF/Cement ratio | High reactivity with Ca(OH)₂ | 25 % [14] |
| Heat treatment at 80-90°C | Accelerate reactions with Ca(OH)₂ and produce additional C-S-H, which reduces porosity and increases strength | |

7.3. Fly Ash (FA)
Fly ash can be categorized into several kinds according to the degree of cementitious properties. The main features of FA are illustrated in Table 5. The pozzolanic reactions between Ca(OH)₂ and SiO₂ in fly ash continue, but slowly to increase the later-age strength. It was found that the 90-day compressive strength is 30 % greater than the strength at 28 days [22]. Fly ash can be used to replace a portion of cement content to enhance the rheological properties of the mixture [19]. Figure 3 summarizes the influence of FA on UHPC properties.

Table 5. The Main Features of FA to Use in UHPFRC.

| Features | Significance or negative impact | Limitation |
|----------|--------------------------------|------------|
| Round ultra-fine particles | Improve the workability. Reduce long term permeability. Enhance resistance to sulfate attack due to its reaction with Ca(OH)₂ [31] | 0.1-45 μm diameter |
| High surface area and packing density | Stimulate the pozzolanic reactions between Ca(OH)₂ and SiO₂ | 300-500 m²/kg |
| Using in UHPC | | lower the heat of hydration. Delay strength gaining at early age. |
7.4. Fine Aggregate (Sand)
The basic principle, in which ultra-high performance concrete was developed, is the granular gradient to obtain the optimum packing density. Since the other components of UHPC have very fine grain sizes (0.1-45) µm, and to make the gradation of grains to be continuous without interruption, it must use fine sand in the mixture. This will reduce voids and enhance strength.

On the other hand, as it is stated in ACI 239R [24], some cementitious grain materials may not contribute to the hydration due to the low water content in the mixture; therefore, they solely act as a fine aggregate in the entire matrix. It is common for (30-50) % of cement content to be hydrated in UHPC, while the residual percentage acts as a fine aggregate. The shape and chemical composition of fine grains of sand and strength of the parent rock, which forms the sand, have a significant role in rheology and the strength of UHPC.

Quartz sand was used in the preparation of UHPC as a fine aggregate, as well as fine graded artificial sand and natural river sand [19,22]. Figure 3 shows the influence of sand on UHPC properties.

7.5. High-Range Water Reducing Admixtures (HRWRA)
The invention of UHPC belongs to the development of a new generation of HRWRA and using silica fume [11,12,39]. HRWRAs are chemically organic fluids, based on carboxylic ether polymer with long lateral chains. This composition improves the dispersion of fine particles of cement, silica fume, and other pozzolanic substances. Also, it acts on the dissociation of the agglomerations of these particles, and do not permit air entrance [38]. The dosage depends on the desired fluidity and consistency, and the percentage of the constituents of UHPC.

7.6. Steel Fibres
Steel fibres can be considered as a micro-reinforcement inside the UHPC matrix, they contribute to transfer high bond stresses; therefore, their effect occurs when the matrix ruptures on the propagation of microcracks and macrocracks. At this stage, the fibres act to obstacle the propagation of these cracks, giving high ductility and increasing tensile strength. The final rupture occurs when the sustained stresses overcome the static friction forces (bond) between the matrix and the fibres [2].

The main significant properties, that are considered in UHPFRC and FRC, are strength, elastic modulus, stiffness, and bond of fibres with concrete. The bond depends on the aspect ratio. The length to diameter ratio represents the aspect ratio, varies between (20-100) [39]. The 1.5% by volume fibres content can slightly increase compressive strength up to about 15% of ordinary reinforced concrete, while the tensile strength may be increased up to 30-40 %. The hooked type of steel fibres has a significant effect on a first crack load, increasing fibres content rises the ultimate load-carrying capacity [21]. Figure 3 shows the influence of steel fibres on UHPC properties.

8. Fibres Orientation and Distribution
The orientation and uniform distribution of the fibres through hardened concrete have a significant role in the results of tensile and flexural strength. When the orientation of fibres is perpendicular to the applied load with uniform spacing distribution between fibres, the tensile strength is greater than that of inclined or irregular distributed fibres. To attain the best results, the flowing fibrous concrete should be poured into the formwork from one side with vibration, to maintain one-direction flow for the fibres [2]. The parallel distribution gives high efficiency for fibres in bridging the cracks when initiated and enhances the tensile strength and other mechanical properties.
9. Mechanical Properties of UHPFRC
The mechanical properties of UHPC with steel fibers are partially affected by fiber type, aspect ratio, the content of fibers in the mixture, the length, size, and type of fiber. Fibers affect the mechanical properties in all failure modes [2,39,40]. The mechanism of fibers in enhancing the strength involves conveying the stress from the concrete matrix to the fiber by interfacial shear or by bond forces between them. Hence, if the surface is deformed, the bond forces are greater and the stress is shared by both the fiber and matrix until fracture of a matrix, regarding that the tensile strength of a fiber is greater than that of a matrix. The bond strength increases with increasing the length of the fiber, decreasing its diameter or rising surface area. That means a high aspect ratio gives more interfacial resistance (bond strength). But higher aspect ratio, greater than 100, causes inadequate workability of concrete mixture and non-uniform distribution of fibers. The pullout mechanism is the dominant mode of failure in steel fiber reinforced concrete [2,39].

