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A STATISTICAL MIX-DESIGN APPROACH FOR ECOLOGICAL SELF-COMPACTING CONCRETE BASED ON RHEOLOGY AND PARTICLE PACKING

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ABSTRACT
The present paper puts forward a simple statistical mix design method for Self-Compacting Concrete (SCC) based on particle packing and targeted flow properties. Even for lower strength of concrete, high amount of binders are needed in production of self-compacting concrete (SCC) to satisfy the required rheological properties. Present research is intended to improve rheological properties of SCC by optimizing aggregate packing and thereby reducing binder content particularly for compressive strength 20-35 Mpa. For achieving this, a new simplified gradation based particle packing approach is used. Furthermore, a simplified mix design approach to produce SCC is given using proposed model. Using the proposed mix design approach, SCC mixes are casted with 20 mm and 10 mm maximum size of aggregate (MSA) and 300 kg, 320 kg cementitious material. For various mix proportions, V-funnel, sieve segregation, L box, compressive strength tests were performed. By present approach Fresh properties were improved as compare to existing SCC mix design approach without compromising compressive strength. The precision of the proposed model is at par with the present most efficient particle packing model (PPM). Moreover, modifications in EFNARC guideline are suggested.

Keywords: Self-Compacting Concrete, Particle Size Distribution, Compressive Strength, Ecological Concrete, Rheological Properties, Particle Packing Model

1. INTRODUCTION
The effects of concrete production on the environment can be reduced by reducing binder content. SCC is not considered environment friendly particularly for grade of concrete 20-35 Mpa, as it requires higher amount of cementitious material to achieve desirable rheological properties. As a result, a lot of work is being done to design and implement SCC with a compressive strength of 20–35 MPa [1]. The percentage volume occupied by aggregates in concrete mix having compressive strength 20-35 Mpa is around 65-70%. So, optimum packing of coarse and fine aggregate is essential to reduce cementitious material content in SCC mixes. For optimum packing of coarse and fine aggregates, work is carried out since long and is discussed below.

Particle packing models are of two types continuous and discrete. Continuous models developed by Anderson, Funk & Dinger [2-4] provides the quantitative packing density (PD) for a particular aggregate grading. Rather than providing the aggregates' quantitative packing density, continuous models [2-4] provide the blended aggregate's particle size distribution (PSD). The modified A&A model provided by Funk and Dinger [4] is the most extensively utilized continuous model available for developing Eco-SCC. Maintaining the distribution modulus between 0.21 and 0.29 in the modified A&A model yields the best PD and is the most appropriate range for SCC [5-8].

In discrete approach [9-19], Smaller particles occupy the spaces left by the larger particles, and smaller particles fill the spaces left by still smaller particles, and so on. Discrete models fall into three categories: multi-component, ternary, and binary mixture models. The size ratio of the accessible particles is the primary focus of discrete models [9–14]. The packing density for binary mixes is calculated by the Toufar Model [11], which does not provide an accurate answer for multi-component mixes. In comparison to other models [13–16], the De Larrard compression packing model (CPM) [12–14] provides a superior prediction of packing density for multi-component mixes. However, the method of determining PD is difficult to implement on site. In present research for finding packing density gradation based approach [34] is used, which is simple and efficient.

Researchers have developed different mix design approaches for production of SCC e.g. Compressive strength testing, close aggregate packing, statistical factorial model-based techniques, paste model rheology, and so forth. After reviewing and contrasting the many mix design techniques for SCC that were accessible, Shi C, et al. [20] came to the conclusion that the particle packing approach to build SCC is less complicated and requires less binders. The particle packing strategy is more beneficial, especially for Eco-SCC, because the aggregate phase has a greater influence on Eco-SCC performance because the aggregate volume is approximately 65-70% [21–22].

For structural concrete, the Indian standard IS: 456-2000 [23] permits a maximum w/p ratio of up to 0.55. Similarly, the highest w/p ratio permitted for the durability requirement is 0.50 according to ACI-301 [24]. As a result, the w/p ratio in the current investigation is restricted to 0.50.

