Journal of Asian Concrete Federation
Vol. 6, No. 1, pp. 26-36, June 2020
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2020.6.6.26

Technical Paper

Optimization and evaluation of ultra high-performance concrete

P. N. Ojha, Piyush Mittal*, Abhishek Singh, Brijesh Singh, V. V. Arora

(Received February 17, 2020; Revised June 9, 2020; Accepted June 9, 2020; Published June 30, 2020)

Abstract: Ultra-High Performance Concrete (UHPC) has been defined as a cementitious based composite material with compressive strength above 150 MPa and enhanced durability via its discontinuous pore structure. The microstructure of UHPC is denser and more homogeneous in comparison to conventional concrete. UHPC has several advantages over conventional concrete but the use of it is limited due to the high cost and limited design codes. Methodology for production and development of UHPC needs to be established. The paper covers both optimization and evaluation of Ultra-High-Performance Concrete along with highlighting the importance of packing density, mixing procedure and curing regimes containing a high volume of mineral admixture and ultrafine materials. Cementitious content of all the mixes in the study was kept in the range of 1000 kg/m^3 and water to binder ratio was kept as 0.17. This study focuses on the methodology to be adopted for optimizing the packing density of UHPC, the challenges associated with it and their influence on compressive strength.

Keywords UHPC; Packing Density; Compressive strength; Distribution Modulus; Curing Regime.

1. Introduction

Over the last two decades, remarkable advances have taken place in the research and application of Ultra-High Performance Concrete (UHPC) [1]. UHPC is the 'future' material with the potential to be a viable solution for improving the sustainability of buildings and other infrastructure components. Ultra-high-performance concrete (UHPC) with more than 150 MPa compressive strength [2] generally incorporates relatively high dosages of silica fume and superplasticizer, with a relatively low concentration of aggregates of small size. Some distinguishing features of UHPC include an optimized gradation of the granular matter for achieving high packing density, and water to cementitious materials ratio of less than 0.25 [3]. The hydrated paste in UHPC has a dense microstructure which provides a distinct balance of strength, impermeability and durability [4, 5]. The superior mechanical and durability characteristics of UHPC have led to its use in the rehabilitation of concrete structures [6, 7]. Recent developments in this field have emphasized the broadening of the raw materials selections and the use of common concrete production methods to facilitate commercial applications of UHPC [7, 8]. The basic principles for the development of UHPC are as follows [9, 10]:

- Minimizing composite porosity by optimizing the granular mixture through a wide distribution of powder size classes and reducing the water/binder ratio.
- Enhancement of the microstructure by the post set heat treatment to speed up the pozzolanic reaction of Silica Fume and other ultrafine cementitious materials to improve the mechanical properties.
- The optimal usage of superplasticizer to reduce water/binder ratio and improve workability.
- Improvement of homogeneity by eliminating the coarse aggregate resulting in a decrease in mechanical effects of heterogeneity.

It has been well recognized by many researchers that increasing the packing density of the granular mix could lead to a better performance of the concrete. Increasing the packing density of the granular mix would decrease the volume of paste needed to

P. N. Ojha *is a Joint director at National Council for Cement and Building Materials (NCB).*
Corresponding author Piyush Mittal *is a Project Engineer at National Council for Cement and Building Materials (NCB).*
Abhishek Singh *is a Project Engineer National Council for Cement and Building Materials (NCB).*
Brijesh Singh *is a Manager at National Council for Cement and Building Materials (NCB).*
V. V. Arora *is a Joint Director at National Council for Cement and Building Materials (NCB)*

fill up the voids and increase the amount of ''excess'' paste that could be utilized to improve the workability of the concrete. Drawing analogy to the case of a paste, increasing the packing density of the cementitious materials would decrease the volume of water needed to fill up the voids and increase the amount of ''excess'' water that could be utilized to improve the flowability of the paste. Hence, the key to the production of UHPC, which demands both a low water/binder (w/b) ratio to be used and high workability to be attained, is the maximization of the packing density of the granular skeleton of the concrete [11,12]. The effectiveness of supplementary cementitious material in filling up the voids or in improving the packing of the cementitious materials is dependent on the fineness of the supplementary cementitious material. In general, a broader range of particle size distribution would yield a higher packing density. This is because, with a broader range of particle size distribution, the medium particles would fill up the voids between the large particles, the fine particles would fill up the voids between the medium particles and the very fine particles would fill up the voids between the fine particles and so on, leading to the removal of more voids by the successive filling effect. The addition of a supplementary cementitious material finer than Ordinary Portland Cement (OPC) would broaden the range of particle size distribution and thus increase the packing density. A supplementary cementitious material with a higher fineness is more effective because it would produce a broader range of particle size distribution. [13, 14, 15]. Particle packing density can be defined as the solid volume of particles in unit volume. It has been reported that when water/cementitious materials ratio was reduced to as low as 0.14 by weight, concrete having the strength of 165–236 MPa was produced [16]. By maximizing the packing of all granular materials in the concrete mix using the same packing model and also applying other advanced production techniques, concrete having strengths in the order of 200–800 MPa was developed [17]. In 1996, packing theory was applied for the design of self-consolidating concrete and based on the successful outcome it was concluded that the performance optimization of concrete is mainly a matter of improving the packing density of its granular skeleton [18]. Particle optimization methods can be divided into three groups (figure 1):

