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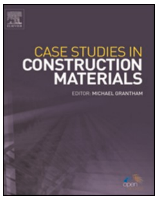

Ultra-high-performance fiber-reinforced concrete. Part V: Mixture design, preparation, mixing, casting, and curing

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ABSTRACTS

Ultra-high-performance concrete (UHPC) is a cement-based composite used for new construction and/or the restoration of existing structures in order to extend their service life. It is a revolutionary composite material that can serve as a suitable substitute for concrete construction in hostile environments. After decades of research and development, a wide variety of commercial UHPC compositions have been created around the world to meet the expanding number of uses and demand for high-quality building materials. Although UHPC has significant advantages over conventional concrete, its application is limited due to restrictive design rules and high cost. Therefore, a careful review of the various properties of UHPC is necessary to offer key information for material testing criteria and methods and to broaden its practical uses. “Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. Part III reviewed the fresh and hardened properties of the UHPFRC. Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. This Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC.” This review is anticipated to increase the fundamental understanding of UHPC and encourage additional study and applications of UHPC.

1. Introduction

UHPC is a high-strength, high-durability cementitious material. It has the potential to be a viable solution for improving the “sustainability of buildings and other infrastructure components [1–7]. UHPC has “grown in popularity in many countries over the last two decades, with applications ranging from building components, bridges, architectural features, repair and rehabilitation, and

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vertical components such as windmill towers and utility towers, to oil and gas industry applications, offshore structures, hydraulic structures, and overlay materials [8–12]. Among all of these applications, road and bridge construction are the most common for UHPC use [13,14]. UHPC is used in a variety of nations, including Australia, Austria, Canada, China, the Czech Republic, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Switzerland, and the United States (US) [8,15,16]. The majority of projects in the aforementioned countries were inspired by government entities as pilot projects to stimulate future implementation. However, with tardy follow-up implementation, most countries' demonstration programs did not achieve the desired acceptability" [17–22]. The "lack of design codes, inadequate knowledge of both the material and production technology, and expensive costs appear to be limiting the implementation of this excellent material beyond the early demonstration projects" [8, 23–25]. Both the business and public sectors are increasingly paying closer attention to and pushing for greater efforts to make use of this novel and promising material" [26–30].

Existing codes for conventional concrete production and structural application do not fully apply to UHPC. Several countries are "developing design guidelines or suggestions for UHPC, including Switzerland [31], Canada [32], Germany [33], Australia [34], Japan [35], and Spain [36]. Each of these nationally evolving design guidelines has various material characterization needs, and each takes a different approach to the design process. Already in 2002, the Association Française de Génie Civil (AFGC) provided design recommendations for UHPC [37]. In 2016, a version of this was adopted in France as a national appendix to the ordinary concrete design code" (Eurocode 2) [38].

Discontinuous fiber reinforcement is "an important component of UHPC [39,40]. Fibers are required to impose the ductility in compression required for structural safety [41–44]. Fibers reduce brittle behavior and may enhance a variety of other material qualities, including as exploitable tensile strength and energy absorption capacity [45–48]. Fibers of various sizes, shapes, and materials are employed [49]. Variations in the distribution and orientation of the fibers are caused by a variety of elements, including the rheological characteristics of the fresh UHPC, the placement procedures, and the geometrical conditions defined by the formwork [50–52]. Variations in fiber composition, shape, combination, distribution, and orientation are all important factors in the complexity of UHPC structural design. Fibers are also a major contributor to UHPC's high unit cost and carbon impact. As a result, greater understanding of the impacts of fiber reinforcement is a critical step toward the establishment of widely approved design guidelines" and the widespread usage of UHPC [45,53–55].

Many researchers have conducted studies on UHPC, but information on materials and structural property of UHPC is still limited [56–60]. This review includes "five parts; Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. Part III reviewed the fresh and hardened properties of the UHPFRC. Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. This Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC. The purpose of this review is to summarize previous progress and to suggest some needs for future" researches.

2. Mixture design

As demonstrated in Fig. 1, "UHPC combinations are intended to create a high particle packing density, which leads to low porosity, high mechanical strengths, and impermeability. To build UHPC with goal performance, it is necessary to thoroughly analyze and evaluate the concepts, methodologies, and benefits and drawbacks of various generally used mixture design approaches [61–72]. The design ideas and attributes of these approaches are summarized in Table 1. The Anderson and Andreasen model is the most extensively used theoretical model for designing the UHPC [73] to get the greatest particle packing density[74,75]. However, because the impact

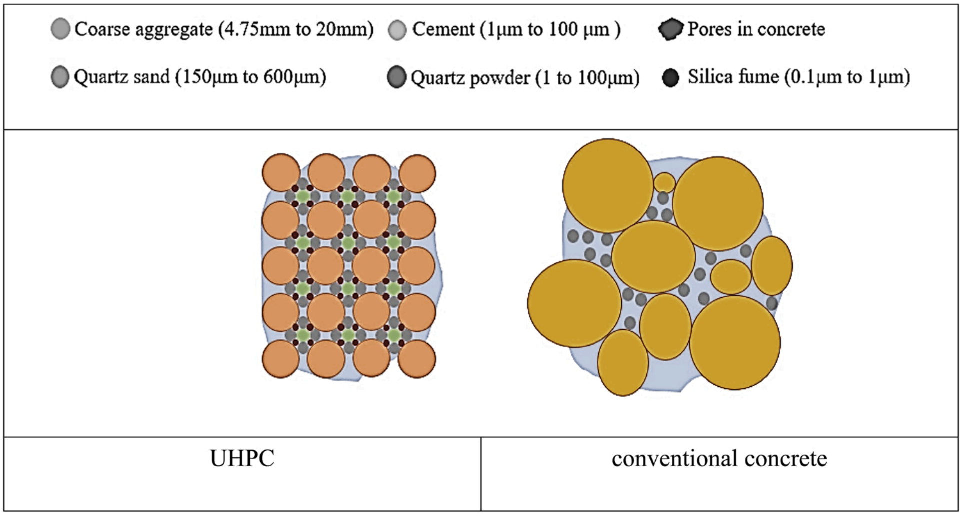


Fig. 1. Schematic particle packing of conventional concrete and UHPC in two dimensions. The particle packing density of the UHPC is greater [80].

of water and other liquids is not included, this approach only assessed particles under dry circumstances, which may not reflect the true particle packing of UHPC [76]. As a result, the wet particle packing density technique was devised to get the actual maximum particle packing [77]. However, because the greatest packing density does not necessarily result in the optimum UHPC performance, the performance-based technique was devised [78,79]. This section discusses two types of UHPC design methodologies: model-based methods (dry particle packing and wet particle packing) and performance-based methods".

