A new gradation based approach for determination of packing of angular aggregates

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Abstract:

The existing discrete particle packing models (PPM) for multi component aggregates have complex methodology to find quantitative packing density (PD). Therefore, in present research, a new simplified gradation-based particle packing approach is developed by adjusting volume and size of particles available in fine and coarse aggregates. The present PPM aims to be utilized in economical concrete production. The PD of aggregates found using new model is verified experimentally for two different sizes of coarse aggregates 20 mm and 10 mm. The experimental PD matches with the analytical PD with less than five percent error. Also, the present PPM is compared with the existing most efficient models. The precision of the proposed model is at par with the present most efficient particle packing model. Also, a particle size distribution for optimum packing of coarse and fine aggregate is given for economical production of concrete.

Keywords: Particle size distribution; Packing density; Particle packing model

1 Introduction:

Particle packing models are of two types discrete and continuous. The application of these models is mainly in ceramic and concrete industry. Special concrete like self compacting concrete (SCC), particularly lower grade SCC in which aggregate content is more, aggregate needs to be optimally packed. As a result, a lot of work is being done to design and implement SCC with a compressive strength of 20–35 MPa [1]. For optimum packing of coarse and fine aggregates, work is carried out for a long time and is discussed below.

In 1907 Fuller, W.B. and Thompson, S.E. [2] had shown that, if aggregate gradation follows **Eq.1**,bestdensity is attainable. Nevertheless, this curve solely addresses the maximum aggregate size; it leaves out the impact of the lowest aggregate size.

$$\mathbf{P(D)} = \left(\frac{\mathbf{d}}{\mathbf{d_{max}}}\right)^{\mathbf{0.5}} \qquad \textbf{Eq. 1}$$

Where “d” is the particle diameter under consideration, “dmax” is the maximum particle size in the mix, and “P(D)” is the cumulative fraction that may pass the sieve with opening D.

According to Andreasen, A. M., & Andersen, J. (1930) [3], distribution modulus q affects aggregate PD. In the more complete equation, he substitutes q for 0.5. Distribution modulus (q) values range from 0.33 to 0.50, signifying the fineness or coarseness of aggregate grading.

$$\mathbf{P(D)} = \left(\frac{\mathbf{d}}{\mathbf{d_{max}}}\right)^{\mathbf{q}} \qquad \textbf{Eq. 2}$$

Dinger D.R. and Funk J.E. [4] changed the Andreasen equation in 1997 by adding a minimum aggregate size requirement.

$$\boldsymbol{P(D)} = \left(\frac{d^q - dmin^q}{dmax^q - dmin^q}\right) \qquad \textbf{Eq. 3}$$

Nevertheless, no formula provided by Fuller, Anderson, Funk & Dinger provides the quantitative 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 concrete mixes. 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.

1.1 Research Significance

As angular aggregates used in production of concrete, have different size, shape and volume, it is complex task to find optimum packing of blended aggregates theoretically. The current study aims to eliminate the ambiguity of existing models by developing a novel, logical, and simplified method to calculate the PD of blended multi-component aggregates.The suggested model's analytical process eliminates the need for intricate mathematical formulas, and a few Microsoft Excel iterations are all that are needed to determine the ideal mixtures of fine and coarse aggregate for the highest possible PD

2 Materials and Method

The present study uses 20 mm and 10 mm down coarse aggregate (CA), 4.75 mm down fine aggregate (FA). 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. Fine and coarse aggregate sieve analyses are carried out in accordance with IS: 383-2016 [24] and IS: 2386-2002 (Part-1) [25]. 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) [26], 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	CA (20 mm)	2.86	1.11
2	FA	2.57	1.89

Bulk density and voids of aggregate is calculated in accordance with ASTM C29 [27]. 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 3Bulk 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

3 Development of PPMand Theory:

Instead of having monolithic particles, CA and FA used to make concrete have a variety of particle sizes in various ratios. Different packing phenomena, such as Mono, binary, and ternary packing, may occur in particles with varying sizes and proportions. By examining this intricate particle packing phenomenon, the packing density in the suggested packing model is predicted for varying degrees of mixing of coarse and fine aggregates.

3.1 Fundamentals of Model

At least a seven-fold difference in individual component sizes is needed for high density multi-component packing [9–10].