2. RESEARCH SIGNIFICANCE

In current research aggregate packing based simplified mix design approach for Eco-SCC is given to reduce binder content to achieve desired rheological properties without compromising compressive strength. Also, based on experimental results, the modification in EFNARC guideline is suggested particularly for SCC having compressive strength 20-35 MPa,

3. MATERIALS AND METHOD

The present study uses Portland Pozzolona Cement (PPC) with a fly ash percentage of 32.60%, 20 mm and 10 mm down coarse aggregate (CA), 4.75 mm down fine aggregate (FA), and Master Glenium Sky BASF 8549, a poly carboxylic ether (PCE) based super plasticizer, for mix proportioning of SCC. Every material used is readily accessible in the area. These materials' critical characteristics, such as their specific gravity, water absorption capacity, gradation, etc., are all identified and displayed. The Master Glenium SKY 8549 satisfies every IS: 9103:1999 requirement [25]. The PPC cement used satisfies guidelines of IS: 1489-1991[26]. Fine and coarse aggregate sieve analyses are carried out in accordance with IS: 383-2016 [27] and IS: 2386-2002 (Part-1) [28]. The sieve analysis results of the CA and FA used in this investigation are displayed in Table 1. Tests for specific gravity and water absorption are carried out in accordance with IS: 2386-2002 (Part-III) [29], and Table 2 displays the results.

Table 1 Sieve Analysis of Coarse and Fine Aggregate

Sr. No.	Sieve Size (mm)	Passing Percentage through Sieve		
		FA	CA 10 mm MSA	CA 20 mm MSA
1	40	-	-	100
2	20	-	-	92.50
3	12.5	-	100	-
4	10	100	90.50	14
5	4.75	97.9	6.50	0
6	2.36	90.6	1	-
7	1.18	73.80	-	-
8	0.6	65.6	-	-
9	0.3	30.5	-	-
10	0.15	6.9	-	-
11	0.075	0	-	-

12	Pan	-	-	-

Table 2 Physical Properties of material

Sr. No.	Material	Specific Gravity	Water Absorption (%)
1	Cement (PPC)	2.9	-----
2	CA (20 mm)	2.86	1.11
3	FA	2.57	1.89
4	PCE based Super plasticizer	1.1	-----

Bulk density and voids of aggregate is calculated in accordance with ASTM C29 [30]. Similar procedure is also adopted in IS: 2386-2002 (Part-III) . Bulk density and voids of the CA and FA taken in this study are presented in Table 3. PD is calculated from voids present in the particles.

Table 3 Bulk density and Voids of Aggregates

Material	Bulk Density (kg/m3)	Voids (%)	PD
CA (20 mm)	1637.40	42.7	0.57
CA (10 mm)	1718.53	39.9	0.60
FA	1885.60	26.6	0.74

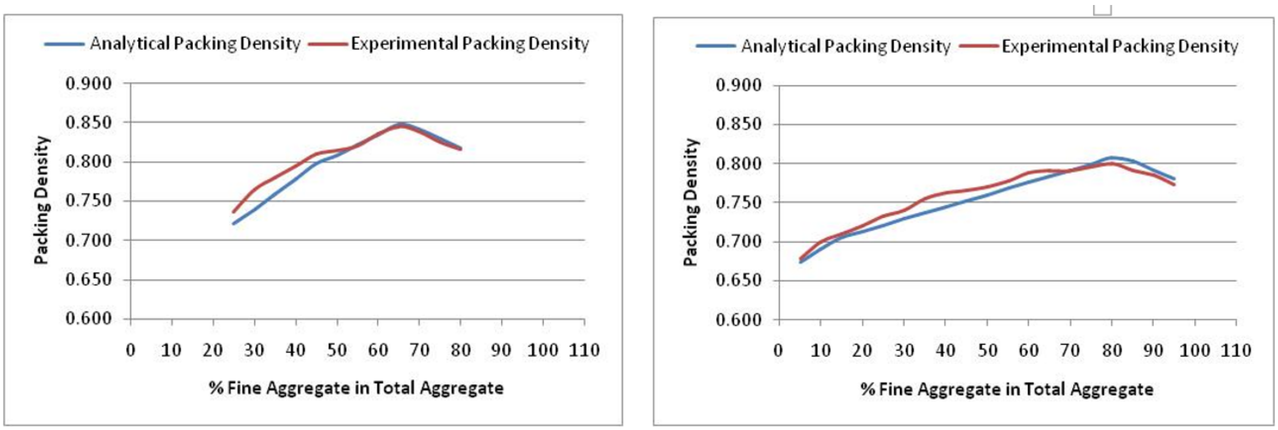
4. OPTIMUM PACKING DENSITY OF BLENDED COARSE AND FINE AGGREGATE USING PARTICLE PACKING THEORY

