International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 6 ǁ June 2023 ǁ PP. 82-87

Review on Design Methodologies for the Sustainable Development of Ultra-High Performance Concrete (UHPC)

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Abstract
Ultra High Performance Concrete is an advanced cementitious material with high strength and excellent durability. Since its introduction, the unique properties of UHPC make it a perfect candidate for the future sustainable and resilient infrastructure. In spite of the constant efforts of researchers to improve the performance of UHPC, the focus is more shifted to the never decreasing issue of sustainability. Sustainable ultra-high performance concrete (UHPC) design is the process in which the individual constituents are varied for their type and quantity in order to reduce the negative effect on environment without affecting the general targets of workability, mechanical properties and durability. This paper mainly focus on three sections: (1) The evolution, design principles and constituents of Ultra High Performance Concrete (2) The design of sustainable UHPC based on the experimental optimization and particle packing models and their limitations and (3) Softwares for particle packing in UHPC.

Keywords: *Ultra High Performance Concrete, Sustainable UHPC, Experiment optimisation, Particle packing models, EMMA Software.*

Date of Submission: 23-05-2023 Date of acceptance: 04-06-2023

I. INTRODUCTION

Reactive powder concrete (RPC), commonly referred to as ultra-high-performance concrete (UHPC), was created in France in the 1990s. UHPC is characterized by low water-to-binder ratio, high particle packing density, high-volume of steel fibers, and proper addition of chemical admixtures. UHPC exhibits good flowability and high mechanical properties including compressive strength and tensile strength and superior durability because its matrix is nearly impermeable to carbon dioxide, chloride, sulphate, etc [1].

During the past three decades, structural applications of UHPC have been recognized in Europe, North America, Australia, Asia and New Zealand. The pre-stressed hybrid pedestrian bridge, which completed in 1997 at Sherbrooke in Canada was the first engineering structure application of UHPC [2]. In 2001, the first UHPC road bridge was designed and constructed at Bourg-lès-Valence in France [3]. However the widespread practical implementation of UHPC is hindered by numerous challenges such as lack of commonly accepted standards for testing methods, design guides for engineers, and quality control methods in manufacturing facilities [4].

During the past years, instead of looking for ways to attain superior strength, the focus of many researchers shift to reduce CO_2 emissions and initial materials cost for more eco-friendly and economical UHPC. The utilization of agricultural and industrial waste as alternatives for cement, aggregate, and reinforcing materials in the production of sustainable UHPC can be a solution [5]. This paper aims to deliver a comprehensive review across the field of sustainable UHPC design specifically, two main approaches, including experimental optimization, and close packing-based design have been discussed. The merit and limitation, of the above methods have been discussed, provide guidance for the design of sustainable UHPC for meeting various design requirements.

1.1 UHPC EVOLUTION AND DESIGN PRINCIPLES

The plain concrete (PCC) made of Portland cement and aggregates is generally considered as the first generation of concrete. But this concrete possess lower tensile strength and ductility, leading to failure in beam and slab structures. This led to the incorporation of reinforcement with steel bars and claimed as the second generation of concrete. This ruled as the dominant construction material throughout the 19th and 20th centuries. In spite of the previous improvements, researchers still look for a solution to achieve higher strength, to stop the penetration of Chloride ions and other harmful materials into the concrete which would lead to iron rebar corrosion and poor concrete durability as well as an alternative materials for Portland cement to reduce the CO_2 emissions This was satisfied by the development of Ultra-High-Performance Concrete or UHPC [6].

The basic idea of producing a concrete with a very high strength and dense microstructure was already developed in the 1980s. However, it was made popular by the development of efficient SP that enabled the production of easy flowing concrete with optimized particle packing and low w/b [3]. The improved characteristics of UHPC is based on the following principles [7]:

I. Reducing the porosity by optimizing the granular mixture by incoperating a wide distribution of powder size classes and reducing the W/B.
II. Improving the microstructure by the post set heat treatment to speed up the pozzolanic reaction of SF and to increase mechanical properties.
III. Improvement of homogeneity by eliminating coarse aggregate and replacing it with well graded fine sand
IV. Introducing very high strength ductile steel fibers in the formulation to improve ductile behaviour.

1.2. CONSTITUENTS OF UHPC

The major principle for producing an effective UHPC is to improve the micro and macro properties of its mixture ingredients in order to escalate mechanical homogeneity, maximum particle packing density and minimum size of flaws [4]. This is achieved by high binder content, low water-to-powder ratio, and incoperation of ductile steel fibers. The basic components of UHPC is shown in figure1.