This extends the idea of packing spherical particles for angular aggregates. When closely packed, mono size spherical particles exhibit 37.5% voids due to their packing density of 0.625 [9–10]. The experimental packing densities of the 10 mm MSA and 20 mm MSA angular CA used in this study are 0.601 and 0.573, respectively, as indicated in **Table 3**. This indicates that there are 40% and 42.7% of voids in these aggregates, respectively.There are more voids in angular aggregates than in spherical aggregates because of the form effect. The proposed approach calculates the initial volume of voids in individual (unblended) coarse and fine aggregates through experimentation. This information is then utilized to compute the packing density of mixed CA and FA. Similar to current packing theory, the shape effect is not taken into account independently when calculating packing density; instead, the experimentally determined initial voids found in the coarse aggregate are used to compute possible additional filling of smaller size particles.

Two parameters form the basis of the current PPM.

1. The presence of finer particles that can fill in the spaces left by coarser particles.
2. Volume percentage needed for incorporating the particles

Table 4 Particle volume and size needed for spherical aggregate packing in single, binary, and ternary configurations [9-10]

Packing of blended aggregate	Aggregate Volume and Size required for packing				Theoretical PD
	Description of Volume and Size ratio of Aggregate	Aggregate P_1	Aggregate P_2	Aggregate P_3	
Ternary Packing	Volume(%)	66%	24.7%	9.3%	0.947
	Size Ratio (P1:P2:P3) (1:7:77)	1	<1/7 of P_1	< 1/77 of P_1	
Binary Packing	Volume (%)	72.7%	27.3%	---	0.859
	Size Ratio (P1:P2) (1:7)	1	< 1/7 of P_1	---	
Single Component	Volume (%)	100%	---	---	0.625
	Size Ratio (P1) (1)	1	---	---	

To explain the packing theory, two different sizes of coarse aggregates having different particle size present in their gradation are taken for study. In **Two parameters** form the basis of the current PPM.

1. The presence of finer particles that can fill in the spaces left by coarser particles.
2. Volume percentage needed for incorporating the particles

Table 4 Particles P1, P2, and P3 are needed for packing in decreasing sequence of size. **Two parameters** form the basis of the current PPM.

1. The presence of finer particles that can fill in the spaces left by coarser particles.
2. Volume percentage needed for incorporating the particles

Table 4 shows the sizeof spherical aggregate and volume needed for ternary, binary and Mono Size packing [9-10]. For ternary packed particles, size ratio required for particles is 1:7:77 and volume required for three particle sizes is 66%, 24.7% and 9.3% respectively, which results in the packing density of 94.7%. Similarly, for binary packed particles for particle size ratio of 1:7 and particle volume of 72.7% and 27.3% results in the packing density of 85.9%. For mono size particles, the optimum packing density achieved is 62.5%.

Table 5 Size requiredfor binary and ternary packing of aggregates as per gradation test

Packing of blended aggregate	Description Size ratio of Particle	Particle P_1	Particle P_2	Particle P_3
Ternary Packing	Size Ratio (P1:P2:P3) (1:7:77)	1	<1/7 of P_1	< 1/77 of P_1
	Aggregate size available in 20 mm MSA Gradation for ternary packing	20 mm	<2.86 mm	< 0.260 mm
	Aggregate size available in 10 mm MSA Gradation for ternary packing	10 mm	< 1.43 mm	< 0.200 mm
Binary Packing	Size Ratio (P1:P2) (1:7)	1	< 1/7 of P_1	---
	Aggregate sizes available for binary packing in 20 mm and 10 mm MSA Gradation	4.75 mm	<0.680 mm	---
		2.36 mm	<0.340 mm	---
		1.18 mm	<0.170 mm	---

Table 5 shows the various particle sizes available in aggregate sample taken for study for ternary and binary packing of aggregates.Depending on the sizes that are available, the leftover particles will be binary packed after ternary packing. The particles will stay unpacked, or single components, since they are neither ternary nor binary packed.

The ratio of various aggregate sizes and volumes should be balanced in order to produce the highest PD. The percentage of CA and FA in the overall aggregate can be changed to achieve this.

