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Research paper

Experimental study on optimization of mid strength high performance concrete using particle packing technique

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Abstract

In the present study, an unified method of HPC mix design was proposed for compressive strength range of 50-60MPa. Puntke test was conducted to determine the optimized combination of Ordinary Portland Cement (OPC) and microsilica (MS). Dry packing test was performed to determine the most dense aggregate combination of different size classes. The results of cementitious materials and aggregates optimization were integrate and imported for the HPC mix design. The volume of surplus paste content was optimized by considering 10%, 15% and 20% additional paste and w/cm ratio of 0.34 and 0.36 in flow table test. Compressive strength and water penetration depth of different HPC mixes were used to substantiate the selection of optimized HPC mix. The Puntke test results indicated an optimized binary blend of 80% OPC and 20% of MS in total cementitious materials. The packing density of three sizes class aggregate blending was found to be 0.900. The mix with 15% surplus paste and 0.34 w/cm was considered as optimized HPC mix based on the recorded flow diameter of 550 mm, compressive strength of 59.15 MPa and least water penetration depth of 6.21mm.

Keywords: *Dry packing test; Flow table test; Optimization of HPC; Packing density; Puntke test.*

1. Introduction

High performance concrete (HPC) exhibits superior performance compared to conventional concrete in various parameters like, ease of placement, density, very low water/cementitious materials, heat of hydration, workability, strength, durability, volumetric stability, lower creep and shrinkage, long-term strength and mechanical properties [1]. To achieve required property of HPC, mix design plays a major role. There is still lack of understanding regarding the combined effects of the various mix parameters and how these parameters should be optimized for achieving best performance of the concrete [2]. However,[3] the mix design of HPC satisfying all the high performance requirements, such as high strength, durability, and workability, is not easy. The particle size distribution concept is vital in the concrete mix optimization and it is represent by packing density. [4] Packing density of particles is defined as the ratio of the solid volume of the particles to the bulk volume occupied by the particles. Since concrete is made largely of particles of different size, its properties are greatly affected by the packing density of its solid ingredients. Particle packing optimization in concrete mixture design covers the selection of right sizes and amounts of various particles. The particles should be selected to fill up the voids between large particles with smaller particles and so on. An increased packing density of solid particle, both cement and aggregate, lowers the required amount of void water. Therefore, increase in packing density enables the design of HPC with low water/cement ratio. [5] The objective of HPC mix design based on packing density should be to achieve maximum mass of solid particles and minimum void.

In order to develop methodology for optimizing HPC mixes by void minimization, the knowledge of particle packing models is considered vital. A number of particle packing models were developed and tested for concrete mix design suitability. Two models were developed by [6]: the Linear Packing Model (LPM) and Compressible Packing Model (CPM). The linear packing was the function of particle size distribution (PSD) to be measured for all constituent materials. The calculation process of the packing density ϕ using CPM was similar to that using LPM. All the packing model were suitable for single or multi grain micro particle optimization. OPC, supplementary cementitious materials (SCM), superplasticizer and water optimal proportion can be find using packing models.

With only OPC used, the voids content (the ratio of the volume of voids to the bulk volume) tends to be quite large. In general, a broader range of particle size distribution would yield a higher packing density. Void content can be reduced by blending with SCMs, such as flyash and microsilica, that are finer than OPC. The effectiveness of a SCMs in filling up the voids or in improving the packing of the cementitious materials is dependent on the fineness of the supplementary cementitious material. Different methods were proposed in the past to find the optimal proportion of paste. Among them finding packing density by [5] wet packing was one of convincing method to optimize the cementitious material proportions in paste. [7] found that a triple blend combination of 35% blast furnace slag (SL) and 40% Class F fly ash (FFA) by mass of the total binder content, exhibit 10% higher packing density compared to the control mixture made with 100% OPC. [8] found that the partial replacement of 12% silica fume (SF), by mass of the total binder content, leads to 30% and 20% increases in yield stress and plastic viscosity respectively compared to the control mortar made with 100% cement. [9] presented an innovative method to produce eco-efficient mixtures of UHPC based on the packing density and statistical mixture design approach. The packing densities of the resulted quaternary mixtures indicated adding the silica fume increases the packing density of the granular materials up to 20%. The quaternary mix with the highest packing density value of 0.81 resulted highest compressive strength.

Agglomeration of particle is most predominant as the particle size becomes smaller. Adhesion of particles due to Van der Waals and electrostatic forces between the particles become more and more important. [10] concluded that the effectiveness of incorporating fillers was higher toward improvement of packing density in the presence of superplasticizer (SP). The SP [11] added to disperse the fine particles resulted in higher fluidity of a cement paste with higher packing density of the particle system. [12] evaluated the effect of high range water reducers (HRWR) dosage on packing density of cement paste. The addition of naphthalene-based HRWR from 0 to 3%, by mass of the total binder content resulted in 4 to 10% improvement in packing density of the cement paste.