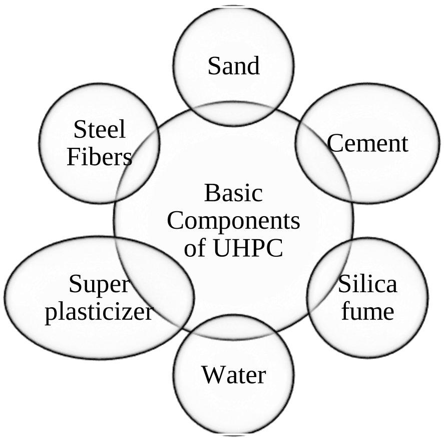


Figure1: Basic components of UHPC Mix

Compared to normal-strength (NS) and high-performance concrete (HPC), a relatively high proportion of cement is used in UHPC and thereby low water/binder ratio (w/b). Because of this very low w/b of UHPC, only part of the total cement hydrates and the unhydrated cement can be replaced with agro industrial residues or by-products. This is satisfied by the incorporation of blast furnace slag, fly ash, silica fume, and other pozzolans such as agricultural ashes [8]. In addition to the microfiller effect, silica fume also enhance the strength properties of UHPC through its pozzolanic reactions [4]. The decrease in the workability of UHPC contributed by very low w/b can be compensated by adding effective superplasticizers (SP). High-range water reducer (HRWR) has been used in UHPC to achieve a self-consolidating property and among the different types the polycarboxylate ethers (PCE) HRWR shows high efficiency in dispersing cement particles [5] as shown in figure 2.

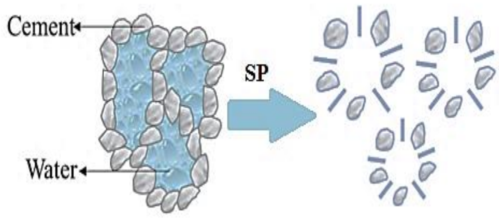


Figure2: The effect of SP on the cement packing in UHPC

Eliminating coarse aggregates in UHPC mixtures reduces weaknesses induced by such ITZ and the fine aggregate like quartz sand plays an important role in reducing the maximum paste thickness [9]. Because of the high strength and homogeneity of UHPC, it is very brittle which can be made ductile by adding steel fibers [10].

II. SUSTAINABLE DEVELOPMENT OF UHPC BASED ON THE EXPERIMENTAL OPTIMIZATION

Experimental optimization continues to exist as the most commonly used and the most reliable method for the design of all type of concrete including UHPC [11]. In order to determine the addition or replacement ratio of alternatives in UHPC, a screening experiment is conducted initially. This is done by exploring the effect of these alternatives on the properties of UHPC. After quantifying the relationship, certain ranges of key factors such as water to binder ratio, aggregate content, superplasticizer (SP) dosage can be determined. Then after conducting trial batches by changing one factor at a time an acceptable design mix can be produced until the performance of UHPC meets the standards.

2.1 ALTERNATIVES INCORPORATED IN UHPC

To satisfy the sustainability needs of UHPC, various alternatives have been used to replace the components like cement, silica fume and aggregates in UHPC. This includes fly ash (FA), limestone powder, rice husk ash (RHA) and glass powder. Type C and Type F fly ash have been used in development of UHPC [5]. The particle shape of fly ash is more spherical than cement, thereby decreasing the inter-particle friction, and thus increases the workability of the concrete as the dosage increases from 0% to 40% [12]. The combination of SF and RHA can increase the total cement replacement percentage up to 40% to produce UHPC [13]. The incorporation of RHA and GGBS improves workability, compressive strength and autogenous shrinkage of UHPC containing RHA [14].

Limestone powder can be a potential contributor to sustainable UHPC due to its very low embedded CO_2 emission, abundant reserve on earth and low cost. An appropriate limestone powder content contributes to a denser pore structures, enhanced strengths and comparable total free shrinkages but when the addition is over 60%, it will considerably weakens both pore structure and strength [15]. In recent years, in the focus of sustainability, waste glass is attempted to use as an alternative supplementary cementitious material (ASCM) or ultra-fine filler in UHPC. This UHGPC offers enhanced fresh behaviour owing to its negligible water-absorption capability and smooth surface, increases workability when used up to 50% replacement and in terms of concrete compressive-strength development, the optimum replace of cement with glass powder was 20% [16].