2.1. Close packing method

2.1.1. Dry particle packing method

2.1.1.1. Discrete models. Table 2 shows the evolution of the discrete model, which assumes that the volume of each particle may be totally compressed according to particle size. The Furnas model [88] believed that particles did not interfere with each other and that proportioning, including superplasticizer dose (PSD), is "continuous, which is unsuitable for multi-component mixtures like UHPC. Following that, Powers [91], and Aīm and Le Goff [92], and others utilized a simple geometric model to describe the role of porosity for binary mixtures. They examined the wall effect interference coefficient to adjust the influence on porosity. Three notion assumptions were examined in the Toufar model: 1) Spherical aggregates; 2) Mono aggregate size; 3) Different sizes of fine and coarse aggregates [93], extending the concept from binary to ternary mixtures [94]. To begin, Roy, Scheetz and Silsbee [95] adjusted the Toufar model and revised the design parameters. If particle surface forces are neglected, the dry packing density suffers from particle form, distribution, and packing method. For multi-component mixtures, LPDM, SSM, and compressible packing model (CPM) were developed to convert traditional particle packing to virtual packing and adjust wall and loosening effect [96]. These discrete models are appropriate for multi-component mixes and have a significant influence on forecasting dry particle packing density". However, both the initial Furnas model and the succeeding CPM model have a flaw[97,98]. The mixed system contains only dry particles, which is considerably different from the actual state of concrete [99–105].

2.1.1.2. Continuous model. In contrast to the discrete models depicted in Fig. 2, the core of most continuous models is changing the composites content to match the goal curve (generated based on the experimental data or empirical statistics). Fuller and Thompson [109] created the first continuous model in 1907 to solve the aggregate packing issue. Talbot, Brown and Richart [110] refined the Fuller curve in 1923 (as shown in Eq. (1)), with the goal of solving the optimal aggregate gradation more simply.

$$P(D) = \left(\frac{D}{D\_max}\right)^{0.5} \tag{1}$$

where P(D) is "the fraction of solid particles less than size D, D denotes particle size (μm), and Dmax denotes maximum particle size (μm). In 1930, Andreasen [111] developed another continuous particle packing model" (see Eq. (2)).

$$P(D) = \left(\frac{D}{D\_max}\right)^{q} \tag{2}$$

where q is not a constant and the suggested value of q ranges from 0.33 to 0.50 depending on the aggregate gradation It is worth noting that the Andreasen and Andersen (AA) model was built differently than the Fuller model, despite the "fact that both models had comparable formulae and goal curves (the comparison results of optimization curves are present in Fig. 3). The target curve of the Fuller model was constructed mostly using experimental data or empirical statistics, whereas the target curve of the AA model was created using the assumption of particle packing similarity, as illustrated in Fig. 4 size analysis and geometry (more closed to the calculation of discrete models). Later, Funk and Dinger introduced the modified Andreasen and Andersen (MAA) model, which took the minimum particle size into account in order to produce more accurate prediction findings". Eq. 3 represents the theoretically ideal particle packing curve.

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \tag{3}$$

Table 1
UHPC mixture design strategies that are often employed [81].

"Methods	Design principles	Ref.
Mixture design method based on artificial neural networks (ANN) model	Train an ANN model using a large amount of experimental data and update the weights of input and output on a regular basis to close the gap between experimental and projected values.	[82,83]
Statistical mixture design method	The raw material percentage is seen as changeable, and UHPC performance is regarded as a reaction. Determine the best UHPC mixing percentage by using suitable models to examine experimental data with mistakes removed.	[84,85]
Method based on rheological properties of paste	The type and percentage of each component are continually modified to meet the goal rheological qualities of UHPC to assure the optimal performance based on the link between rheology and raw materials.	[86,87]
Close packing method	Obtain increased strength and durability by ensuring the tightest packing of the solid particles of UHPC by changing the quantity of cementing components and fine aggregates.	[88–90]"

Table 2
Summarization of discrete particle packing models [81,106].

“Year	Models	Packing system			Effect on particle packing		Main features	Refs
		Multi-component	Ternary	Binary	Wall effect	Loosening effect		
1929	Furnas model			✓			Assuming particles to be independent	[88]
1967	Aim and Goff model			✓	✓		Proposed wall effect coefficient	[92]
1969	Powers model			✓	✓	✓	Considered wall and loosening effects	[107]
1977	Toufar model		✓		✓		Separation of ternary into numerous binary systems	[94]
1986	LPDM	✓			✓	✓	Calculated packing density when particles are spread continuously.	[108]
1994	SSM	✓			✓	✓	Proposed virtual packing density and extensively used	[96]”
1999	CPM	✓			✓	✓		

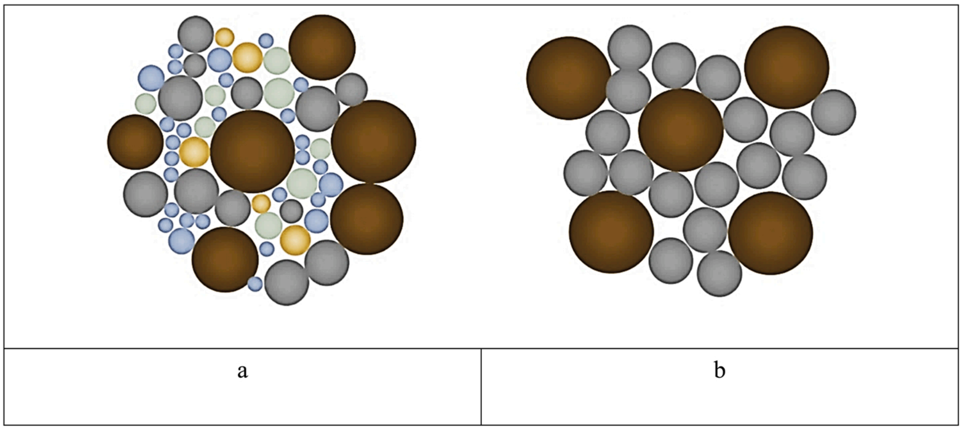


Fig. 2. The schematic graphic reveals the primary distinctions between binder packing models (a) discrete models and (b) continuous models [112,113].