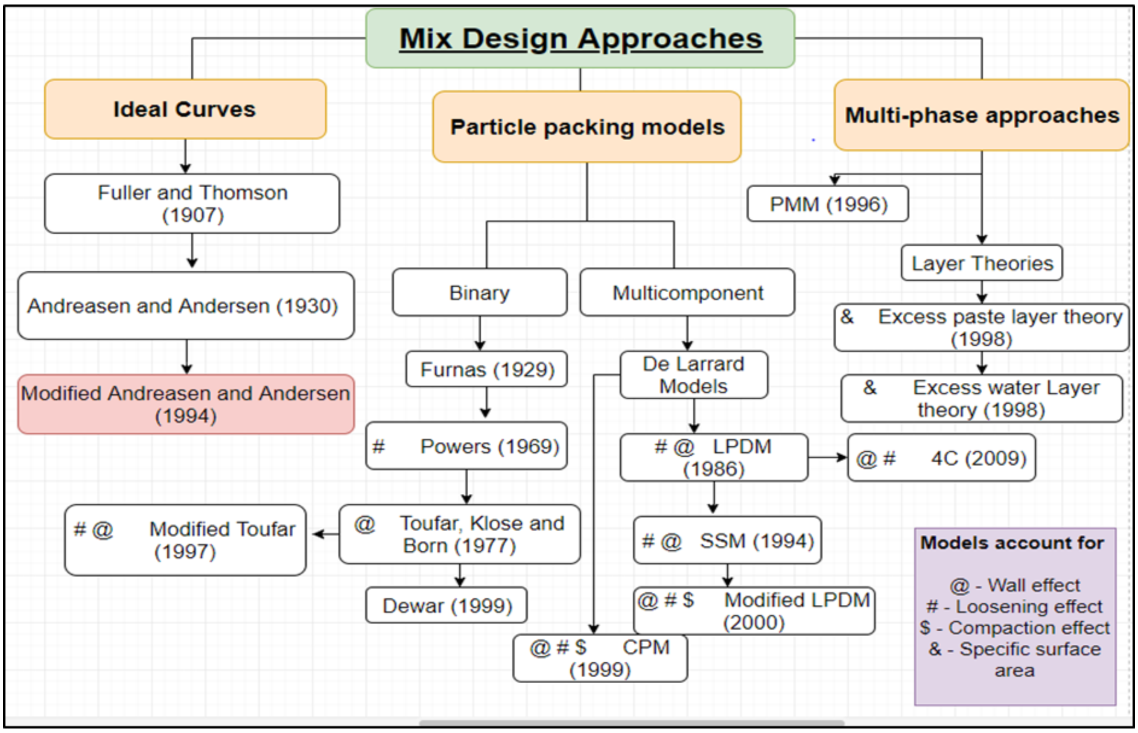

Fig 1: Mix design approaches for optimizing packing density [13]

- Optimization curves: Groups of particles, with a specific particle size distribution, are combined in such a way that the total particle size distribution of the mixture is closest to an optimum curve.
- Particle packing models: These models are analytical models that calculate the overall packing density of a mixture based on the geometry of the combined particle groups.
- Discrete element models: With numerical models, a 'virtual' particle structure from given particle size distribution is generated.

In the present study, approach of the ideal curve has been adopted for the optimization of concrete mix to attain the maximum possible packing density. The fundamental work of Fuller and Thomsen showed that the packing of concrete aggregates is affecting the properties of the produced concrete [19]. They concluded that a geometric continuous grading of the aggregates in the composed concrete mixture can help to improve the concrete properties. Based on the investigation of Fuller and Thompson [19, 20] & Andreasen and Andersen, a minimal porosity can be theoretically achieved by an optimal particle size distribution (PSD) of all the applied particle materials in the mix as per empirical equation 1 below:

$$\mathrm{P(D)} = \left(\frac{\mathrm{D}}{\mathrm{D_{max}}}\right)^{\mathrm{q}} \ldots\ldots\ldots\ldots\ldots (1)$$

Where P (D) is a fraction of the total solids being smaller than the particle size D (μm), D_{max} is the maximum particle size (μm) and q is the distribution modulus. However, in the above empirical equation, the minimum particle size is not incorporated, while in reality there must be a finite lower size limit. In continuation of this study, Funk and Dinger proposed a modified model based on the Andreasen and Andersen Equation. In this study, all the concrete mixtures are designed based on modified Andreasen and Andersen model, which is as follows [20,21]:

$$P(D) = \frac{d^q - d^q_{min}}{d^q_{max} - d^q_{min}} \ \ldots\ldots\ldots\ldots (2)$$

Where D_{min} is the minimum particle size (μm). Using the above particle packing model, UHPC mixes were optimised and compressive strength of about 150 MPa at 28 days with low binder content was achieved. The modified Andreasen and Andersen packing model has already been successfully employed in optimization algorithms for the design of normal density concrete and Lightweight concrete [9, 10].

Different types of concrete mixes can be designed using above equation 2 by applying different values of the distribution modulus q, as the value of q influences the ratio between coarse and fine particles. Higher values of distribution modulus (q>0.5) lead to coarser mixtures whereas smaller values (q<0.25) results in mixes that will be rich in fine particles [20]. A very high value of q above 0.50 leads to higher aggregates to paste volumetric ratio and therefore, the lesser paste will be available to lubricate the fine aggregate particles, which in turn will have decreased workability. Few trials were conducted with a value of q below 0.37 and in those trials as the value of q was lower, the concrete mix was found to be stiff and required high-efficiency water reducers. Hence, to obtain a workable mix with available water reducing admixture and well-graded particle size distribution, the value of distribution modulus q has been taken as 0.37 in this study, keeping in view the findings of the studies done by the past researchers [20, 22]. Elrahman et al. also mentioned the work of Andreasen et al, wherein it was suggested to use the exponent q in the range of 0.35 to 0.50 because fine particles are not able to pack similar to bigger particles [22].