By finding out the PD and thereby voids in the blended coarse and fine aggregate, it is possible to precisely determine the amount of paste needed to fill up voids and estimate the amount of free paste needed for flow, the mix design of SCC based on compacted PD is more straightforward and universal.

The comparison between the analytical and experimental packing densities using packing approach [34] is displayed in Table 4. It is evident that the suggested model works incredibly well for calculating the PD of blended aggregate with varying sizes.

Table 4 Comparison of Analytical and experimental Packing density calculated through model

Blend of Aggregate	Analytical PD	Experimental PD	Error (%)
35% 20 mm CA + 65% FA	0.846	0.845	0.067
35% 10 mm CA + 65% FA	0.784	0.787	0.395



20 mm MSA mixed with FA 10 mm MSA mixed with FA

Figure 1 Comparison of Experimental and Analytical packing density

PD is determined both analytically using the suggested model and experimentally for every 5% increase in fine aggregate. When mixing 10 mm and 20 mm MSA with FA, the PD is computed. Analytical PD derived from the suggested model agrees with the experimental PD, as seen in Figure 1.

Concrete with a higher volume of aggregate may normally benefit more from the particle packing method. Particle packing will have less of an impact on the fresh and hardened properties of SCC if the aggregate volume is reduced and the paste volume is raised. Therefore, concrete with a compressive strength of up to 35 N/mm2, or concrete with an aggregate volume of roughly 60% to 70%, is better suited for this particle packing strategy.

It is believed that the paste will entirely fill any spaces between aggregates when the current model is used to create SCC, and that free paste will enhance the rheological characteristics of SCC.

5. EXPERIMENTAL PROGRAM, RESULT AND DISCUSSION

As suggested in [31] sand fines (smaller than 150 micron) should be around 3-4 % in total aggregate for good cohesive mix without compromising strength. In present study sand fines are around 4% in total aggregate. Also, according to EFNARC guideline [32], fine aggregate content should make up between 48% and 55% of the total aggregate. While as per the suggested PPM, the packing density of the aggregates used in this study is higher for FA:CA ratios of 60:40, 55:45, and 52:48, as well as for 65% FA blended with 35% CA. Therefore, a total of 11 mixes were constructed in order to test the effects of packing density and coarse aggregate volume. Table 5, shows the design mixes considered in this study. Initially, total 9 mixes were prepared keeping aggregate and paste volume constant and varying proportion of fine and coarse aggregate in total aggregate to check the effect of packing density of aggregate. Ten mm MSA was used to prepare five mixtures, while twenty mm MSA was used to prepare four. The following ratios of fine to coarse aggregate were measured for a 20 mm MSA: 65:35, 60:40, 55:45, and 52:48. The fine and coarse aggregate proportions for a 10 mm MSA were measured as follows: 65:35, 60:40, 55:45, 52:48, and 48:52. Paste composition and volume are maintained constant in all mixtures.

After casting of 9 mixes, 2 more mixes with lesser cementitious material and without adding any viscosity modifying agent and with w/c ratio allowed for structural concrete were casted to show that with higher packing density even with less cementitious material fresh properties of SCC can be achieved. For all the mixes Slump Flow, T 500 time, V funnel, L-Box, Sieve segregation test are performed as per the EFNARC guideline and Cube Compressive strength tests were performed as per the guidelines given in IS:516 [33]. According to IS:456-2000 [23], the water-to-cementitious material ratio cannot be maintained at more than 0.55 for RCC work in conditions of mild exposure and 0.50 for RCC work in conditions of moderate exposure. Therefore, the investigation is restricted to w/c ratios of 0.50 for each blend.