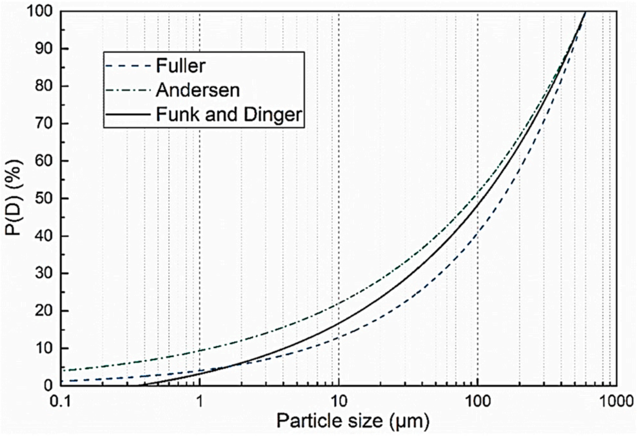


Fig. 3. A comparison of the optimization curves of several continuous models [112].

D denotes “particle size, while P(D) is the fraction of solid particles smaller than D. Dmax and Dmin are the maximum and smallest particle sizes, respectively, while q is the distribution modulus. In the MAA model, higher values of the distribution modulus (q more than 0.5) result in coarse mixtures, whereas lower values (q less than 0.25) result in fine-particle-rich concrete mixes” (typically UHPC).

As previously stated, “the packing problem was handled by modifying the material percentage to approach the desired curve, and it

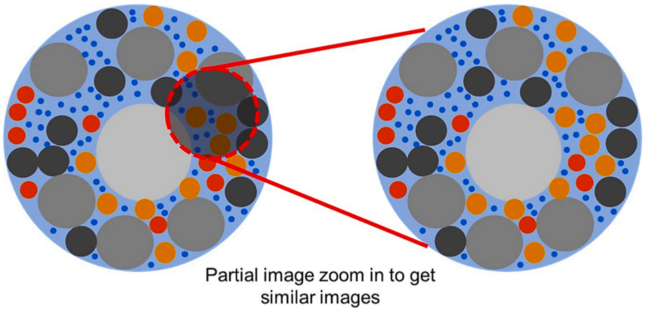


Fig. 4. The schematic illustration of the particle accumulation similarity assumption in the AA model [113,114].

was frequently solved using an iterative algorithm. Furthermore, the sum of the squares of the residuals (RSS) value was utilized to calculate the model's deviance. Specifically, an optimal fit between the composed mixture and the target curves might be achieved by modifying the proportions of each individual ingredient using an optimization technique based on the Least Squares Method (LSM)," as shown in Eq. (4).

$$\sum_{i=1}^{n}[P_{min}(Di)-P_{tar}(D_i)]\text{^}2 \tag{4}$$

where P_{mix} and P_{tar} are the composed mixture and the target grading calculated from Eq. (3). So far, the MAA model has been utilized effectively to develop UHPC and sustainable UHPC, as mentioned in the following section.

2.1.2. *Wet particle packing method*

When the fine particles are dry, "the high particle friction prevents the packing density from increasing [115]. The presence of water can help to reduce friction. The force can be removed when fine particles are saturated or over-saturated [116]. Furthermore, the addition of HRWR can alter the thickness of the water coating on particles, hence affecting the packing density of UHPC [117]. As a result, the wet particle packing model achieves a greater particle packing density than the dry packing model, as illustrated in Fig. 5. A high wet packing density improves UHPC's macro-meso-micro pore structure" and compressive strength [117–119].

The wet particle packing model was presented [77], "taking into account the effects of water and HRWR. The following techniques should be followed to achieve the wet particle packing density: (1) determine the starting w/b; (2) weigh and mix the water and cementitious materials; (3) transfer the mixture to a cylinder mold and weigh the quantity of paste; and (4) compute the solid concentration (Φ) and void ratio (u) using Eqs. (5)–(7); (5) repeat the preceding stages with a reduced w/b ratio" until the maximum packing density is obtained.

$$V_c=\frac{M}{p_w u_w+p_a R_a+p_\beta R_\beta+p_\gamma R_\gamma} \tag{5}$$

$$\mathrm{u}=\frac{\mathrm{V}-\mathrm{V_c}}{\mathrm{V_c}} \tag{6}$$

$$\varphi=V_c/V \tag{7}$$

where M and V are "the mass and volume of paste in the cylindrical mold (the mold has a diameter of 62 mm and a height of 60 mm); ρ_w is the density of water, ρ_α, ρ_β and ρ_γ the corresponding solid density of different cementitious materials; R_α, R_β and R_γ are the volumetric ratios of different cementitious materials[120–122]."

Fig. 6 depicts "an example of calculating the minimum void ratio (u) and maximum solid concentration (*Φ*). Given the maximum wet packing density, the optimal w/b may be derived."

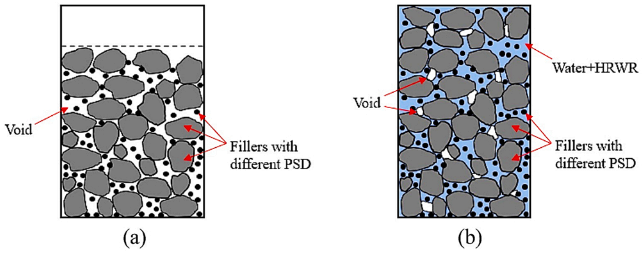


Fig. 5. There are two particle packing models: (a) dry particle packing and (b) moist particle packing. The moist particle packing model has a greater packing density [123].

However, “the maximum particle packing density does not necessarily result in UHPC performance. For example, high particle packing does not guarantee the UHPC mixture’s strong fire resistance since a relatively high porosity is desired to release pore pressure in a high-temperature environment.”

2.2. Rheology-based mixture design method

The rheology-based mixture design approach determines the optimal mixture composition and fraction of UHPC with desired rheology and toughened performance based on the interaction between components and rheological characteristics of paste. “The deformation and flow characteristics of UHPC under the application of external force are referred as its rheological properties. UHPC’s major rheological metrics are yield stress and plastic viscosity. Yield stress is the highest stress that prevents UHPC plastic deformation, while viscosity reflects UHPC flow properties and controls phase dispersion and direction in fresh UHPC matrix. Uniform fiber distribution and sufficient mechanical strength and toughness may be achieved using UHPC with suitable rheological characteristics [86]. Particle properties [124], fibers content [125], skeleton wet packing density, admixture, water content [126], and external environment humidity and temperature are all factors influencing UHPC rheological properties”. Fig. 7 depicts the effect of each component on the rheological characteristics of cement-based materials.