An essential step of producing HPC is to enhance the packing density of the aggregate skeleton. For a given paste volume, an increase in aggregate packing density can improve workability, which is due to the increase in excess paste thickness surrounding the aggregate particles. [13] found maximum possible packing density of mortar for different replacement percentage of ground granulated blast furnace slag (GGBS). Particle packing studies conducted on mortar indicated the ideal recipe of powder to sand ratio as 40: 60 and the super plasticizer dosage of 2%. [14] apprehended that the optimum self-compacting ultra high-performance concrete (UHPC) mixes exhibited 2-14% of higher compressive strength with maximum grain sizes of 1mm, 2.5 mm and 4 mm. The combination of different aggregates will change the particle packing density of the whole concrete for a constant proportion of cementitious material, water-cement ratio, superplasticizer and the paste volume. [15] optimized the paste and mortar phase of light weight aggregate self compacting concrete (LWASCC) by wet packing method. Outperforming pastes combination were further investigated for optimization of mortar phase (maximum aggregate size < 4 mm). Mini slump-flow, mini V-funnel and strength tests were also conducted to affirm the best mortar phase of LWASCC.

The packing density technique for optimization of granular ingredients was accepted as the vital process in sustainable HPC mix design. A strong aggregate structure [16] with a high packing density will restrain the amount of shrinkage and creep and the concrete strength depends on the aggregate spacing to be bridged. In general, [17] increased packing density of the aggregate leads to the lesser volume of voids to be filled and the larger will be the amount of excess paste for lubrication.

No typical technique exists that is appropriate for determination of the packing of aggregates. [4] measured the packing densities of unblended and blended aggregate under wet condition. Test results indicated ,the water present could increase the packing density of fine aggregate by 18% but marginally increase the packing density of coarse aggregate. It was advocated that the dry packing method can be replaced by the wet packing method even for aggregates also. [18] apprehended the packing of aggregate was dependent on the size distribution and shape of the aggregate particles. Digital Image Processing (DIP) technique was employed to analyze the geometry of the particle boundaries. Flakiness ratio, elongation ratio, sphericity, shape factor, convexity ratio, and fullness ratio were the shape parameters measured. It was found that shape factor and the convexity ratio were influencing the packing of aggregates to a larger extent.

Studies were conducted to design the concrete mix by optimizing the paste, mortar and aggregate content independently. The influence of packing density was substantiated by measuring the fresh and hardened properties of HPC.[19] proposed HPC mixture proportioning based on the granular optimization of all constituents materials according to the ideal Fuller curve. [14] advocated step-wise optimization of particle packing density for UHPC mix design based on ideal combination of blended aggregate volume. The spread-flow test and compressive strength of UHPC mixes were used as the optimizing parameters. For water-cementitious material ratio of 0.25, the compressive strength of 190 MPa was achieved with good workability.

A systematic mix design procedure was developed by [20] with an aim to achieve a densely-compacted cementitious content for UHPC with enhanced fresh, mechanical properties and relatively low cost. Optimization of binder combinations was based on the flow characteristics, fresh and hardened properties, and rheological properties. 70 % river sand and 30 % masonry sand combination was optimized based on flow properties and 28-days compressive strength. [21] developed packing density mix design method for lower grades concrete based on the concept of void minimization. Results indicated decrease of w/c ratio as the grade of concrete increase in the case of packing density method. Workability of concrete achieved was more in packing density method compared to IS 10262-2009 code method. Quantity of aggregate required was more due packing. Marginal increase in strength was observed for concrete grade proportioned with packing density concept.

The HPC designed based on packing density concept requires validation in terms of mechanical strength and durability. Compressive strength, porosity, oxygen permeability, oxygen diffusion and chloride migration were carried to evaluate the short and long-term properties of HPC with mineral admixtures [22]. Resistance to water penetration was measured by water permeability test. With only 10% of SF , the water penetration depth in HPC was reduced by 60% [23].

It is evident from the previous research works carried on optimization of paste/mortar/aggregate content for HPC/UHPC mix, the proposed methods are suitable when applied to individual ingredient or content. Packing models and optimization curves were assume an uniform particle size (mono-disperse), which is not true in the case of HPC. Wet packing of binary and ternary blend of cementitious material is one of the realistic method to find the right combination of cement and SCMs. Studies were conducted to optimize the aggregate content by wet packing method also. Most of the studies are concentrated on the optimization of paste or mortar phase. The maximum particle size of the ingredients are less that 2mm. Thrust was more to find different methods to determine the right combination of cementitious materials and aggregates with larger particle size. There is a scope to design a field oriented HPC mix where the concrete grade is between 50 to 60MPa with nominal maximum size of aggregate less than 20mm. Nowadays usage of the 50MPa and above are more in the mass housing and infrastructure projects.