Table 1 Physical properties of materials

S. No.	Properties	Cement	G.G.B.S	Flyash	UFGGBS	Silica Fume
1.	Fineness(m^2/kg)	323	400	310	2026	16701
2.	Specific Gravity	3.15	2.93	2.28	2.88	2.28

Table 2 Chemical properties of materials

S.No.	Properties	Cement	G.G.B.S	Flyash	UFGGBS	Silica Fume
1	Loss of Ignition (LOI), %	2.3	0.33	0.4	0.17	2.73
2	Silica (SiO_2), %	20.71	34.41	60.95	33.05	85.03
3	Iron oxide (Fe_2O_3), %	4.08	1.18	5.7	0.58	-
4	Aluminium oxide (Al_2O_3) , %	5.15	18.45	26.67	20.40	-
5	Calcium oxide (CaO), %	59.96	36.46	2.08	33.14	-
6	Magnesium oxide (MgO), %	4.57	7.00	0.69	7.62	-
7	Sulphate (SO_3), %	1.84	0.097	0.29	0.19	-
8	Na_2O, %	0.42	0.30	0.06	0.19	0.73
9	K_2O, %	0.56	0.37	1.46	0.58	2.96
10	Chloride, %	0.012	0.022	0.009	0.016	-
11	Insoluble Residue, %	1.25	0.40	-	0.86	-

2. Materials

Properties of UHPC are highly dependent on the type of material used in its production. In this study cementitious material were selected in such a way that particle size distribution has a wide range that leads to the higher packing density of the concrete. Cementitious Materials used in the study are OPC 53G, GGBS, ultrafine GGBS and Silica fume, Nano-silica. Similarly, to increase the packing density of aggregates, three different types of aggregates namely Fine Quartz sand, Ground Quartz and Coarse Quartz sand were used.

2.1 Cementitious materials

Cement: Ordinary Portland Cement (OPC) of 53 grade complying with IS 269: 2015 [23] was used throughout the study. The physical properties of cement are tabulated in Table 1. Chemical properties of cement have been listed in Table 2. Particles of OPC 53 were in the range of 1.375 to 175 microns. Particle size distribution has been shown in figure 5.

Ground granulated blast furnace slag (GGBS): GGBS complying with IS 16714:2015 [24] was used in this study. Physical and chemical properties have been listed in Table 1 and Table 2 respectively. Particles of GGBS were in the range of 1.15 to 250 microns. Particle size distribution has been shown in figure 5.

Ultra-Fine Ground granulated blast furnace slag (UFGGBS): Ultrafine ground powder of GGBS used in this study has ultra-fineness which shows improvement in the properties of regular GGBS like high surface area. UFGGBS is a specially processed product based on high glass content with high reactivity obtained through the process of controlled granulation. For the production of UFGGBS, the granulated slag with value-added material is ground in a ball mill attached with a high-efficiency classifier, which classifies the material and ensures that only the required micro size particle enters the final product. The entire process is operated by an automatic process controller. Ultrafine GGBS commercially available as Alccofine-1203 is a low calcium silicate-based mineral additive which is generally used as a replacement of silica fume in high-performance concrete. Its latent hydraulic property and pozzolanic reactivity results in the enhanced hydration process. UGGBS complying with IS 16715: 2015 [25] was used in this study. Physical and chemical properties have been listed in Table 1 and Table 2 respectively. Particles of Ultra-Fine Ground granulated blast furnace slag are very fine and were found to be in the range of 1 to 18 microns. Particle size distribution has been shown in figure 5.

Silica Fume: Silica fume complying with IS 15388 [26] was used in this study. Physical and chemical properties have been listed in Table 1 and Table 2 respectively. Majority of the particles of Silica fume were found to be in the range of 0 to 10 microns. Particle size distribution has been shown in fig.5.

Fly ash: Flyash complying with IS 3812 [27] was used in this study. Physical and chemical properties have been listed in Table 1 and Table 2 respectively. Particles of Flyash are slightly coarser than the particle size of OPC and are in range of 1 to 300 microns. Particle size distribution has been shown in figure 5.

Nano Silica: The mechanism of influence of Nano silica on the cement hydration are available in the literature. The studies indicated that the hydration heat of Ordinary Portland Cement blended with Nano silica in the main period increases significantly with an increased surface area of silica and the hydration of tri-calcium silicate (C_3S) gets accelerated by the addition of Nano-scaled silica or CSH particles. A Nano silica slurry is selected as a pozzolanic material to be used in this study. The solid content and Brunauer–Emmett–Teller (BET) fineness are 20 (% w/w) and 24 m^2/g. The specific density of Nano silica was found to be 2.21 g/cm^3.