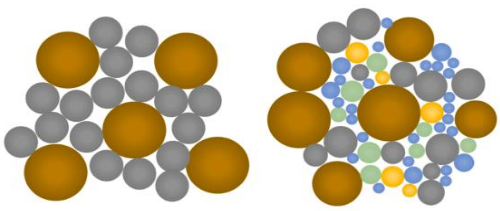
III. SUSTAINABLE DEVELOPMENT OF UHPC BASED ON THE PARTICLE PACKING MODELS

The UHPC mix designs aims to achieve superior particle packing density that contributes to low porosity, high mechanical strengths, and impermeability. Packing models are used to determine the packing density/ void ratio to improve the properties of the concrete by reducing void content [17]. The concept of voids is that the voids between the large particles will be filled by the smaller particles and their voids will be filled by the further smaller particles and so on as shown in figure3.

With the efficient packing, the need of cement paste required to fill the voids between the smallest particles (the fines) can be reduced and hence the carbon emission by the cement industry. The filling and occupying effects would increase the packing density, while the loosening and wall effects would decrease the packing density. When the coarse particles are dominant, the wedging effect occurs when some isolated fine particles are entrapped in the gaps between the coarse particles instead of filling into the voids thereby wedging the coarse particles and when the fine particles are dominant, the wedging effect occurs when some gaps between the coarse particles are too narrow to accommodate one complete layer of fine particles making only isolated fine particles present at the gaps. There are two main classification of particle packing theory. A higher particle packing density will be achieved using the wet particle packing model than that determined by the dry packing model.

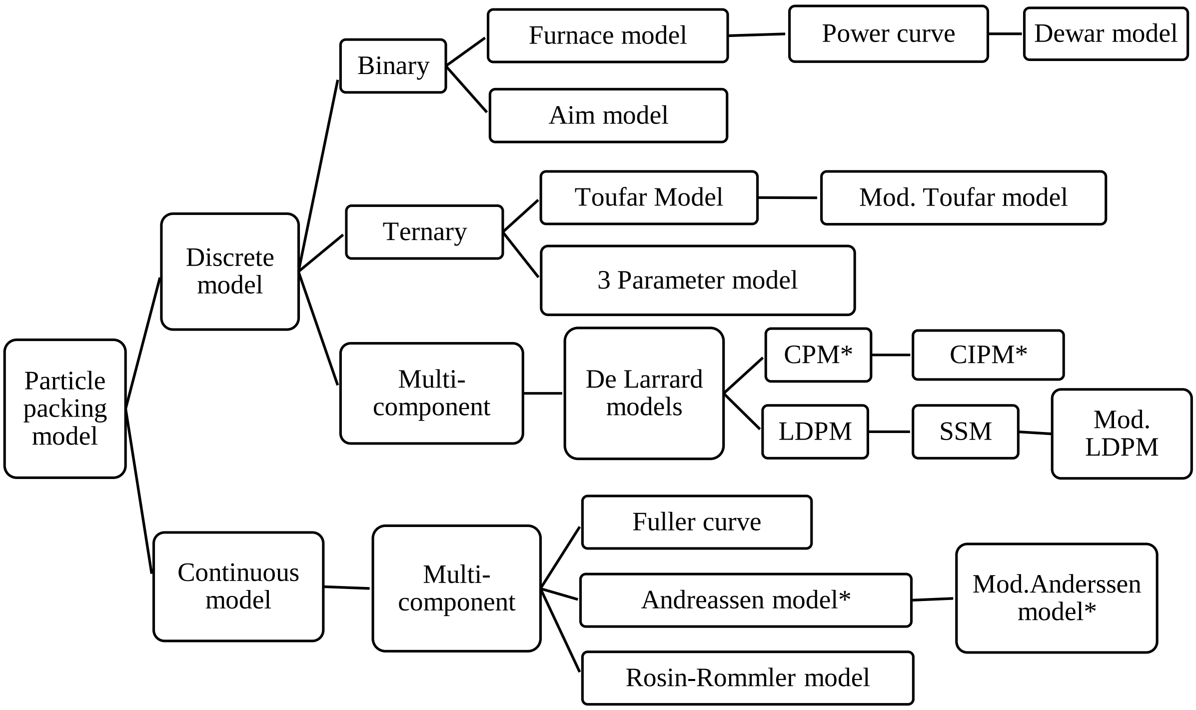
3.1 DRY PARTICLE PACKING MODELS

For the dry particle packing method, there are two typical models for the mixture design: the discrete model and the continuous model as shown in figure3. The continuous model is more preferred in UHPC design because it can achieve a denser particle skeleton. The summary of evolution of packing models is shown in figure4.