The process of mixture design technique (performance-based method) developed by Meng, Valipour and Khayat [127] to “optimize rheological characteristics and compressive strength of UHPC is shown in Fig. 8. Following rheological property adjustments and radar chart analysis, binary, ternary, and quaternary cementitious systems with regularly utilized content ranges were chosen. With 28-d compressive strength of 120–125 MPa under conventional curing and 178 MPa during heat curing, the produced UHPC mixes were self-consolidating and stable.”

The fundamental benefit of the performance-based technique is “that mixture design parameters such as w/b, fiber content, and binder to sand ratio may be computed immediately and correctly based on the link established between the variables and the goal performance.”

2.2.1. Effect of fibers on rheological properties of UHPC

Fiber is “required in UHPC to provide high tensile strength and toughness [129]. Fibers’ strengthening and toughening effects are primarily determined by fiber dispersion and orientation throughout the system, as well as the bonding characteristics between fibers and matrix [130]. According to Young modulus, fiber form, and mixture consistency, the fibers frequently utilized in UHPC may be classified as stiff or flexible [131]. The inclusion of fibers may have a significant impact on particle packing and, ultimately, the rheological characteristics of the paste. When the fibers are changed from disordered to dense, and the aspect ratio of the fibers is small enough, the packing density approaches that of the particles, as illustrated in Fig. 9 [131]”. Rigid fiber may block particle packing by pushing particles apart, but flexible fiber can boost packing density by filling the space between particles [124].

Incorporating fibers may make UHPC more viscous, “reducing fiber dispersion and orientation and, finally, reducing flowability and impairing UHPC hardened performance [125]. The following three components are involved in the underlying action mechanisms for lowering flowability: (1) decreased free water content due to absorption on the surface of the fibers; (2) mutual winding associated with uniform fiber dispersion and distribution; (3) increased requirement for cement paste to cover the surface of the fibers [132]. Controlling the flowability of the paste allows for homogeneous dispersion and distribution of fibers [133]. The interlocking of steel fibers and coarse aggregate in UHPC, on the other hand, considerably limits its workability. Steel fibers cannot fully wrap coarse aggregate with high particle size, and the bonding action between aggregate and fibers is diminished. The proper steel fiber length and aggregate gradation should be chosen [134]. According to studies, the maximum particle size of coarse aggregate should be less than 25 mm, and the steel fiber length should be between 2 and 5 times the maximum size of coarse aggregate [135].”

The aspect ratio and volume fraction of fiber in UHPC have a considerable impact on its performance. The possibility of fiber heterogeneous dispersion and flocculation in UHPC rises as the fiber aspect ratio increases [136]. To reduce excessive fiber content, “UHPC is made with less fiber and a higher fiber aspect ratio [137]. According to research, when the critical fiber content is exceeded, the flocculation of fibers renders flow under UHPC’s own weight impossible [138]. To manufacture UHPC with acceptable workability,

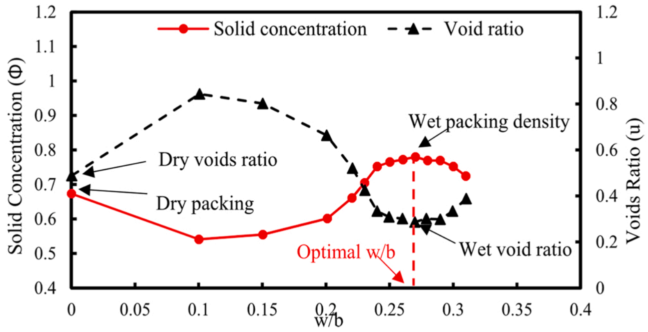


Fig. 6. Solid concentration and void ratio trends of common mixes vs w/b The ideal w/b for the maximum moist particle packing may be obtained using this relationship [76].

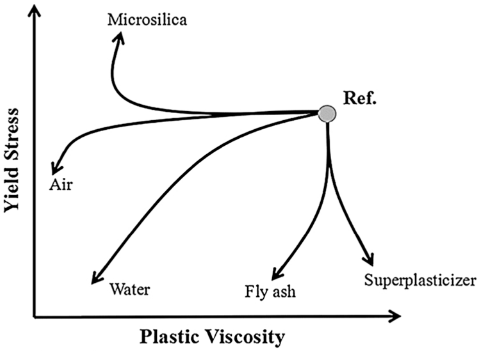


Fig. 7. Effects of additives on concrete rheology [128].