5.1. MIX DESIGN APPROACH USING PROPOSED PPM

Step-1 Ascertain the specific gravity, gradation, water absorption, and bulk density of an ingredient.

Step-2 Find the aggregate mix that yields the highest packing density based on gradation and the suggested PPM. Aggregate in this context refers to any filler material utilized in addition to fine and coarse aggregate. Calculate any voids in the aggregate by using the packing density as well. For example, a combination of 65% FA and 35% CA has an ideal packing density of 0.845.

Step-3 Experiment to confirm the packing density for the specified aggregate combination.

Step-4 Determine the ideal PCE-based additive dosage for the cement being used and the specified water-to-cement ratio using the Marsh Cone Test. For instance, the dosage of super plasticizer for a W/C ratio of 0.5 is 0.6% by weight of cement. Super plasticizer dosage can be changed depending on the finished mixture.

Step-5 Assume the weight of the cementitious material and the water to cementitious material ratio based on the target cube compressive strength and slump flow. Determine the volume and weight of the admixture, water, and cement.

Step-6 Calculate the paste volume, taking into account the volume of water, admixture, cementitious material, and air that is assumed. Calculate the free paste volume that remains after the aggregate voids are filled. The target slump flow is determined by the paste composition and free paste volume.

Step-7 Determine the aggregate's weight and volume.

Volume of aggregate = 1000 - volume of paste, since the volume of paste is known.

For instance, if the paste volume is 360.84 liters and the blended aggregate has 65% fine aggregate and 35% 20 mm aggregate, the aggregate volume will be 639.16 liters.

$$\text{Therefore, weight of aggregate } W = \frac{V}{\frac{P_{FA}}{G_{FA}}+\frac{P_{10mm}}{G_{10mm}}+\frac{P_{20mm}}{G_{20mm}}+\frac{P_{filler}}{G_{filler}}}$$

Where V is the blended aggregate's total volume, Wis The mixed aggregate's total weight, G is the material's specific gravity; P is the percentage of aggregate in the overall aggregate

$$W = \frac{639.16}{\frac{0.65}{2.57}+\frac{0}{2.86}+\frac{0.35}{2.86}+\frac{0}{2.72}} = 1703.08 \text{ kg}$$

W_{FA}=0.65X1703.08=1107 kg and

W_{20mm}=0.35X1703.08=596.08 kg

Step-8 Determine the final ratio and account for free moisture and water absorption.

Table 5 Experimental Program

Mix Designation	**Combination of Aggregate**			**20 mm (kg)**	**10 mm (kg)**	**Sand (kg)**	**Cement (kg)**	**Water (kg)**	SP (%cement weight)
	FA	**10 mm**	**20 mm**						
Mix 1	65:00:35			596.08	0.00	1107.00	400	200	0.60
Mix 2	60:00:40			684.83	0.00	1027.25	400	200	0.60
Mix 3	55:00:45			774.53	0.00	946.65	400	200	0.60
Mix 4	52:00:48			828.81	0.00	897.87	400	200	0.60
Mix 5	65:35:00			0.00	596.08	1107.00	400	200	0.60
Mix 6	60:40:00			0.00	684.83	1027.25	400	200	0.60
Mix 7	55:45:00			0.00	774.53	946.65	400	200	0.60
Mix 8	52:48:00			0.00	828.81	897.87	400	200	0.60
Mix 9	48:52:00			0.00	901.72	832.36	400	200	0.60
Mix 10	65:00:35			628.32	0.00	1166.89	360	180	0.65
Mix 11	65:00:35			644.05	0.00	1196.09	340	170	0.70