In the present study, an unified field oriented mix design procedure is proposed for mid strength HPC. Puntke test was performed to find the right combination of OPC and MS. Single and blended combination of aggregates were determined in dry packing test. The optimum amount of superplasticizer was found by Marsh cone test for the best binary blend of cementitious materials. Water - cementitious material (w/cm) ratio was determined by the flow test. The principle of HPC mix design is to find minimum amount of paste required to fill the voids in the aggregate content and also excess paste to coat the aggregates. The excess paste was required to ensure that no two aggregates were in direct contact and it was determined based on the flow test results. The amount of voids was calculated by subtracting the total packing of blended aggregate content from absolute zero void packing. The compressive strength and water penetration depth were measured to substantiate the optimized mid strength HPC mix.

2. Materials

Ordinary Portland (OPC) cement and micro silica (MS) were used in the experiments. The OPC which had been tested to comply with [24] and tested properties are tabulated in Table 1. The MS used in the study was complied with [25]. The surface area of the MS measured as 22000 m^2/kg with SiO_2 82% , bulk density 600 kg/m^3 and specific gravity 2.20. Superplasticizer (SP) used was a polycarboxylate based admixture with a solid mass content of

22% and a relative density of 1.08. According to the supplier, the preferred dosage of SP, measured in terms of liquid mass, should be 0.5–3.0% by mass of cementitious material.

Table 1: Properties of OPC and MS

Properties	OPC	MS
SiO_2 %	20.1	90.5
Al_2O_3 %	4.6	0.35
FeO_3 %	3.8	0.72
CaO %	62.3	1.25
MgO %	3.1	-
Compressive Strength at 28 days moist curing, MPa	58.2	-
Blain's surface area, m^2/kg	345	18,000
Specific gravity	3.15	2.2

Three size classes of aggregate, including one size class of fine aggregate and two size classes of coarse aggregate complied to [26] were used for the packing density tests. The size class details and specific gravity of the aggregates are depicted in Table 2. The single size particle distribution of aggregates are shown in Fig. 1.

Table 2: Aggregate Properties

Aggregate type	Size class	Particle size	Aggregate material	Specific Gravity
Coarse aggregate	C1	12.5 - 4.75mm	Crushed granite	2.70
	C2	20 - 4.75mm	Crushed granite	2.70
Fine aggregate	F	4.75mm - 150µm	Crushed granite sand	2.60

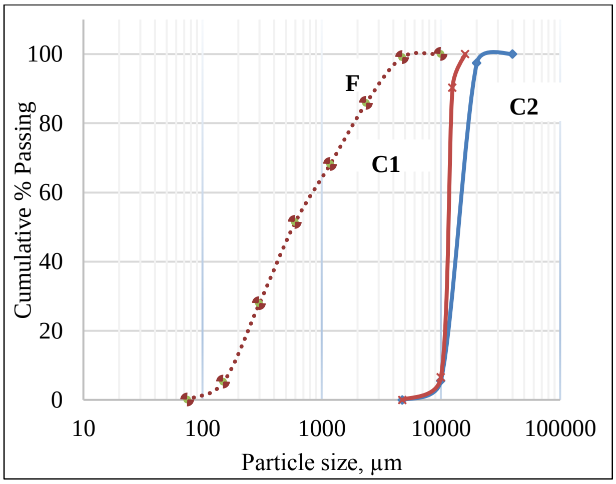

Fig. 1: Particle Size Distribution of Aggregates.

3. Test program

The purposes of the testing program were to design a concrete with grade more than 50 MPa based on packing concept. In the proposed test program, different contents of HPC were optimized independently with an common intention of minimum void content. The procedures test program are described below:

3.1. Puntke test

Puntke test ([27]) was performed to find the optimum combination of OPC and MS. One of the advantages of this technique was that the tests were performed in wet condition, which closely resembles the field practice. The basic principle of this test was that the water added to the dry materials fill the voids in between the particles and acts as a lubricant to make the materials compact efficiently. The water, which was in excess after completely filling the voids, appears at the surface of the mixture, indicating the saturation limits. Puntke test was also affirm the wet packing method suggested by [3], [8-7], [17]. Puntke test involves the selection of binder proportion by volume. Dry mix of selected volume of solid materials were mixed minimum four times for homogenization. Calculated increment of potable water added to the dry mixture with continuous manual mixing and simultaneous pressing of mixture against the sides of the container wall. Twenty times the container needs to be tapped by keeping on the flow table. This procedure need to repeat for addition of each increment of water until the saturation point (shinning/glossy surface) was reached. The experiment was done in three stages to get the least water required to achieve saturation.

3.2. Marsh cone test

Marsh cone test was performed to find the optimum dosage of superplasticizer (SP). The dosages were determined for cementitious slurry prepared using different amount of SP. Marsh cone time was recorded for different dosage of SP by % of cementitious material.