2.2 Fine aggregates

Ground Quartz: Particle size of Ground Quartz used in this project is on the coarser side of the particle size of cement particles. It is used as a micro filler to optimize the packing density of the powder mix. Its particle size ranges from 0.5 to 140 microns. Particle size distribution has been shown in figure 5. The microstructure of ground quartz by Optical microscopy (Fig. 2) suggests that the minerals present in order of abundance are quartz, orthoclase-feldspar and iron oxide. Subhedral to anhedral quartz grains with sharp grain margins are well-graded and homogenously distributed. The majority of quartz grains are in the size range of 20µm to 30µm. The strained quartz percentage is about 9% and their undulatory extinction angle (UEA) varies from 10^0 to 12^0. Subhedral orthoclase grains with smooth grain margins are fresh in nature. Subhedral iron oxide grains with sharp grain margins are randomly distributed in the sample.

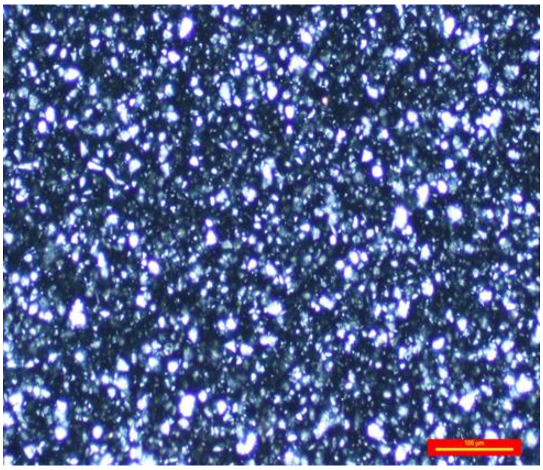

Fig 2: Distribution of minerals grains in Ground Quartz. (5x, X-Nicols)

Fine Quartz Sand: UHPC mixes were produced using quartz sand having a particle size ranging from 150 to 996 microns. Particle size distribution has been shown in figure 5. The microstructure of ground quartz sand by optical microscopy (Fig. 3) suggests that it has a subhedral to anhedral quartz grains with sharp grain margins which are well-graded and homogenously distributed. The majority of quartz grains are in the size range of 300µm to 600µm.

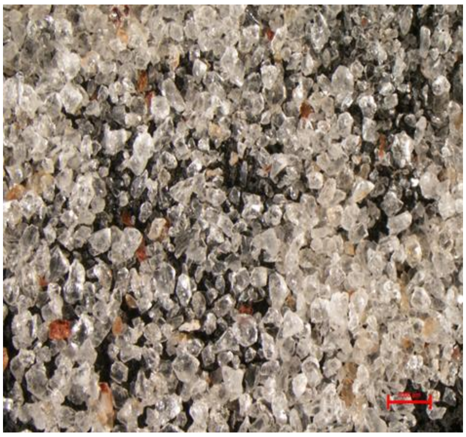

Fig 3: Distribution of minerals grains in fine Quartz sand (11.25x)

Coarse Quartz sand: Coarse quartz sand used in this study have a particle size ranging from 1mm to 3mm. The microstructure of coarse quartz sand by optical microscopy (Fig. 4) suggests that it has a subhedral to anhedral quartz grains with sharp grain margins which are well-graded and homogenously distributed.

Fig 4: Distribution of mineral grains in Coarse Quartz sand sample (11.25x)

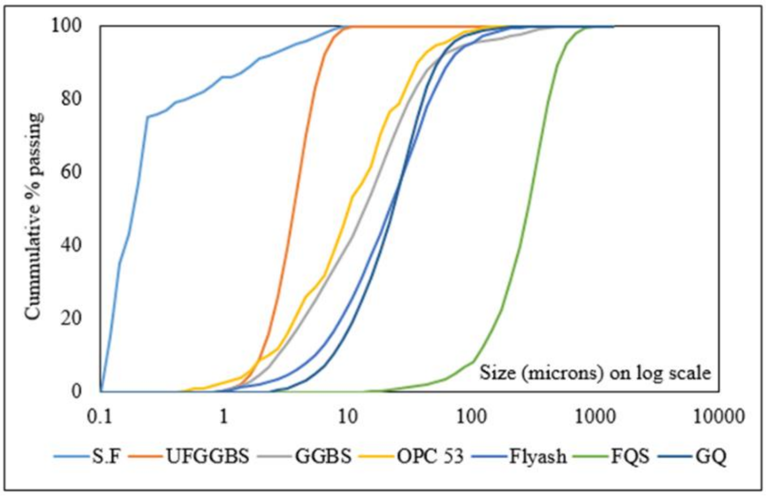

Fig 5: Particle size distribution of materials

3. Experimental

3.1 Packing density

In the present research, the ideal curve methodology has been adopted. In this method, materials are combined in such fractions that there combined grading lies close to a certain optimum curve given by Modified Andreasen and Andersen equation as mentioned above in equation 2. The proportions of each material in the mix are adjusted until an optimum fit between the composed mix and the target curve is reached, using an optimization algorithm based on the Least Squares Method (LSM), as presented in equation 3. When the deviation between the target curve and the composed mix expressed by the sum of the squares of the residuals (RSS) at defined particle sizes, is minimized, the composition of the concrete is treated as the most optimum one.

$$RSS = \sum_{i=1}^{n}(P_{mix}(D_i^{i+1}) - P_{tar}(D_i^{i+1}))^2 \ldots (3)$$

where, P_{mix} is the composed mix and P_{tar} is the target grading.