Table 6 Result of Experimental Program

Mix Designation	Paste Volume (litre/m3)	Packing Density	Free paste (litre/m3)	Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	L Box	Sieve Segregation Portion (%)	Compressive Strength	
									7 Days	28 Days
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mix 2	360.8	0.835	255.4	680	1.59	4.4	0.95	6.65	21.3	39.36
Mix 3	360.8	0.820	245.8	650	3	2.4	0.95	10.35	23.46	39.92
Mix 4	360.8	0.810	239.4	640	3.12	1.66	1.0	13.25	26.9	41.37
Mix 5	360.8	0.791	227.1	635	2.4	3.86	0.95	4.36	21.77	39.55
Mix 6	360.8	0.788	225.35	630	2.57	4.84	0.95	5.25	22.33	39.09
Mix 7	360.8	0.778	218.9	620	3.6	5.99	0.95	5.80	21.59	41.38
Mix 8	360.8	0.771	214.5	610	2.68	9.47	0.95	6.95	20.66	38.18
Mix 9	360.8	0.761	208.1	600	2.42	10.5	0.90	9.75	19.96	38.93
Mix 10	326.3	0.845	222.4	650	2.85	6.72	0.90	4.70	22.58	35.29
Mix 11	309.4	0.845	202.4	560	3	8.60	0.82	3.65	22.5	33.54

Table 6 displays all of the combinations' fresh and hardened characteristics. The paste volume for Mixes 1 through 9 remains constant at 360.8 liter/m3, while the fine and coarse aggregate proportions and aggregate size are changed to alter the PD. The free paste volume that remains after filling in blended aggregate voids is computed and shown in Table

6 based on the PD of blended aggregates and the total volume of blended aggregate. It has been noted that Mix 1 through Mix 9 exhibit varying slump flow values for the same paste volume of 360.8 liter/m3, and that slump flow increases with an increase in free paste volume. Figure 2 shows the relationship between slump flow and free paste volume.

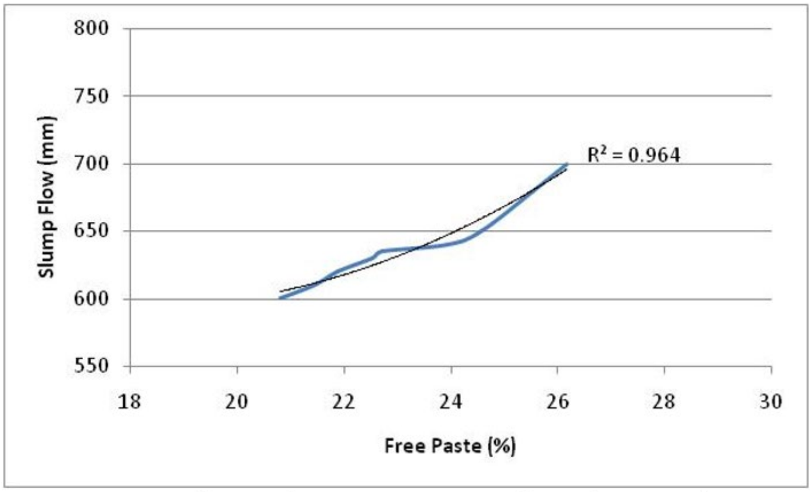


Figure 2 Slump Flow vs. Free Paste for Mix 1 to Mix 9

In comparison to 10 mm aggregates, 20 mm aggregates have a higher packing density for the same FA:CA ratio. As shown in Figure 3, SCC mixes with 20 mm MSA have larger free paste volume than those with 10 mm MSA due to the higher packing density, which results in better fresh characteristics. Mix 10 and Mix 11 are cast using 20 mm MSA with a lower paste volume and an FA:CA proportion of 65:35 because it provides the highest packing density for the FA:CA ratio of 65:35. Figure 4 illustrates slump flow and compressive strength. In comparison to SCC mix with 10 mm MSA, SCC mix with 20 mm MSA provides more slump flow without sacrificing compressive strength. For mixes 1 through 9, the compressive strength is almost constant due to the consistency of the paste volume and composition.