3.3. Dry packing test

Best combination of selected two size classes of coarse aggregates C was found based on the packing density. Combined sieve analysis of coarse aggregates was performed for different percentages by volume of C1 and C2 and checked for affirmation as per [26]. Selected blend codes of C1 and C2 were checked for their bulk density as per testing guidelines mentioned in [28]. The blended aggregate was filled about one-third full of the cylindrical measure of volume 15 litres and tamped with 25 strokes. Procedure was repeated to fill the cylindrical measure in three layers. Further, the determined best coarse aggregate combination C was again blended with single size class fine aggregate F. This blending ensures the filling of gaps between the coarse aggregate and minimization of void amount in aggregate content. Thus so obtained aggregate portion was well represent the availability of particle size varies from 20mm to 150µm. Among eligible C & F blends, the blend with highest packing density was determined. The proportion of aggregate was expressed as volumetric ratio of C1, C2 and F. Aggregate blending was carried in dry condition.

3.4. HPC mix design based on packing technique

Based on packing density, the HPC mix was proportioned. The paste proportion and the aggregate proportions were determined based on the least void volume and maximum packing density. The mix design procedure involves the determination of following parameters:

- Total aggregate proportion/ratio determined as discussed in dry packing test of aggregate.
- Total packing density of aggregate, determined by considering the packing density (Ø) of unblended C1, C2 and F size classes as per the Eq. 1:

$$Ø = \frac{\text{Bulk density x Volume fraction of individual aggregate size class in total aggregate}}{\text{Specific gravity of considered aggregate size class}} \quad (1)$$

- void content was important in deciding the minimum paste content and calculated as per Eq.2:

$$\text{Void content } = 1 - (Ø_{C2} + Ø_{C1} + Ø_{F}) \quad (2)$$

Where, $Ø_{C1}$ is the packing density of coarse aggregate of size class 12.5 - 4.75mm , $Ø_{C2}$ refers to packing density of coarse aggregate of size class 20 - 4.75mm and $Ø_F$ is the packing density of fine aggregate of size class 4.75mm - 150µm.

- Total paste content was the sum of the void content in blended aggregate portion and excess paste required to coat the aggregate particles. Flow table test was carried out in affirmation with [29] to decide the excess paste contents required to form the workable mix for different w/cm ratio and excess paste content. Six HPC mixes with two w/cm ratio of 0.34 and 0.36 were tested in flow table. Three excess paste contents of 10%, 15% and 20% by volume of paste were selected for the determination of optimum excess paste content. The optimized HPC mix was selected based on the spread flow % and cohesiveness.

- After determining revised paste volume by considering excess paste, the total solid volume of aggregate in HPC was calculated by the Eq.3:

$$= \frac{\text{Volume fraction of C1}}{\text{Specific gravity of C1}} + \frac{\text{Volume fraction of C2}}{\text{Specific gravity of C2}} + \frac{\text{Volume fraction of F}}{\text{Specific gravity of F}} \quad (3)$$

- Further, mass of each aggregate size class was calculated using the Eq.4:

$$= \frac{\text{Revised volume of total aggregate}}{\text{Total solid volume of aggregate}} \times \text{Volume fraction of C1/C2/F} \times 1000 \quad (4)$$

Revised volume of total aggregate was calculated as per Eq.5:

$$= 1 - \text{Revised total paste content/volume} \quad (5)$$

- The w/cm ratio was determined based on the result of flow table test. The volume fraction of OPC and MS was determined in Puntke test. Masses of OPC, MS and SP were calculated proportionately in the total paste content.

3.5. Compression test

The HPC mixes designed based on packing concept were tested for mechanical properties. 150 x 150 x150mm cube specimen were tested at 7 days and 28 days of water curing to ascertain the compressive strength in accordance with [30].

3.6. Water permeability test

Water permeability test of concrete specimen was determined as per German standards [31]. The test was carried out to determine the impermeability of concrete to water. The concrete cube specimens of dimensions 150 x 150 x150mm, were casted and cured for 28 days. The specimens were tested under water pressure of 5 bar for 72 hours. After the test duration of 72 hours, the depth of penetration and distribution of water in cross section of the specimen was measured.

4. Result and discussion

4.1. Optimum combination of OPC and MS

In Puntke test, the packing density of selected eight cementitious mixtures was calculated by Eq.6:

$$= \emptyset = 1 - \left[\frac{V_w}{(V_s+V_w)}\right] \quad (6)$$

Where, Vw is the volume of water, Vs refers to volume of solid particle. The constant volume of solid materials considered was 20 cm^3. From the Puntke test, packing density of each binary mixture of OPC and MS was calculated and the results are tabulated in the Table 3. From these results, it can be seen that, the packing densities of the mixture increases with the MS volume in total solid volume. Requirement of water to achieve saturation was also decreases up to the optimized blend of OPC and MS. Beyond this point, the water requirement was marginally increases and the packing density decreases. Among all the binary mixture, OPC80MS20 requires less water to achieve maximum packing density of 0.540.