Around 40 mixes with cementitious materials of OPC-53, GGBS, UFGGBS & Silica fume, Flyash and aggregates including Fine Quartz Sand, Quartz powder and Coarse Quartz sand were theoretically optimized for optimum particle packing with the help of above mentioned Modified Andreasen and Andersen equation. The value of q adopted in this research is 0.37 based on the literature. The mixes with the least value of RSS were selected for experimental study. Mixing of UHPC requires equipment that provides more energy and shear than regular concrete mixers due to the low water content and high powder content. In general, the expected performance (including fresh and hard-solid properties) of the selected mixture cannot be achieved when low-energy mixers are used to mix UHPC. Moreover, the use of a low-energy mixer will also increase the turnover time of the mixture, causing the temperature of the mix to rise, which is detrimental to the UHPC mixing process [28, 29]. Therefore, for homogeneous mixing of UHPC authors designed and developed planetary mixer of 60 litre capacity with high mixing efficiency that can be operated at variable speed with maximum speed up to 325 RPM. Selected mixes were cast using the developed planetary mixer. Compressive strength was measured using a cube with a specimen size of 70.6 mm. Wet packing density was also determined using the below-mentioned equation given by Kwan [30, 31, 32]. If a UHPC mix consists of several different materials denoted by α, β, γ and so forth, ρ and R are solid density and volumetric ratio of the respective material. u_w is the ratio of water to solid content. Then, the solid volume of the cementitious materials V_c and wet packing density ϕ may be worked out from equations 4 and 5 mentioned below:

$$V_c = \frac{M}{\rho_w u_w + \rho_\alpha R_\alpha + \rho_\beta R_\beta + \rho_\gamma R_\gamma} \qquad (4)$$

$$\phi = \frac{V_c}{V} \qquad (5)$$

As per numerous researchers, the packing density of concrete is in the range as given below in table 3.

Table 3 Packing density of different types of concrete [27]

Type of Concrete	Packing Density range
Normal strength Concrete	0.65 - 0.72
High Strength Concrete	0.72 – 0.8
Ultra high-performance concrete	More than 0.8

3.2 Curing regimes

Heat treatment of concrete plays a significant impact on the rate of strength development and also has a strong influence on mechanical properties as well as micro-texture of UHPC. Apart from the effect of accelerating the curing process and increasing early strength, heat treatment could be useful for cementitious systems containing supplementary cementitious materials such as silica fume, granulated blast furnace slag, fly ash by influencing the reaction rate of these mineral additions compared to the same system cured at ambient conditions. Compared to the UHPC cured under ambient conditions, heat-treated specimens of UHPC show generally a denser microstructure that can lead to an increase in compressive strength and thus can improve overall mechanical properties of UHPC [33, 34]. In the present study, three different curing regimes are used as given below:

a) Autoclave curing at 2.1 MPa and 215ºC for 8 hours followed by Standard curing till the age of testing (up to 07 days)
b) Steam curing at 90ºC and 100% RH for 24 hours followed by Standard curing till the age of testing (up to 28 days)
c) Standard water curing until the age of testing (28 days).

3.3 Mix design details

In the present study, the proportion of individual cementitious material was decided using the Modified Andreasen and Andersen equation. Out of 40 mixes that were theoretically optimized, three final mixes were cast in the laboratory for a study on compressive strength. The details of the composition of the cementitious material of these three optimized mixes are discussed later. The total cementitious content in concrete mixes is kept around 1000 kg/m^3. To attain better particle packing density, a combination of three fine aggregates were used i.e. Ground quartz, Fine quartz sand and Coarse quartz sand in the proportion of 30:40:30 respectively. The nano-silica was used as a 3% replacement to OPC content. Dosage of PC based superplasticizer was kept as 2% by weight of cementitious material.

3.4 Mix methodology

UHPC has been produced using a wide variety of mixers, ranging from laboratory-sized pan mixers to revolving drum truck mixers. In general, mixing UHPC is a somewhat different process than mixing conventional concrete. UHPC typically includes a limited amount of water and no coarse aggregate. As such, the UHPC requires the input of extra mixing energy both to disperse the water and to overcome the low internal mixing action from the lack of coarse aggregate. Different researchers have adopted various mixing protocols to achieve homogenization of the UHPC mixture in a shorter span. Although specific details of the overall mixing process differed, all researchers were unified in that UHPC components had to be dry mixed before adding water and superplasticizer. Dry mixing intends to ensure higher bulk density and lower moisture requirements. A typical mixing process involves first charging the mixer with the dry components and ensuring that the mix is blended homogenously. Thereafter, water and chemical admixtures are added and dispersed. Mixing continues, sometimes for an extended period depending on the mixer energy input, until the UHPC changes from a dry powder into a fluid mixture. The mixing methodology adopted in this study is given in Table 4.

Table 4 Mixing methodology to prepare concrete mixes in this study

Step No.	Mixing methodology	Duration
Step 1	Dry mixing of all cementitious material and aggregates at low speed of 125 rpm	3 minutes
Step 2	Adding 100% water & 75% superplasticizer and mix at medium speed of 250 rpm	5 minutes
Step 3	Add remaining superplasticizer and mix the constituents at high speed of 325 rpm	5 minutes
Step 4	Mixing continues until concrete achieve the required flow	-

Table 5 (a) Details of proportion (% of total cementitious content) of several combinations of cementitious materials

Mixes	OPC 53 (%)	Silica Fume (%)	GGBS (%)	UFGGBS (%)	Flyash (%)	RSS
M1	40	10	20	30	-	424.8
M2	40	10	10	40	-	465.3
M3	35	-	35	30	-	454.3
M4	20	15	35	30	-	434.0
M5	30	10	40	20	-	439.4
M6	70	10	-	10	10	442.2
M7	60	20	-	10	10	424.0
PM 1	60	10	20	10	-	418.0
PM 2	80	20	-	-	-	417.0
PM 3	60	10	-	10	20	380.0