Table 6, **Table 7** and **Error! Reference source not found.**provide a logical explanation of how likely it is that ternary, binary, and single component packing will occur in blended CA and FAfor a 20 mm size CA combined with FA using the packing idea previously discussed. The packing density calculation of 35% CA combined with 65% FA is displayed for illustrative purposes.

3.2 Analytical Packing Density for 20 mm MSA combined with fine aggregate (FA) with suggested methodology

Table 6 displays the combined gradation result for a blend of 35% 20 mm size CA and 65% FA. In **Table 6**, column 4, the percentage of aggregate retained between two sieves is calculated and displayed. As shown in Table 3, in 20 mm size CA, 42.7 % voids are present, so in column 5, 42.7% voids are taken for each range of particles.

In column 7 of **Table 6**, It calculates the volume of particles that can be used to fill up spaces between coarser particles. For example, there are 30.10% accessible particles in the 20 mm to 10 mm sieve. The void in a 10 mm sieve is 1.43 mm in size, while in a 20 mm sieve, it is 2.86 mm. Thus the particles of size 2.36 mm – 1.18 mm will fit readily between voids of 20 mm – 10 mm particles. Particles between 2.36 and 1.18 mm make up 11.54% of the total. 12.85% of the necessary particles are needed to fill the spaces between 30.10% of the particles; however, in this case, 1.31% fewer particles are available. Column 8 thus represents the difference between columns 7 and 5. A comparable computation is provided for alternative particle ranges. **Table 6** displays the various particle sizes for ternary packing in green and yellow.

Table 6 Particle availability and combined gradation for FA (65%) coupled with20 mm MSA (35%)

Sieve Size (mm) (1)	Volume of passing Particles (%) (2)	Considered size of aggregate (mm) (3)	Particle held in between two sieves in succession (%) (4)	Volume of voids between particles (42.7%) (5)	Range of void sizebetween aggregates(mm) (6)	Volume of particles that are available to fill in gaps % (7)	Volume of Excess/less Availability of particle for filling voids (8)
20	97.38	20-10	30.10	12.85	2.36-1.18	11.54	-1.31
10	69.90	10-4.75	8.67	3.70	1.18-0.6	6.34	2.64
4.75	61.23	4.75-2.36	6.27	2.68	0.6-0.3	20.18	17.50
2.36	54.96	2.36-1.18	11.54	4.93	0.3-0.15	13.29	8.37
1.18	43.42	1.18-0.6	6.34	2.71	0.15-0.075	3.09	0.38
0.6	37.08	0.6-0.3	20.18				
0.3	16.90	0.3-0.15	13.29				
0.15	3.61	0.15-0.075	3.09				
0.07	0.52		0.52				

3.2.1 Ternary packing of blended aggregate

The ternary packed particle computation is displayed in **Table 7**. 1.18–0.6 mm particles will fit in the first feasible ternary packing between gaps of 10–4.75 mm particles, and 0.15–0.075 mm particles will occupy the space in subsequent smaller voids. As can be seen in column 4, the volume of the 10–4.75 mm particles is 8.67%, and the voids in them have a volume of 3.70%, which are filled by the 1.18–0.6 mm particles. The 0.15–0.075 mm particles, with a volume of 1.58%, will fill the remaining smaller voids. Thus, 13.95% of the particles will be ternary packed. Column 5 displays the extra particles that were left over after vacancies were filled.In a similar vein, 45.31% of particles are ternary packed for the second Ternary packing. Consequently, 59.26% of the total ternary packed particles will be used in the 65% FA and 35% 20 mm CA blend. The packing density attained is 0.947, and the theoretical volume of spherical particles needed for ternary packing is 66%, 24.7%, and 9.3%, respectively. The volume of particles for ternary packing in this case is 62.1%, 26.5%, and 11.3%, respectively (column 6), which is close to the theoretical value of spherical particles because 42.7% of the voids between the angular aggregates are taken into account.