Table 3: Mix Proportions and Puntke Test Results for Binary Blend Mixture

Mixture Code	OPC, % by vol.	MS, % by vol.	OPC ,gms	MS, gms	Water, cm³	Ø
OPC95MS5	95	5	59.85	2.22	19.00	0.512
OPC90MS10	90	10	56.70	4.44	18.50	0.519
OPC85MS15	85	15	53.55	6.66	18.00	0.526
OPC80MS20	80	20	50.40	8.88	17.00	0.540
OPC75MS25	75	25	47.25	11.10	17.30	0.536
OPC70MS30	70	30	44.10	13.32	17.30	0.536
OPC65MS35	65	35	40.95	15.54	17.40	0.534
OPC60MS40	60	40	37.80	17.76	17.50	0.533

4.2. Superplasticizer (SP) dosage

The optimum dosage of SP was determined in Marsh cone test for the mixture OPC80MS20 by keeping the w/cm ratio constant. Different dosage of SP considered, % by mass of cementitious material, starting from 0.60 to 1.40. Time taken by the one litre of cementitious slurry to empty Marsh cone was recorded. The variation of time taken by the cementitious slurry to empty the Marsh cone and the dosage of SP is plotted in Fig. 2. The results indicated an optimum SP dosage of 1.20 % by mass of cementitious material, which is considered in the HPC mix design.

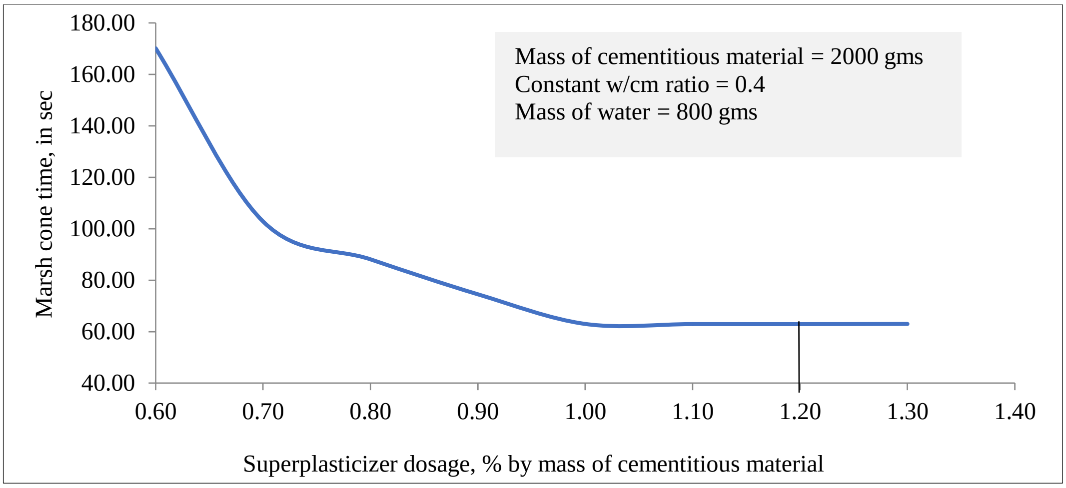

Fig. 2: Variation of Marsh Cone Time with Different Dosage of Superplasticizer.

4.3. Optimization of aggregate content for HPC

Coarse aggregate size class C1 and C2 were blended and combined sieve analysis was conducted for 12 mixtures. Maximum mass of C1 and C2 blended mixture was the selection criterion for optimum combination. The blend code, bulk density and packing density of different mixtures are listed in Table 4. Bulk density was gradually increased with C2 size class aggregate up to 60 % by volume. Later there was a gradual decrease in the bulk density. C1 size class aggregate was combined to minimize the void volume in total coarse aggregate. Inclusion of C1 size class aggregate result in improvement of packing density from 0.538 (lowest packing density) to 0.644 (peak packing density). It can be observed that for blend code C1 40C2 60 the voids ratio reached a minimum value and the packing density reached a maximum value. The blend code having peak packing density was taken as the optimum blend of coarse aggregate for further test.

The obtained blend ratio of C1 40C2 60 was designated as C and it was further blended with fine aggregate of size class F (4.75mm - 150µm). F was blended with C by % volume of total aggregate for eight combinations. Dry packing test, combined sieve analysis and bulk density results were recorded for each aggregate combinations. For illustration, particle size distribution in accordance with [9] for the blend ratio C60F40 are plotted in Fig. 3. Packing test results, void content and packing density for different fine aggregate to total aggregate (F/T) ratio are depicted in Table 5.