(a) **(b)**

Figure3: (a) Discrete model (b) Continuous model



LDPM-Linear packing density model
SSM-Solid suspension model
CPM-Compressible packing model

Figure4: Summary of Particle packing model (*: the model used for UHPC design)

Discrete models use idealized sets of specifically sized particles rather than continuous grading in developing UHPC [11]. Based on the number of specific sizes taken into consideration, discrete models can be further classified into binary, ternary, and multiple systems. Furnace model is based on the Furnas formula by considering the effect (wall effect) of the interaction between large-size aggregates and small-size aggregates. However, neither the Furnas model nor Aim model was suitable for concrete design due to the binary nature. This leads to the development of the Toufar model in 1976, the Dewar model in 1986 and the linear packing density model (LPDM) in 1986 [8]. After that, by introducing the concept of virtual packing density, De Larrad developed the second packing model, i.e., the solid suspension model (SSM) in 1994 in which the design of UHPC was developed for the first time, with a w/b of 0.14 and a compressive strength of 236 MPa [18].

For the sake of more accurate and reliable packing models, De Larrad proposed the compressible packing model (CPM), the third generation of packing models, in 1999 that introduced the concept of virtual packing density (γ), and a factor-the compaction index, K, based on which the actual packing density can be determined from the virtual packing density. The continuous packing model is based on the assumption that all possible sizes are present in the particle distribution system, that is, discrete approach having adjacent size classes' ratios that approaches 1:1 and no gaps exist between size classes. Fuller and Andersen developed the first continuous model by introducing target particle size distribution P(D). Considering the effect of minimum particle size on particle packing, Funk and Dinger developed the Modified Andreasen & Andersen model [5] and introduced D_{min} as:

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

Where, herein, D refers to the particle size, P(D) is the proportion of the solid particles less than size D. D_{max} and D_{min} represent the maximum and minimum particle sizes, and q is the distribution modulus. In MAA model, higher values of the distribution modulus (q greater than 0.5) lead to coarse mixtures, while lower values (q less than 0.25) result in concrete mixes which are rich in fine particles (typically UHPC).

3.2 WET PARTICLE PACKING MODELS

By including the influence of water and other liquids and to obtain the "real" maximum particle packing, the wet particle packing density method was introduced. To obtain the wet particle packing density, the following procedures should be conducted: (1) set the initial w/b, (2) weigh the water and cementitious materials and mix them; (3) transfer the mixture to a cylinder mould and weigh the amount of paste, (4) calculate the solid concentration (Φ) and void ratio (u), (5) repeat the above steps at a lower w/b ratio until the maximum packing density is achieved [5].

3.3 SOFTWARE BASED ON PARTICLE PACKING THEORY

MixSim is the software in which concrete designs may be realized with as many as 3 cementitious components, 3 fine aggregates or fillers and 3 coarse aggregates together with 3 liquid ad-mixtures [19]. COMPASS stands for Concrete Mixture Performance Analysis System which aims to optimize the material selection and proportions based on requirements. EMMA stands for Elkem Materials Mixture Analyser which is the most commonly used software for UHPC design. EMMA is used for the design of wide variety of concrete designs ranging from self-compacting to roller-compacted and conventional strength to ultra-high performance. EMMA is a software that calculates and display the particle size distribution of a mixture of components [20]. In UHPC, EMMA software is used for mainly two purpose, to optimize concrete design and to calculate the CO_2 impact of concrete mixture. The designer will use the Particle Size Distribution (PSD) of their sand, gravel & cementing materials as inputs and EMMA will predicts the optimum blend of those materials to make the best concrete. After optimizing the particle packing performance, EMMA can be used to calculate its CO_2 loading and can be used to replace cement in order to reduce the carbon footprint.

IV. CONCLUSIONS

Concrete mix proportioning by conventional, methods consumes substantial amount of cement which will cause serious environmental degradation of earth. This emphasizes the need to find alternate methods for UHPC mix design, along with efficient use of waste resources. Experimental optimization drawn much attention in designing sustainable UHPC in the field of practical engineering. Experimental optimization is more convenient for designers due to the simplex design processing and acceptable design result, regardless of professional statistical knowledge or programming skills of the designers. But experimental optimization is unable to provide a generally accepted mixture proportion where quantitative performance requirements need to be satisfied and also it become insufficient when multiple performance requirements need to be satisfied. The employment of close packing-based design is more in line with the theoretical foundation of UHPC (dense particle packing). Also, the number of trials for getting an optimized mix design is greatly reduced with the help of packing models which brings economical and environmental benefits. But the relationship between physical particle packing and the hydration process needs to be further discussed to upgrade the model. The upgrade and modification of experimental optimization, and close packing-based design will continuously help designers to develop sustainable UHPC exhibiting improved properties.

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