Table 7 Ternary Packing of particles for 20 mm MSA (35%) blended with FA (65%)

	Size Range of particle (mm) (1)	**Available Particle (%) (2)**	**42.7% Voids (3)**	**Packed particle (%) (4)**	**Unpacked Particle (2)-(4) (%) (5)**	**Volume of Particles (6)**
Ternary Packing 1 (Yellow Colour in Table 6)	10-4.75	8.67	3.70	8.67	0.00	**62.1%**
	1.18-0.6	6.34	1.58	3.70	2.64	**26.5%**
	0.15-0.075	3.09	----	1.58	1.51	**11.3%**
	Total	18.10		**13.95**	4.14	100%
Ternary Packing 2 (Green Colour in Table 6)	20-10	30.1	12.85	28.84	1.26	**63.7%**
	2.36-1.18	11.54	4.93	11.54	0.00	**25.5%**
	0.30-0.15	13.29	----	4.93	8.37	**10.9%**
	Total	54.93		**45.31**	9.93	100%
Total ternary packed particles=				**13.95+45.31= 59.26 %**		

3.2.2 Binary and Single Component packing of blended aggregate

Same as ternary packing of particles, the binary and single component (mono size) particle packings are displayed in **Error! Reference source not found.**.According to theory [9–10], 0.859 packing density is attained and 72.7% and 27.3% of the volume of particles are needed for binary packing of spherical particles. The volume of the binary packed particle, according to current theory, is between 71.4% and 28.6%, which is not too far from the theoretical value. The combined volume of single-component and binary packed particles is 28.03% and 12.71%, respectively.

When 10 mm size coarse aggregates are blended with fine aggregates in proportion of 35% CA and 65% FA in total aggregate, the results obtained as per proposed particle packing theory are as below.

Binary and single component packing of particles for 20 mm MSA (35%) blended with FA (65%)

Size of Particles	**Particle remained after ternary packing**	**Volume of Voids (42.7%)**	**void size between aggregates (mm)**	**Volume of particles that are available to fill in gaps**	**Volume of Particles used for packing (%)**	**Binary packed particles (%)**	**Volume of coarser particle (%)**	**Volume of finer particle (%)**	**UnpackedParticle (%)**
20-10	1.26%	0.54	2.36 to 1.18	0	0	0			1.26%
10-4.75	0.00%	0.00	1.18 to 0.6	2.64%	0	0			0
4.75-2.36	6.27%	2.68	0.6 to 0.3	20.18%	2.68%	8.95%	**70.1%**	**29.9%**	-2.68%
2.36-1.18	0.00%	0.00	0.30 to 0.15	8.37%	0	0			0
1.18-0.6	2.64%	1.13	0.15 to	1.51%	1.13%	3.76%	**70.1%**	**29.9%**	-1.13%
0.6-0.3	20.18%	----	----	0	0	0			20.18%
0.3-0.15	8.37%	----	----	0	0	0			8.37%
0.15-	1.51%	----	----	0	0	0			1.51%
0.075-Pan	0.52%								0.52%
Total	40.74%					**12.71%**			**28.03%**

Total Ternary packed particle.	59.26
Total Binary packed particle	12.71
Total Unpacked particle	28.03
Total	100

$$\text{Packing Density} = \frac{59.26 * 0.947 + 12.71 * 0.859 + 28.03 * 0.625}{59.26 + 12.71 + 28.03} = \mathbf{0.846}$$

3.2.3 Packing Density Calculation for 10 mm MSA mixed with FA

When 10 mm size coarse aggregates are blended with fine aggregates in proportion of 35% CA and 65% FA in total aggregate, the results obtained as per proposed particle packing theory are as below.

Total Ternary packed particle.	29.90
Total Binary packed particle	26.26
Total Unpacked particle	43.84
Total	100.00
Packing Density =	**0.784**

3.3 Computationof experimental packing density to confirm packing density computed analytically with the suggested model

As seen in **Figure 1**, a cylindrical container is used to find the experimental packing density in compliance with ASTM C29 [27]; the only change adopted with respect to ASTM C29 guidelines is way of compaction. In ASTM C29, Compaction of aggregate layers is recommended by roding, jigging or shoveling, but in this study mechanical vibration is adopted for compaction of aggregates, which results in better and full compaction [9].CA and FA is first dry mixed in desired proportion. Then these blended aggregates are put into a cylinder of known volume in three layers. On a table vibrator, the filled cylinder is subsequently compacted to determine the blended aggregate's bulk density is. Finally, packing density (PD) is calculated using bulk density as a base. The PD of blended aggregate is determined by averaging the three processes that are repeated.