10. Conclusions
UHPFRC is a superior form of concrete, has more than 150 MPa compressive strength and high tensile and flexural strengths. As well as high durability and ductility. UHPC is produced by using fine granular materials to reach the optimum packing density with condensed microstructure and very small porosity. Commonly, coarse aggregate is omitted, but some researchers have been able to produce UHPC with coarse aggregate. The use of coarse aggregate in the mixture causes heterogeneity and formation of interfacial transition zone which is responsible for the impairment of mechanical properties of concrete.

Several models were developed to express the concept of particle size distribution on the preparation of UHPC mixtures, these models arranged to obtain the optimum packing density of the blend. Of these models; linear packing density model (LPDM), densified small particles (DSPs)

The invention of UHPC belongs to the use of SF and a high dosage of HRWRA. The effect of SF on the mechanical properties occurs on heat treatment and at later ages, while in traditional curing in water, the SF acts as a filler. Heat treatment activates the reactions between Ca(OH)\textsubscript{2} produced from cement hydration and SiO\textsubscript{2} in the SF and other cementitious materials to generate extra C-S-H which reduces the porosity and enhances the strength and durability.
UHPC commonly contains high cement content up to 1700 kg/m$^3$ to reach the highest strength and substitute the omission of coarse aggregate. Other cementitious constituents such as SF, FA, and metakaolin which have a high percentage of SiO$_2$ are used to replace a portion of cement or as additives. Also high dosage of HRWRA for the fluidity and well dispersion of constituents’ particles. Besides, fine and ultrafine sand and steel fibres as micro-reinforcement to enhance the ductility, post cracking strains, and tensile strength, and prevent the brittle failure.

The percentage of cement that is hydrated in UHPC is ranged between 30-50 % due to the low w/cm ratio, while the remaining percentage acts as a filler to enhance the packing density. Therefore, part of cement can be replaced by other cementitious materials. Replacing 20 % of cement by silica powder can increase the compressive strength up to 15 % at the same w/cm. The optimum silica fume content is 25 % of cement content. The mixture containing slag develops higher compressive strength, at later ages than that including fly ash. Also, using FA or slag in UHPC can improve workability, reduce water requirements, lower heat of hydration, while strength gaining is delayed up to later ages, beyond 90 days.

Cement with high surface area (over 400 m$^2$/kg) leads to faster reactions with pozzolanic materials and improve the strength. Cement type with C$_3$A content less than 8% and high content of C$_3$S and C$_2$S is preferred in UHPC.

The mixing time of the UHPC mixture depends on the type, capacity, and efficiency of mixer; batch size; particle size of ingredients; the degree of filling of a mixer. The best curing regimen for UHPC is heat curing for 28-day due to the effect of heat treatment on the acceleration of pozzolanic reactions.

Type, aspect ratio, and quantity of fibres influence the resistance of UHPC failure. Pouring of UHPFRC in the formwork from one side helps to spread the fibres in one direction with most percentage is parallel to the base side of formwork, the vibration helps in uniform distribution of fibres. This enhances the activity of fibres to obstacle the cracks and increases the tensile strength and ductility. The mode of failure in UHPFRC is a pull-out of fibres.

The effect of steel fibres is more clearness on the tensile strength than on compressive strength. As well as fibre content and silica fume affect the tensile strength of UHPFRC.

## Abbreviation

| Abbreviations | Description |
|---------------|-------------|
| C-S-H         | Calcium Silicate Hydrates |
| FA            | Fly Ash |
| FRC           | Fiber Reinforced Concrete |
| HPC           | High Performance Concrete |
| HSC           | High Strength Concrete |
| NSC           | Normal Strength Concrete |
| RPC           | Reactive Powder Concrete |
| SCC           | Self-Consolidating Concrete |
| UHPFRC        | Ultra High Performance Fiber Reinforced Concrete |
| w/cm          | Water to cementitious materials ratio |

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