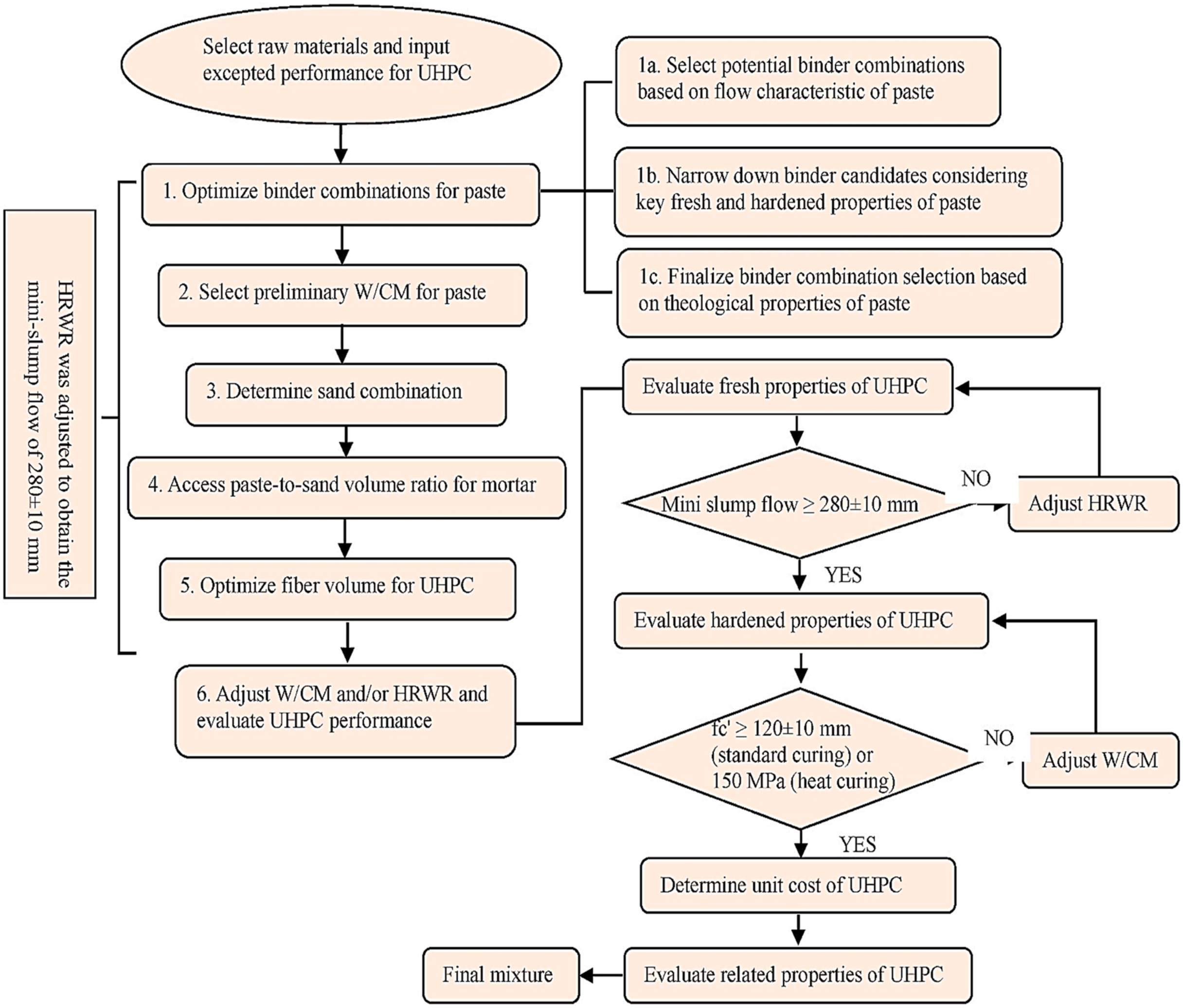
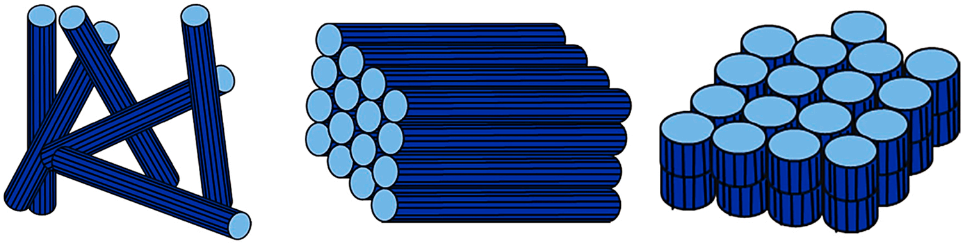


Fig. 8. UHPC mixture design based on rheological characteristics and compressive strength [127].

the aspect ratio of fiber utilized in UHPC varies between 50 and 100 [139], and the volume fraction of fiber is 0.5% – 2.5%. Sun, Yu, Shui, Wang, Qian, Rao, Huang and He [140] discovered that the maximum percentage of steel fibers in UHPC is 2.5% to fulfill flowability criteria. When the same fiber volume is used, short fiber promotes higher compressive strength of UHPC than long fiber. This might be because longer fibers are more prone to aggregation, producing UHPC problems with vibration and flow" [141].



(a) Random packing of fibers

(b) Most densely packed fibers

(c) Close to the packing of spherical particles

Fig. 9. Different stiff fiber packing states [131].

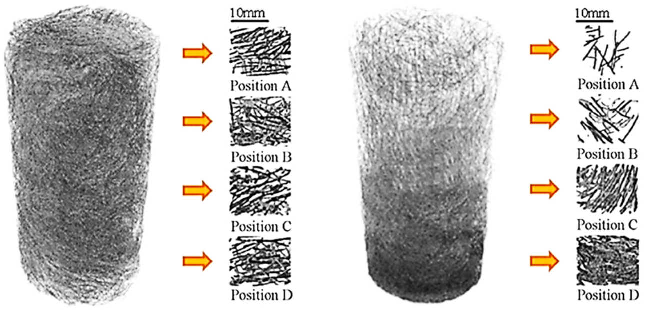
Fiber sinks naturally in concrete due to gravity and collects in the specimen's middle and bottom parts. Wang, Gao, Zhang and Han [142] discovered significant sedimentation of 2% fibers after combining 1% and 1.6% superplasticizer in UHPC. Steel fibers, on the other hand, are "equally dispersed in UHPC with 1% superplasticizer, exhibiting high yield stress as seen in Fig. 10. When the steel fiber content was raised from 0.5% to 2.5%, the slump value of UHPC reduced dramatically from 4.29 to 1.10 [73]. Furthermore, interlaced fibers created greater air void, which is detrimental to UHPC strength [143]. Teng, Meng and Khayat [144] discovered that when fiber concentration grew from 1% to 3%, fiber dispersion and orientation were directly linked to UHPC plastic viscosity".

Wang, Gao, Huang and Han [86] chose four w/b ratios and superplasticizers to modify the rheological characteristics of cement mortar while controlling fiber distribution in UHPC. "Fiber dispersion was poor when the w/b ratio was low and the fiber concentration was high. Furthermore, the impact of superplasticizer on steel fiber dispersion was more pronounced at higher w/b ratios. The development trend of the distribution coefficients of UHPC specimens with varied fiber contents is comparable, as shown in Fig. 11, and decreasing rheological parameters might worsen the non-uniform dispersion of fibers in a particular range. Better stability was seen when the fiber concentration was 3%, which might be attributed to mechanical interlocking of additional fibers. Other investigations [15,144,145] have shown that when the rheological characteristics of the paste are reasonable, the dispersion of steel fibers is ideal. Under the same dispersion and orientation coefficient, the plastic viscosity of UHPC mortar increases from 1% to 3%, and the change in fiber distribution is restricted after surpassing the ideal value. It can also be shown that for UHPC with a larger fiber concentration," optimum fiber dispersion necessitates a higher paste viscosity.

The rheological characteristic of cement paste is "used as a baseline in the UHPC mixture design to manage the distribution of steel fibers. Sufficient rheological characteristics of UHPC may be produced by continuously adjusting the w/b ratio and superplasticizer content to achieve uniform dispersion and orientation of steel fibers. The assessment of UHPC mixture ratio using rheological characteristics alone as a reference is often one-sided, and many repeated trials are required. Furthermore, rheological test results is very susceptible to factors" such as the external environment.