Table 5 (b) Details of proportion (% of total fine aggregates) of several combinations of fine aggregates

Mixes	Fine Quartz sand (%)	Coarse Quartz sand (%)	Ground Quartz (%)	RSS
C1	70	10	20	437.3
C2	50	30	20	275.5
C3	30	50	20	291.7
C4	10	70	20	486.1
C5	50	10	40	340.9
C6	30	30	40	295.5
C7	10	50	40	428.1
C 8	60	10	30	367.5
C9	40	30	30	263.8
C10	20	50	30	338.2

4. Results & discussion

4.1 Optimization of mix

As mentioned earlier, in the present study the ideal curve methodology was used for the optimization of particle packing of concrete mix. For optimization of concrete mix, proportions of cementitious materials and fine aggregates were optimized separately. Several mixes were theoretically analyzed with help of Modified Andreasen and Andersen equation and mix with least RSS values were used for laboratory study. Out of several sets of combinations having different proportions, 10 sets of combinations for cementitious materials and 10 sets of combinations for fine aggregates with least RSS values have been tabulated below in table 5(a) and 5(b). D_{min} and D_{max} (for optimizing the proportion of cementitious materials) used in modified Andersen and

Andreasen equation for the ideal curve are 0.112 microns and 1408 micron. Whereas, D_{min} and D_{max} (for optimizing the proportion of inert fine aggregates) used in modified Andersen and Andreasen equation for the ideal curve are 0.5 microns and 2360 micron respectively. Out of all the cementitious combinations, PM1, PM2 and PM3 were selected to prepare concrete. For fine aggregates, combination C9 was selected to be used for all the three mixes (having optimized cementitious combinations of PM1, PM2 and PM3) as it has the least RSS value in comparison to other combinations. The combined particles size distribution of selected cementitious combination along with ideal particle size distribution calculated using Modified Andreasen and Andersen equation is given in Fig 6. The details of the composition of selected concrete mixes are given in Table 6.

Table 6: Details of mix design

Mix	Cement kg/m³	Silica fume (SF) + GGBS (BS) + UFGGBS (UFBS) + Flyash (FA) + Nano Silica (NS) kg/m³					W/B	Fine Quartz Sand (FQ) + Ground Quartz Sand (GQ) + Coarse Quartz Sand (CQ) kg/m³			Super Plasticizer kg/m³
		SF	BS	UFBS	FA	NS		FQ	GQ	CQ	
PM1	582	100	200	100	0	18	0.17	498.4	292.6	371.0	20
PM2	776	200	0	0	0	24	0.17	501.0	294.1	372.9	20
PM3	582.0	100	0	100	200	18	0.17	489.9	287.6	364.7	20

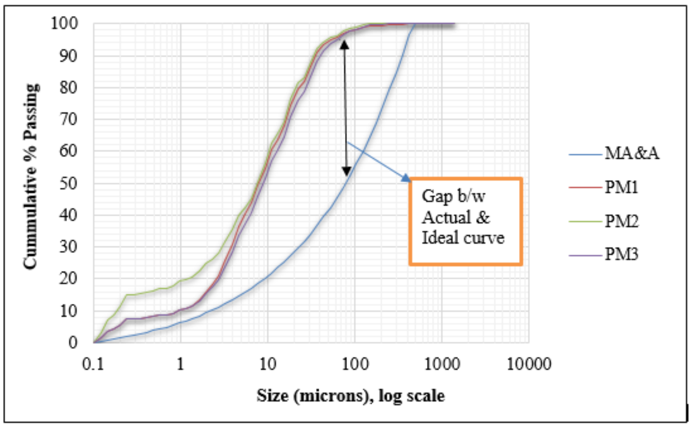

Fig 6: Grading of ideal curve and designed mixes

4.2 Compressive strength

As discussed earlier in section 4.1, cementitious combinations, PM1, PM2 and PM3 with combination C9 of fine aggregates were selected to prepare concrete. Concrete specimen of all the three mixes were subjected to three curing regimes (mentioned in 3.2) and were evaluated for compressive strength. For each mix, nine cubes were cast and an average compressive strength of three cubes for each curing regime has been plotted for these three selected mixes (Fig 7). Apart from the interfacial transition zone (ITZ) between aggregate and cement paste, the role of the particle packing density is a major factor governing the compressive strength of the UHPC.

For all three curing regimes studied, PM3 has a highest compressive strength in comparison to PM1 and PM3. Wet packing density was determined as per equation 4 and 5. It was observed that for all the three mixes, value of wet packing density (ϕ) is more than 0.8. Such a high value of wet packing density suggests that mixes optimized using ideal curve methodology have a dense microstructure that helps in achieving ultra-high compressive strength. Compressive strength in the case of the Autoclave curing regime is significantly higher in comparison to the other two curing regimes for all the three optimized mixes. The maximum compressive strength achieved is 186.5 MPa for mix PM3 in the case of an autoclave curing regime. The increment in compressive strength in case of steam curing varied from 12% to 47.3% and in the case of autoclave curing it varied from 19.11% to 81.9%. Under the conditions of high temperature and pressure, the chemistry of hydration is substantially altered. CSH forms but is converted to a crystalline product α -calcium silicate hydrate (α-C_2S) which causes an increase in porosity and reduction in strength. However, in the presence of silica α -C_2S converts to tobermorite ($C_5S_6H_5$) on continued heating thus high strength can be obtained. On the other hand, prolonged autoclaving may cause the formation of other crystalline calcium silicate hydrates with a strength reduction. It is believed that the complete conversion to tobermorite is not desirable and that there is an optimum ratio of amorphous to crystalline material for maximum strength [35, 36]. The strength level after autoclaving generally cannot be reached even with 24-hour steam curing for all three mixes. This can be explained by the different hydration mechanisms due to these curing methods. While steam curing increases the reactivity of ingredients, autoclaving leads to the development of different phases and incorporation of ultrafine material is essential to achieve ultra-high compressive strength.