Table 4: Packing Density Results of C1 and C2 Size Class Aggregate Blending

Blend Code	C1, % by vol.	C2, % by vol.	Mass of aggregate, kg	Bulk Density, gm/cm^3	Ø
C1 80C2 20	80	20	21.77	1.451	0.538
C1 75C2 25	75	25	22.15	1.477	0.547
C1 70C2 30	70	30	22.21	1.481	0.548
C1 65C2 45	65	35	23.04	1.536	0.569
C1 60C2 40	60	40	23.77	1.585	0.587
C1 55C2 45	55	45	24.35	1.623	0.601
C1 50C2 50	50	50	25.04	1.669	0.618
C1 45C2 55	45	55	25.31	1.687	0.625
C1 40C2 60	40	60	26.08	1.739	0.644
C1 35C2 65	35	65	25.51	1.701	0.630
C1 30C2 70	30	70	24.86	1.657	0.614
C1 25C2 75	25	75	24.08	1.605	0.595

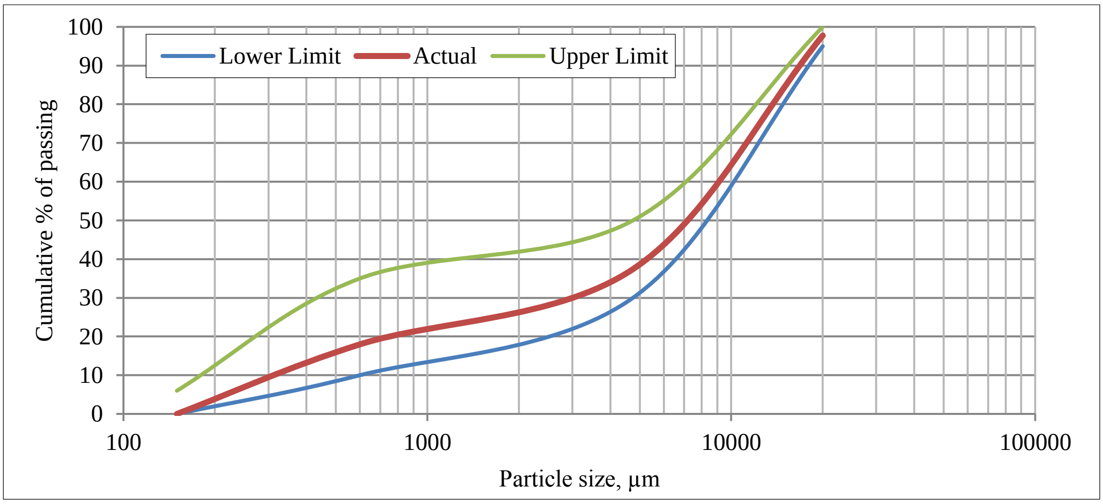

Fig. 3: Particle Size Distribution of Blend Ratio C60F40.

Table 5: Packing Density Result of C and F Size Class Aggregate Blending

Blend Code	C, % by vol.	F, % by vol.	Mass of combined aggregate, kg	Bulk Density, gm/cm^3	Voids Content	Ø
C80F20	80	20	30.65	2.043	0.120	0.880
C70F30	70	30	31.78	2.119	0.105	0.895
C60F40	60	40	32.02	2.135	0.100	0.900
C50F50	50	50	31.46	2.097	0.106	0.894
C40F60	40	60	30.85	2.057	0.112	0.888
C30F70	30	70	30.35	2.023	0.117	0.883
C20F80	20	80	29.82	1.988	0.122	0.878
C10F90	10	90	29.28	1.952	0.127	0.873

From the dry packing test results for C and F size class aggregate blending, it was seen that void content in total aggregate reduces from 0.356 (as observed in blending of C1 and C2 size class aggregate) to 0.100. This reduction clearly indicates the filling effect

([2]) of the F size class aggregate. These results revealed that, the peak packing density of the blended coarse aggregate for the blend ratio C1 40C2 60 was 0.644. With inclusion of F size class aggregate, the packing density was increased to 0.900. As the F size class aggregate increased from 20% to 40% by volume of total aggregate, the packing density increased. However, after reaching a certain optimum: 40% by volume of total aggregate, the packing density ceased to increase and started to decrease as the fine aggregate % further increased in total aggregate.

4.4. Mix Proportioning of HPC based on packing density

The C2 size class coarse aggregate (20 - 4.75 mm) to C1 size class coarse aggregate (12.5 - 4.75 mm) ratio in total coarse aggregate C was determined as 60:40. On the other hand, from the blending results of C and F size class fine aggregate (4.75mm - 150µm), the best blend ratio C60F40 was selected. The independent ratio of different size class aggregate in total aggregate is as follows,

C2: C1: F = 36:24:40

From Table 4, the bulk density of best blend ratio C60F40 was found to be 2.135 gm/cm^3. Packing density of individual size class of aggregate was calculated as per equation (1),

Packing density of C2 size class aggregate, $Ø_{C2}$

$$= [(2.135 \text{ X } 0.36) / 2.70]$$

= 0.284 gm/cm^3

Packing density of C1 size class aggregate, $Ø_{C1}$

$$= [(2.315 \text{ X } 0.24) / 2.70]$$

= 0.189 gm/cm^3

Packing density of F size class aggregate, $Ø_F$

$$= [(2.315 \text{ X } 0.40) / 2.62]$$

= 0.325 gm/cm^3

Total packing density of aggregate content, $Ø = (Ø_{C2} + Ø_{C1} + Ø_F)$

$$= 0.284+0.189+0.325$$

= 0.798 gm/cm^3

The void content was calculated as the volume of free space available in total aggregate from equation (2)

Void content = 1 - $(Ø_{C2} + Ø_{C1} + Ø_F)$

$$= 1 – 0.798$$

= 0.202 gm/cm^3

Minimum paste content was the sum of the paste required to fill the voids in total aggregate and excess paste required to coat the aggregate particles. The Flow table test was conducted to determine the paste content and the results are tabulated in Table 6.
Sample calculations of revised paste content, volume of total aggregate, total solid volume of aggregate, mass of individual size class of aggregate, OPC, MS, SP and free water for mix HPC15034 are depicted as below. Similar calculation were done for other mixes and the results are tabulated in Table 6.