2.3. Other methods

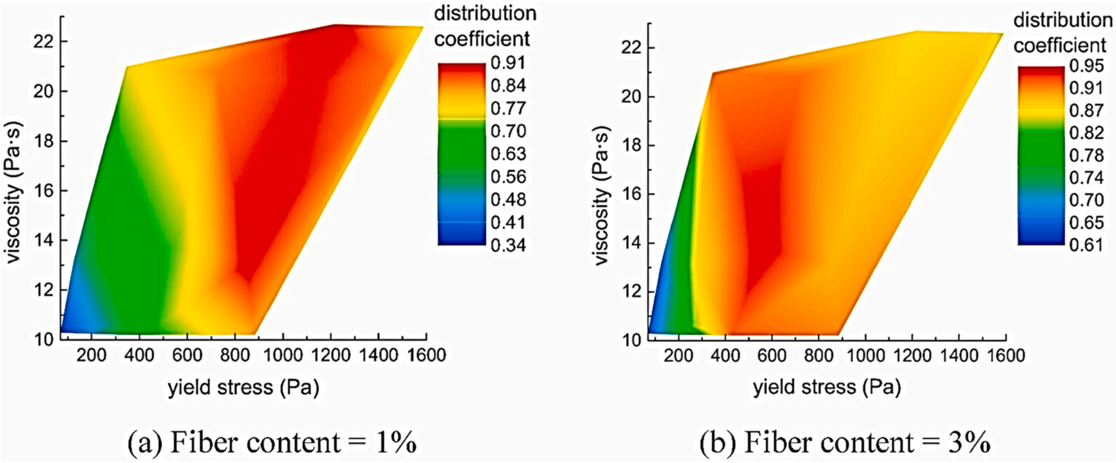
In addition to empirical approaches, statistical experimental design methods based on artificial neural networks (ANN) are employed in UHPC product and process optimization [146]. These methodologies have previously been used in many concrete behavior experiments to "optimize the UHPC mixture in order to achieve the necessary performance [147]. Based on the mix design and curing circumstances, Taghaddos, Mahmoudzadeh, Pourmoghaddam and Shekarchizadeh [148] suggested using an adaptive neuro-fuzzy inference system (ANFIS) to estimate the compressive strength of UHPC. Aside from cement dosage, the cost and availability of steel fibers used in UHPC mixtures are key challenges. Ghafari, Costa and Júlio [149] used response surface methodology



(a) SP dosage 1.0%

(b) SP dosage 1.6%

Fig. 10. Steel fiber distribution in UHPC cylinders [142].



(a) Fiber content = 1%   (b) Fiber content = 3%

Fig. 11. Variations in viscosity and yield stress values of cement mortar with different distribution coefficients at 1% and 3% fiber concentrations [86].

(RSM) to construct a statistical model for estimating the maximum flexural strength of self-compacting steel fiber-reinforced UHPC with different steel fiber contents. Fiber content optimization may be anticipated using this methodology. Ghafari, Costa and Júlio [84] employed a statistical mixture design (SMD) methodology to optimize the UHPC mixture design. Individual constituents and their interactions were investigated in order to estimate the compressive strength of UHPC with a minimum cement concentration of less than 670 kg/m3 and without employing heat curing” [84].

As previously stated, “the curing condition of UHPC has a significant influence on its compressive strength. The aforementioned models, however, have not addressed this issue. Ghafari, Costa and Júlio [149] proposed numerous ANN models for forecasting UHPC performance under various curing circumstances. Because of its distributed and nonlinear character, this ANN model can forecast compressive strength and slump flow with more accuracy than the SMD model. Based on this model research, the optimal quantity of cement and silica fume in concrete was determined to be 24% and 9% by volume, respectively” [84].

Over the last 25 years, advances in concrete technology have enabled the manufacture of UHPC with excellent rheological behavior, including “workability, self-placing, and self-densifying properties, as well as improved mechanical and durability performance with very high compressive strength and non-brittleness behavior [150]. UHPC development typically begins with the design of the granular structure of the aggregates, with the selection and characterisation of acceptable fines for optimal packing density being critical. UHPC is designed to provide a densely compacted cementitious matrix with high workability and strength [151]. In brief, well-chosen raw ingredients and complex technological techniques are often needed to achieve the admirable characteristics of a UHPC. Most publications base their UHPC mixture designs on the benchmark mixture produced by Richard and Cheyrezy [80]. In the manufacturing of UHPC, a high binder quantity and SP dose are often used in comparison to CC. UHPC may be made with a sufficient blend of cementitious materials, correct sand gradation, and the insertion of fiber reinforcement and SP to provide excellent flowability with better mechanical qualities and durability [80]. These exceptional mechanical qualities, however, need expensive and advanced technical preparation. The expensive material cost, difficult production technology, and limited accessible resources severely restrict its commercial growth and implementation in contemporary building, particularly in underdeveloped nations” [152]. These constraints encourage the development of cost-effective UHPC that uses alternative materials with comparable functionality to replace the

Table 3
shows the advantages and disadvantages of different mixture design strategies [81].

“Methods		Advantages	Disadvantages
Mixture design method based on rheological properties of paste		Adjusted ideal rheology to provide generally equal dispersion of the solid skeleton, particularly fiber, and improved UHPC hardened performance	There was a lack of a theoretical model for estimating the new performance of UHPC coupled with fiber.
Close packing model	Based on wet packing density	More exact and real packing density value when water and superplasticizer effects on solid particles are taken into account	Reduced wet packing density as a result of fine particle aggregation
	Based on dry packing density	Increased particle packing density; decreased porosity and enhanced UHPC strength	Lower dry packing density without taking into account the interaction of the solid and liquid phases of water and superplasticizer; lower UHPC strength
Mixture design method based on ANN model		Predicted consistency and strength of freshUHPC; Reduced number of experiments	To train the model, a vast quantity of data was required. Data overfitting occurred.
SMD method		The association between mixture proportioning and UHPC performance has been established; the number of trials has been reduced.	Reduced model accuracy as a result of component interaction”

pricey UHPC composites in order to enhance its acceptability level.

2.4. Comparison of different mixture design methods

The advantages and disadvantages of the current UHPC design approaches are outlined in Table 3 based on the aforesaid findings.