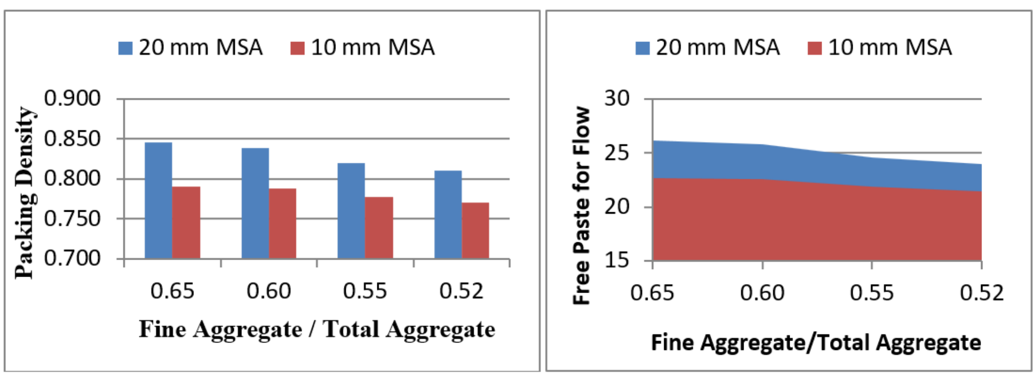


Figure 3 Packing Density and corresponding free paste for flow SCC mix 1 to 8

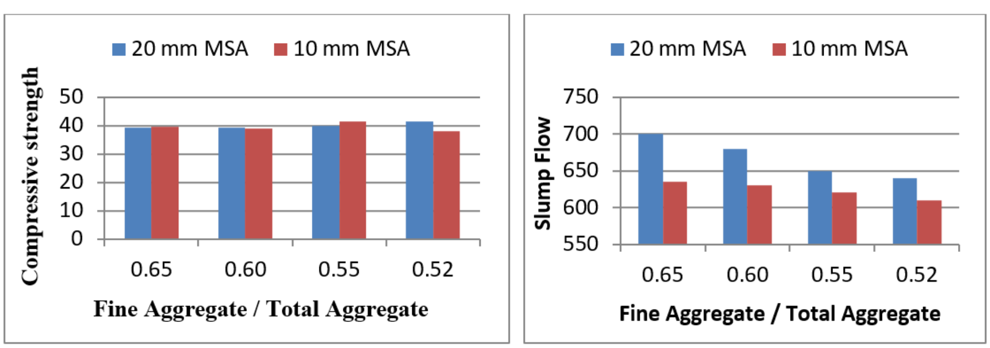


Figure 4 Compressive Strength and Slump Flow for SCC mix 1 to 8

Every SCC mixes are cohesive. It has been noted that the likelihood of segregation and bleeding increases with decreasing fine aggregate volume. Bleeding and segregation begin when the 20 mm aggregate makes up 48% of the overall aggregate. Similarly, bleeding was seen when the 10 mm aggregate makes up 52% of the overall aggregate. As can be observed in Table 6, SCC mix is made with paste volume as low as 30% and a water to cementitious material ratio (w/c) of 0.5 utilizing the suggested particle packing technique.

6. CONCLUSION

10 mm CA blended with FA, shows lesser packing density comparing to 20 mm CA. Therefore, in Indian perspective to produce SCC mix having aggregate volume 65-70% in concrete mix and compressive strength up to 20-35 N/mm2, it is recommended to use 20 mm MSA.

A combination of 35% of 20 mm CA with 65% FA has optimum packing and least voids and hence for given volume of paste maximum free paste is available for flow. This is conclusive as maximum flow is achieved for this combination of aggregate without compromising strength.

It can be seen that, for same cementitious material slump flow ranges from 700 mm to 610 mm, which shows importance of particle packing in production of SCC.

Proposed particle packing based simplified mix design approach is efficient for producing SCC, which satisfies all testing criteria as per EFNARC guideline.

To create a cost-effective SCC mix with less cementitious material, the EFNARC standards need to be adjusted. The water/powder ratio by volume is employed in the current study up to 1.45 for 20 mm MSA and up to 1.23 for 10 mm MSA. EFNARC recommendations indicate a water/powder ratio of 0.85–1.1. Similar to this, the recommended weight ratio of sand to total aggregate is 0.48–0.55, although in the current study, it has been effectively increased to 0.55-0.65 for 20 mm MSA and 0.52-0.65 for 10 mm MSA.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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