4.5. Sample calculation for HPC15034

The revised total paste content by considering 15% excess paste to fill the aggregate particle was determined as:

Revised total paste content = 0.202 + 0.15 x 0.202

= 0.232 gm/cm^3

The revised volume of total aggregate = 1 – 0.232 = 0.767 gm/cm^3
Total solid volume of aggregate was calculated as per the equation (3).

$$= \frac{0.36}{2.70} + \frac{0.24}{2.70} + \frac{0.40}{2.62}$$

= 0.374 gm/cm^3

Individual solid mass of each aggregate size class was calculated using the equation (4).

Solid mass of C2 size class aggregate,

$$= \frac{0.767}{0.374} \times 0.36 \times 1000$$

= 738.28 kg/m^3

Solid mass of C1 size class aggregate,

$$= \frac{0.767}{0.374} \times 0.24 \times 1000$$

= 492.19 kg/m^3

Solid mass of F size class aggregate,

$$= \frac{0.767}{0.374} \times 0.40 \times 1000$$

= 820.32 kg/m^3

Selected w/cm ratio for mix HPC15034 was 0.34. From the Punkte test, the optimized combination of OPC and MS was 80:20. Ratio of MS and OPC was 0.25. Volume of the total paste consist of OPC, MS and water is represent in the equation (7),

$$= \frac{\text{OPC}}{\text{OPC specific gravity}} + \frac{\text{MS}}{\text{MS specific gravity}} + \frac{0.34 \text{ x } (0.80 \text{ x OPC} + 0.20 \text{ x MS})}{\text{Water specific gravity}} \quad (7)$$

Where, the volume of water was represent in term of cementitious materials: OPC and MS to simply the calculation . Even the MS was also expressed in terms of OPC. Equation (7) revised as below,

$$= \frac{\text{OPC}}{3.15} + \frac{0.25 \text{ x OPC}}{2.20} + \frac{0.29 \text{ x OPC}}{1.00}$$

The volume of total paste expressed in OPC = 0.721
The mass of OPC in HPC mix,

$$= \frac{0.232}{0.721} \text{ x } 1000$$

= 321.77 kg/m^3

Mass of MS was calculated as, 0.25 x OPC = 80.44 kg/m^3

The total mass of cementitious material in HPC = 321.77 + 80.44

= 402.21 kg/m^3

The mass of free water = 0.34 x cementitious materials

= 136.75 kg/m^3

Superplasticizer (SP) volume was optimized as 1.2 % by mass of cementitious materials

The mass of SP in HPC mix = (1.2/100) x 402.21

= 4.82 kg/m^3

Table 6: Flow Table Test Results

w/cm ratio	Mix code	Excess paste content, % by vol.	Water, kg/m³	OPC, kg/m³	MS, kg/m³	C1, kg/m³	C2, kg/m³	F, kg/m³	HPC Spread on flow table	Flow diameter, mm	Average compressive strength, MPa		Average depth of water penetration, mm
											7 days	28 days	
0.34	HPC10034	10%	130.85	307.90	76.97	498.60	747.91	831.01		490	38.15	52.25	10.06
	HPC15034	15%	136.75	321.77	80.44	492.19	738.28	820.32		550	45.35	59.15	6.21
	HPC20034	20%	142.64	335.64	83.91	485.77	728.66	809.62		460	47.65	63.50	6.56
0.36	HPC10036	10%	138.55	307.90	76.97	498.60	747.91	831.01		510	30.05	43.05	12.11
	HPC15036	15%	144.79	321.77	80.44	492.19	738.28	820.32		450	40.95	55.90	7.13
	HPC20036	20%	151.03	335.64	83.91	485.77	728.66	809.62		530	43.25	59.45	7.89