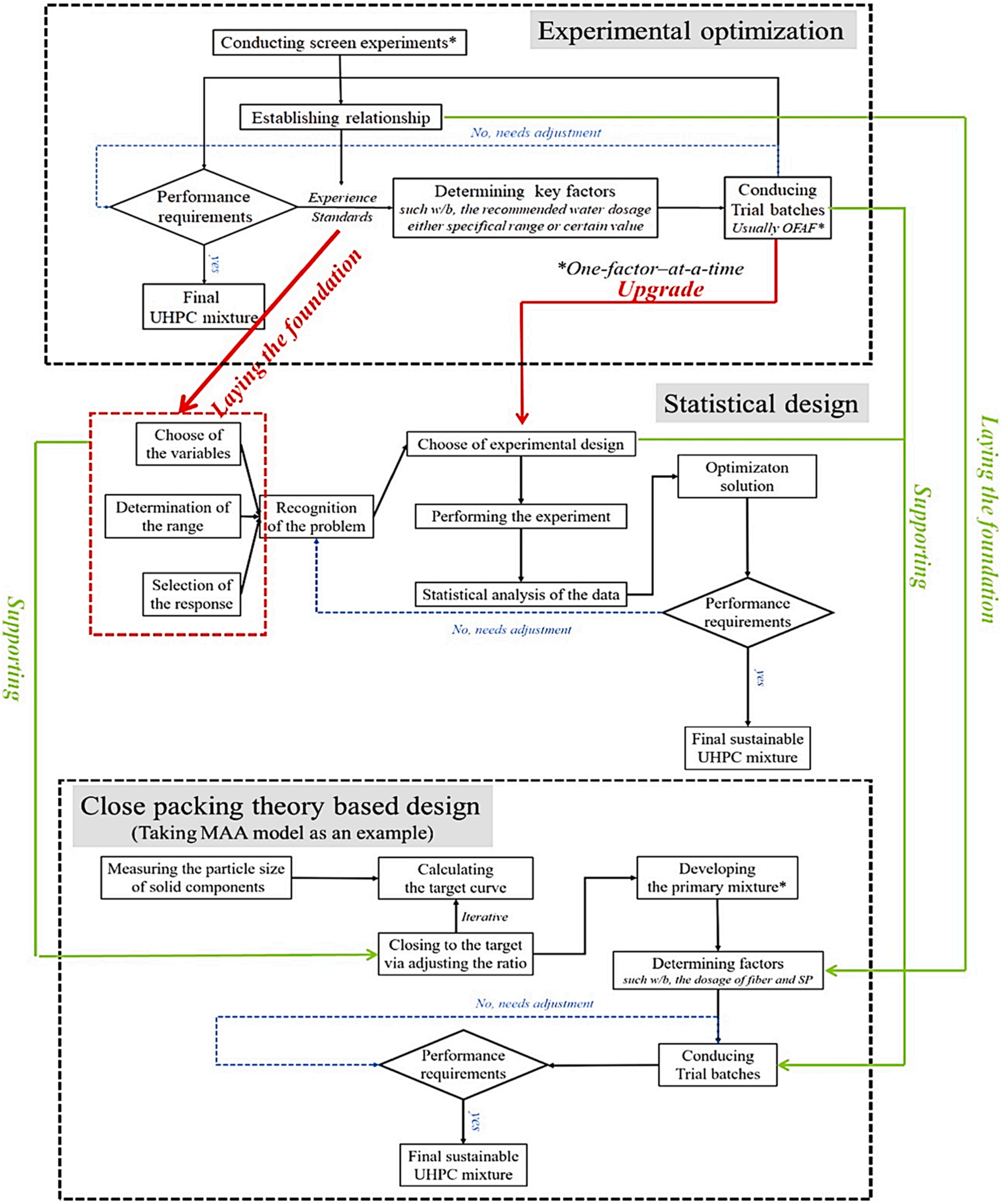


Fig. 12. The inherent link between sustainable UHPC design methodologies[113].

At the moment, “the design technique based on particle packing is extensively employed. However, most models fail to account for the influence of liquid phase on solid particles, resulting in a discrepancy between predicted and actual outcomes. The impacts of different components in UHPC, such as aggregate, fibers, and superplasticizer, on the yield stress and viscosity of UHPC must be considered in a rheology-based mixture design technique for UHPC. Many trial tests are necessary to get the best rheological characteristics by altering the combination amounts. Although statistical analysis may minimize the number of trials, accuracy is determined by independent factors and the model used”. Although the ANN model is based on the biological nervous system, its usefulness is restricted because to over-fitting.

2.5. Practical recommendations

Wang, Wu, Zhang, Yu, Hou and Shui [113] previously applied the “experimental optimization, statistical technique, and close packing-based design strategy in the field of sustainable UHPC mixture design. There are no visible boundaries between the three techniques, as shown in Fig. 12, which can be observed in experimental optimization when statistical approaches such as orthogonal design and univariate linear model are used in either screening experiment design or trial batches. In addition, mixed utilization will be a trend in the hybrid design of sustainable UHPC (for example, the blending of packing model and statistical approach can be used to define the packing and flow coefficients of sustainable UHPC).”

3. Sample preparation, mixing, casting, and curing

3.1. Sample preparation extraction

Using external or internal energy, such as vacuum mixing and pressure before and during setting, during sample preparation is “an efficient technique to minimize the volume of pores and produce the necessary mechanical properties of UHPC [153]. Dils, De Schutter, Boel and Braem [154] used vacuum mixing with three different pressure levels, vacuum (100 mbar), semi-vacuum (500 mbar), and atmospheric pressure (1013 mbar), and discovered that decreasing the mixing pressure increased compressive strength while decreasing the air content of concrete. İpek, Yilmaz and Uysal [155] used pre-setting pressure on RPC and found that the unit weight value of RPC with pre-setting pressure at 5 MPa was 2585 kg/m^3, up 3.5% from 2498 kg/m^3 without pressure. It climbed by about 1% at each pre-set pressure interval until it reached 25 MPa. After 25 MPa of pre-setting, the unit weight value and volume of RPC rose by 8.6% (2712 kg/m3) and dropped by 7.9%, respectively, compared to control RPC. Meanwhile, pre-setting pressure considerably enhanced RPC, toughness, and Young’s modulus [156]. When the materials were pre-setting pressured at 25 MPa, their compressive strengths and Young’s modulus were 420.31 MPa and 84 GPa, respectively, while they were 206.36 MPa and 58 GPa without” [156]. These advanced technologies, however, are too expensive to fulfill the need for large-scale project engineering.”