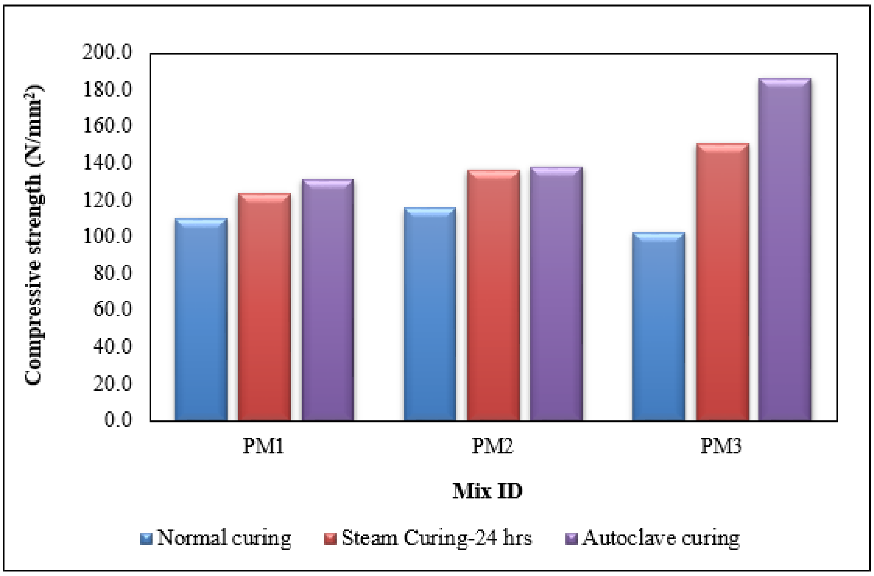

Fig 7 Compressive strength for three different curing regimes

5. Conclusions

(1) In order to obtain a workable and satisfactory mix with available water reducing admixture and well-graded particle size distribution, the value of distribution modulus q was adopted as 0.37. Ideal curve methodology has been used for the optimization of particle packing of concrete mix. For the preparation of concrete mix, proportions of cementitious materials and fine aggregates were optimized separately. Several mixes were theoretically analyzed and optimized with help of Modified Andreasen and Andersen equation and mixes with least RSS values were used for laboratory study. Mixes optimized and prepared using lower values of q may result in higher compressive strength. However, such mixes were found to be very stiff and required very high-efficiency water reducers

(2) Wet packing density was determined as per the method given by Kwan. It was observed that the value of wet packing density (ϕ) for all the three mixes is more than 0.8. Such a high value of wet packing density suggests that mixes optimized using ideal curve methodology have a dense microstructure that helps in achieving ultra-high compressive strength.

(3) Cementitious content (fine particles) in a UHPC mix is quite high in comparison to a normal strength concrete mix. Mixing methodology and type of mixer used for the preparation of UHPC have a large influence on the mixing efficiency and uniformity of UHPC which eventually affects its properties in a fresh and hardened state. The mixing methodology adopted in this study and preparation of concrete mix using planetary mixer developed for this study ensured homogeneous mixing without any lump formation.

(4) The curing regime plays a vital role in the development of hardened properties of the UHPC mix, which contains a high amount of mineral admixtures. Post set heat treatment enhances the microstructure by speeding up the pozzolanic reaction of Silica fume and other ultrafine cementitious materials to enhance the mechanical properties. From results, it can be observed that the maximum compressive strength achieved was 186.5 MPa in case of autoclave curing for mix PM3. The percentage improvement in compressive strength in case of steam curing varied from 12% to 47.3% and in the case of autoclave curing it varied from 19.11% to 81.9% in comparison to the compressive strength observed in case of standard curing.