Mix codes represent the amount of excess paste (10%, 15% and 20%) and the w/cm ratio considered (0.34 and 0.36). From the results of HPC mixes tabulated in Table 6, bleeding and uneven distribution of aggregate were observed for the mixes with w/cm ratio 0.36. Mix HPC10036 was bleeded more with clear separation of free water from aggregate content. Impressive flow diameter of 530 mm was observed for the mix HPC20036. But, the mobility of aggregates was poor and aggregates were restricted at the centre of flow. Stiff and less flow were observed for the mix HPC20034 due to the resistance offered by the excess paste. Available of less paste between aggregate particles resulted in reduced aggregate movement for the mix HPC10034. It was observed that, the mix HPC15034 achieved a flow diameter of 550 mm without any sign of bleeding and segregation. The space between the aggregate and surface of the aggregate particle were completely filled by the optimum amount of paste. The compressive strengths at 7 and 28 days of the evaluated mixtures ranged from 30.05 to 63.50 MPa. The highest 28 day compressive strength of 63.05 MPa was observed with w/cm ratio of 0.34 for the mix HPC20034. Mix HPC10036 was experienced less compressive strength both at 7 and 28 days of water curing due to bleeding and segregation of aggregate content from paste. Water permeability test results indicated highest penetration depth of 12.11mm for the mix HPC10036 and least depth of 6.21mm for HPC15034.

5. Conclusions

In the present experimental study, an integrated mix design procedure was proposed for mid strength HPC by integrating the individual packing of cementitious materials and aggregate. The influence of packing density on the optimization of cementitious materials: OPC and MS was evaluated. The advantages of having wide range of particle size distribution in HPC was experienced by blending aggregates of different sizes in dry condition. The flow table test and strength results were considered to choose optimum mix for HPC. Test results indicated the possibility of optimizing the paste and aggregate contents with least possible void content using packing density concept. Based on the experimental results the observations, following conclusions were drawn:

The Puntke test provides an effective results towards optimizing the binary blend of OPC and MS based on the least amount of free water required to saturate the cementitious materials. It could be effective, yet easily adoptable filed test for cementitious material optimization. The test results indicated an optimized blend with 80 % OPC and 20% MS by volume of cementitious material with least void content.

Dry packing proved to be a convincing test method for optimization of aggregate. Blending of different size class aggregate ensures the presence of wide range of particle size. An optimum combination of C1:24, C2:36 and F:40 % by volume of total aggregate was found based on the packing density and maximum aggregate mass in a constant volume. The requirement of more volume F size class (4.75mm - 150µm) aggregate was well represent the effective filling of voids between the C1 and C2 size class aggregate. The filling effect of F size class aggregate resulted in the enhancement of packing density from 0.644 to 0.900 in overall aggregate content.

The HPC mix design by packing concept distinctly consider the total packing density of aggregate for void content determination.

The mix design procedure explained, has an objective of least possible void content in HPC. The advantage of designing the HPC mix based on packing concept, guaranteed the sufficient paste volume, not only to fill the void in aggregate content, but also to lubricate the aggregate. An excess paste volume was resulted in improvement of aggregate mobility. It was observed from the results tabulated in Table 6 that, any variation in paste volume leads to the changes in aggregate volume.

Flow table test proved to be a credible method to validate the mix proportioning of HPC. The additional HPC fresh properties: aggregate mobility, bleeding, segregation and satisfactory amount paste were observed in flow table test. Lack of satisfactory amount of paste and higher w/cm led the mix HPC10036 to bleed with clear separation of paste and aggregate content. The mix HPC10034 was indicated depressed aggregate movement from center to periphery of flow table due to inadequate paste . The optimum combination of paste and aggregate content were obtained for the mix HPC15034 shows a maximum spread diameter of 550mm which is 22% higher than mix HPC15036. This clearly contradict the requirement of more free water for better flowability. On the other hand, mix HPC20036 recorded a flow diameter 530mm, very near to HPC15034, but indicated inadequate aggregate movement. No signs of bleeding and segregation were observed for mix HPC20034. But, less flow diameter was observed due to the resistance offered by surplus amount of paste to aggregate mobility. Flow table test results distinctly highlighted the necessity of satisfactory paste volume and w/cm for increased mobility of aggregate.

Average compressive strengths were more for HPC mixes with w/cm ratio 0.34. Mix HPC20034 recorded highest compressive strength of 63.50 MPa among all HPC mixes. Mixes HPC10036, HPC15036 and HPC20036 attained relatively less strength compared to respective mixes with w/cm ratio 0.34. Least compressive strengths of 30.05 MPa and 43.05 MPa at 7 and 28 days of curing were observed for the mix HPC10036. Due to optimum w/cm ratio of 0.34, the compressive strength of mix HPC20034 was 6.81% higher than its counterpart mix HPC20036.

A nominal difference of 4.35 MPa was recorded between HPC20034 and HPC15034. But in the flow table test, the mix HPC15034 exhibited 1.19 time more flow diameter than the HPC20034. The aggregate mobility and cohesiveness were the vital parameters in achieving the desired properties of HPC.

Due to less paste availability and more w/cm ratio, the mix HPC10036 exhibited water penetration depth of 12.11mm in water permeability test. HPC mixes with w/cm ratio 0.34 showed less water penetration compared HPC mixes with 0.36. From the results, the w/cm ratio of 0.34 was selected and the mix HPC15034 was considered as optimized mid strength HPC.

Compliance with ethical standards

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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