Furthermore, the processes for creating and/or acquiring UHPC samples for material testing are “not materially different from those utilized for conventional concrete. Cast specimens may be formed into any shape requested using typical concrete molds. However, it is crucial to note that UHPC flow during casting might result in preferred fiber orientation, which can affect subsequent test findings [157].”

Extraction of specimens from bigger components may be performed using typical concrete procedures. In general, “UHPC and ordinary concrete are made up of identical ingredients. Conventional cutting and grinding equipment, unsurprisingly, has been proven to be both suitable and effective [157].”

3.2. Mixing and casting

UHPC is close enough to traditional concrete that the vast majority of traditional concreting processes remain relevant and usable. UHPC may be mixed with almost any ordinary concrete mixer. As indicated in Fig. 13, “the elements of UHPC are currently mixed, cast, and vibrated like ordinary concrete. After mixing the dry powder components for around 10 min, the water and superplasticizer are added and combined for another 5–10 min. Fibers are added as required when the mortar matrix demonstrates acceptable flow ability for optimal workability and viscosity. When incorporating hybrid fibers of varying sizes, micro fibers are added to the mortar mixture by hand first, followed by macro-fibers” [158].

However, “it should be noted that UHPC uses more energy than regular concrete, therefore the mixing time will be longer. Because of the higher energy input, as well as the decreased or deleted coarse aggregate and low water content, special methods are required to guarantee that the UHPC does not overheat during mixing. This issue may be solved by using a high-energy mixer or by cooling the ingredients and partly or completely replacing the mix water with ice. UHPC may now be mixed in ordinary pan and drum mixers, including ready-mix trucks” [157].

UHPC placement may “occur immediately after mixing or may be delayed until more mixes are done. Although elements like as temperature and chemical accelerators may impact the dwell time prior to the commencement of the cement hydration processes, it often takes several hours before UHPC begins to set.” The UHPC should not be permitted to self-desiccate during any lengthy dwell period [157].

Fiber-reinforced concrete casting necessitates specific considerations in “terms of placement procedures. UHPCs have rheological properties comparable to traditional self-consolidating concretes, which may need greater form preparation while simultaneously allowing for decreased during-cast efforts. Because of the fiber reinforcement, internal vibration of UHPC is not suggested,” although minimal exterior form vibration may be used to promote the escape of entrapped air.

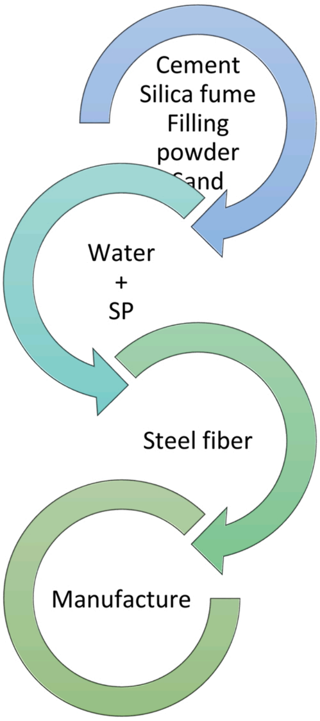


Fig. 13. UHPC mixing techniques [159].

Casting processes may alter the long-term mechanical and durability qualities of UHPC because they influence the dispersion and orientation of the fiber reinforcing. First, during casting, fiber reinforcement has a tendency for aligning in the direction of flow. When developing a casting process for a component, this behavior must be identified and taken into account. Second, the capacity of the fiber reinforcement to remain suspended in the UHPC is determined by the concrete's rheology. As a result, any changes to the rheology or dependence on form vibration must be carefully evaluated.

3.3. Curing procedures

The use of proper curing processes is "critical to the performance of any concrete, particularly UHPC. UHPCs, like other concretes, need hydration water; but, unlike other concretes, UHPCs have been created to require very little extra water, instead encouraging acceptable rheological behaviors via the use of an optimized granular material gradation. Because of the lower water content in a UHPC mix, curing methods must be carefully monitored to ensure that the incorporated water does not escape prior to hydration" [157].

Any exposed UHPC surface must be covered with "an impermeable layer immediately after casting. Metal, plastic, or plastic-coated wood are suitable materials for surface sealing. The seal should lay against the UHPC and leave no gap between the covering material and the new concrete. Surface sealing prevents surface dehydration," which may cause cracking and severe loss of final material properties [157].

After installation, further heat may be supplied to UHPC castings to hasten setting characteristics and achievement of final qualities. It is critical that any additional heat helps to enhance the temperature of the UHPC while preventing material dehydration.

The UHPC should be sealed in the formwork until it has developed sufficient characteristics to maintain itself and not dehydrate. A compressive strength of 97 MPa is sometimes used as a surrogate metric to indicate that an acceptable amount of hydration has been achieved.

The application of a steam treatment may be used to "complement the natural curing process of UHPC. This treatment may both improve and speed up the acquisition of UHPC's ultimate mechanical and durability qualities. A typical steam treatment involves exposing the UHPC to a 190 °C, 95% humidity atmosphere for at least two days. This process is typically used at a precast concrete facility shortly after form stripping. This treatment is not required and may be skipped if the qualities of the as-cast UHPC are suitable for the application under consideration" [157].

4. Conclusions

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

The main ideas behind designing UHPC are to make it less porous, improve its microstructure, make it more uniform, and make it stronger.

The characteristics of UHPC are significantly influenced by the raw ingredients, preparation method, and curing regimens.

Before the method can be used effectively, the most important questions must be answered. These include how the physical packing system affects the hydration process of sustainable UHPC and how the van der Waals force affects the packing state.

Using a design based on close packing is more in line with UHPC's theoretical background, which is based on dense packing.

The particle packing of UHPC and the flowability of paste should be considered when determining water and superplasticizer needs.

It is worth mentioning that continuous packing models often yield an appropriate fraction of solid particles. So, parameters like the ratio of water to binder, the amount of fibers, and the dose of superplasticizer need to be set up more, either through experiments or statistics.

The rheology of UHPC can be changed by changing the proportions of the mixture. This includes the type and amount of fibers, the w/b ratio, and the superplasticizer dose.

The rheology-based mixture design approach may be used to manufacture UHPC with sufficient flowability, ensuring generally uniform dispersion and orientation of strengthening components such as fiber and aggregate to improve UHPC performance.

Experiments have been conducted in order to "determine the optimal rheological characteristics of UHPC mixed with fibers, and the rheological test data is vulnerable to external influences" such as environment.

Declaration of Competing Interest

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

Data Availability

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

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