Reference

1. Norzaireen Mohd Azmee; and Nasir Shafiq (2018) "Ultra-High Performance Concrete: From Fundamental to Applications", Case Studies in Construction Materials
2. Wille K.; Naaman A. E.; and Parra-Montesinos G. J. (2011) "Ultra-high performance concrete with compressive strength exceeding 150 MPa: A simpler way", ACI Materials Journal, 108(1):46–54
3. Schießl P; Mazanec O; and Lowke D (2007) "SCC and UHPC - Effect of mixing technology on fresh concrete properties", Advances in construction materials 513–522, Heidelberg, Germany, Springer
4. Graybeal B. A. (2006) "Material property characterization of ultra-high performance concrete", Report No: FHWA-HRT-06-103 p.188
5. Russell H. G.; and Graybeal B. A. (2013) "Ultra-high performance concrete: A state-of-the-art report for the bridge community", Federal Highway Administration, McLean
6. Richard P.; and Cheyrezy M. (1995) "Composition of reactive powder concretes", Cement and Concrete Research, p. 1501–1511
7. Sbia L. A.; Peyvandi A.; Lu J.; Abideen S.; Weerasiri R. R.; Balachandra A. M.; and Soroushian P. (2017) "Production methods for reliable construction of ultra-high performance concrete (UHPC) structures", Materials and Structures
8. Yang Chen; Faris Matalkah; Parviz Soroushian; Rankothge Weerasiri; and Anagi Balachandra (2019) "Optimization of ultra-high performance concrete, quantification of characteristic features", Cogent Engineering
9. Senthil Kumar V.; and Manu Santhanam (2004) "Use of a particle packing model to produce HPC at optimum cement content", The Indian Concrete Journal
10. A.S. Dili; and Manu Santhanam. (2004) "Investigation on reactive powder concrete: A developing Ultra high-strength technology", The Indian Concrete Journal
11. Ghoddousi P.; Javid A. A. S.; and Sobhani J. (2014) "Effects of particle packing density on the stability and rheology of self-consolidating concrete containing mineral admixtures", Construction and Building Materials, p. 102–109
12. "Ultra-High-Performance Concrete: An Emerging Technology Report" (2018), Reported by ACI Committee 239
13. Fennis S.; and Walraven J. (2012) "Using particle packing technology for sustainable concrete mixture design", Delft University of Technology, Netherlands
14. Caijun Shi; Zemei Wu; Jianfan Xiao; Dehui Wang; Zhengyu Huang; and Zhi Fang (2015) "A review on Ultra high performance concrete: Part I. Raw materials and mixture design", Construction and Building Materials, p. 741–751
15. A.M. Said; M.S. Zeidan; M.T. Bassuoni; and Y. Tian (2012) "Properties of concrete incorporating nano-silica", Construction and Building Materials, p. 838–844
16. De Larrard F.; and Sedran T. (1994) "Optimization of ultra-high performance concrete by the use of a packing model", Cement and Concrete Research, p. 997–1009
17. Richard P.; and Cheyrezy M. (1995) "Composition of reactive powder concretes", Cement and Concrete Research, p. 1501–1511
18. Sedran T; De Larrard F; Hourst F; and Contamines C (1996) "Mix design of self-compacting concrete", Proceedings of the international RILEM conference on production methods and workability of concrete, Paisley, Scotland, p. 439 - 450
19. Fuller W. B.; and Thompson S. E. (1907) "The laws of proportioning concrete", Transactions of the American Society of Civil Engineers, p. 222 - 298.
20. Hüsken G.; and Brouwers H. J. H. (2008) "A new mix design concept for earth-moist concrete: A theoretical and experimental study", Cement and Concrete Research, p. 1246 - 1259
21. Yu Q. L.; Spiesz P.; and Brouwers H. J. H. (2013) "Development of cement-based lightweight composites - Part 1: Mix design methodology and hardened properties", Cement and Concrete Composites, p. 17 - 29
22. Mohamed Abd Elrahman; and Bernd Hillemeier (2014) "Combined effect of fine fly ash and

packing density on the properties of high performance concrete: an experimental approach" Construction and Building Materials

23. IS: 269-2015 "Ordinary Portland Cement - Specification", Bureau of Indian Standards, New Delhi
24. IS: 16714-2015 " Ground Granulated Blast Furnace Slag for Use in Cement, Mortar and Concrete", Bureau of Indian Standards, New Delhi
25. IS: 16715-2015 " Ultrafine Ground Granulated Blast Furnace Slag — Specification", Bureau of Indian Standards, New Delhi
26. IS: 15388-2003 "Silica Fume Specification", Bureau of Indian Standards, New Delhi
27. IS 3812 (Part 2) : 2013, "Pulverised Fuel Ash-Specification, Part 2 For Use as Admixture in Cement Mortar and Concrete", Bureau of Indian Standards, New Delhi
28. Xinpeng Wanga; Rui Yua; Qiulei Songa; Zhonghe Shuia; Zhen Liua; Shuo Wua; and Dongshuai Houd (2019) "Optimized design of Ultra high performance concrete (UHPC) with a high wet packing density", Cement and Concrete Research
29. Parameshwar N. Hiremath; and Subhash C. Yaragal (2017) "Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete", Construction and Building Materials, p. 271 - 288
30. Li L. G.; and Kwan A. K. H. (2014) "Packing density of concrete mix under dry and wet conditions", Powder Technology, p. 514 - 521
31. Wong H. H. C.; and Kwan A. K. H. (2008) "Packing density of cementitious materials: part 1 - measurement using a wet packing method", Materials and Structures, p. 689 - 701
32. Kwan A. K. H.; and Wong H. H. C. (2008) "Packing density of cementitious materials: part 2 - packing and flow of OPC + PFA + CSF", Materials and Structures, p. 773 - 784
33. Libya Ahmed Sbia (2014) "Contribution and Mechanism of action of graphite nano materials in Ultra High Performance Concrete ", Ph.D. thesis, Michigan State University
34. Halit Yazıcı (2007) "The effect of curing conditions on compressive strength of Ultra high strength concrete with high volume mineral admixtures", Building and Environment, p. 2083 - 2089
35. Glasser F. P.; and Hong S. Y. (2003) "Thermal treatment of C–S–H gel at 1 Bar H2O pressure up to 200 C", Cement and Concrete Research
36. Quanbing Yang; Shuqing Zhang; Shiyuan Huang; and Yaohui He (2000) "Effect of ground quartz sand on properties of high-strength concrete in the steam-autoclaved curing", Cement and Concrete Research