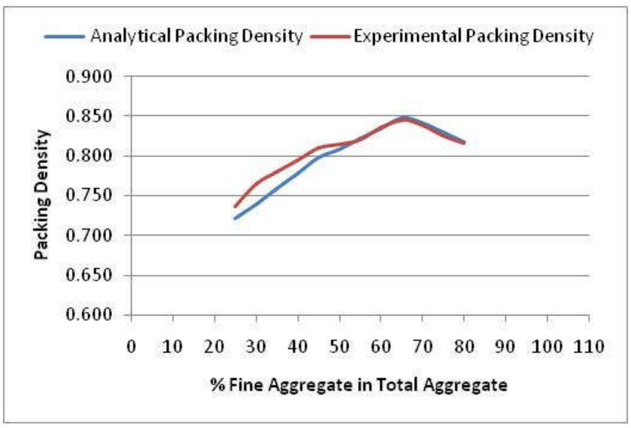
Figure 1 Test procedures to calculate experimental packing density

The most effective method of compaction for mixed particles of varying sizes is mechanical vibration, which allows fine particles to fill in the spaces left by coarser particles and maximizes compaction [9]. The amount of compacting effort and the quantity of PD attained everywhere will be the same when the compacted PD of aggregate is determined by mechanical vibration; however, if loose PD is detected, loosening, wall and wedge effect needs to be considered, Additionally, the method of finding and the amount of compacting effort affect loose PD. The value of PD will nearly always stay the same in compacted packing density attained by mechanical vibration, regardless of changes in laboratory conditions. In compacted PD, particles achieve best position after countering wall, loosening and wedge effect and this process remains continue unless they achieve maximum PD.

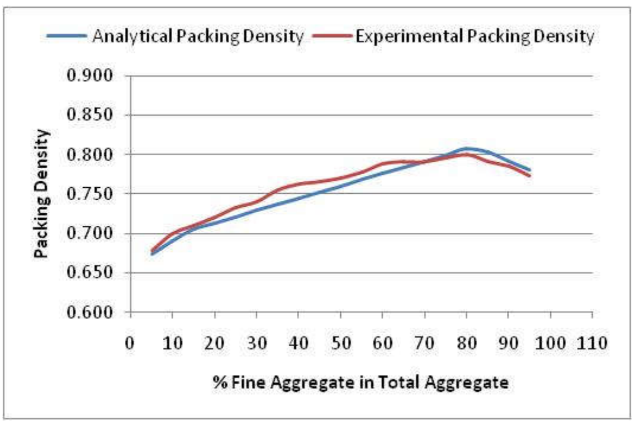
The comparison between the analytical and experimental packing densities is displayed in **Table 8**. It is evident that the suggested model works incredibly well for calculating the PD of blended aggregate with varying sizes.

Table 8Comparison 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



(a) 20 mm MSA mixed with FA



(b) 10 mm MSA mixed with FA

Figure 2 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 2**.

3.4 Discussion on PPM

Table 9 Comparison of particle packing of 20 mm and 10 mm MSA

Sr.No.	Particle Packing	35% 20 mm CA + 65% FA	35% 10 mm CA + 65% FA	Difference
1	Ternary	59.26	29.90	-29.36
2	Binary	12.71	26.26	+13.55
3	Single Component	28.03	43.84	+15.81
4	Voids	15.5%	21.6%	6%

When 20 mm aggregate is utilized, ternary packed particles are more and unpacked particles are fewer compared to 10 mm particles, as seen in **Table 9**from the packing pattern of 20 mm and 10 mm particles. Moreover, 10-4.75 mm particles out of all unpacked particles are greater when 10 mm MSA and fine aggregate are combined than when 20 mm is. Similar unpacked particles can be found in both the 20 mm and 10 mm MSAs. Consequently, the 10 mm MSA has a lower packing density because of 10-4.75 mm particles. When 20 mm MSA is utilized, 6% fewer voids are produced because to the increased packing density.

Upon careful examination of the particle packing phenomena, it is possible to determine that, in order to achieve higher packing, the size and volume of the blended CA and FA should be adjusted to maximize ternary packed particles and minimize unpacked particles.

Table 10 Suggested combined gradation for optimum packing density based on the model

Recommended PSD for concrete mix			
Sieve	**Passing (%)**	**Range of sieve**	**Passing (%)**
20	96-97	**20-10**	27-35
10	61-70	**10-4.75**	8-9
4.75	52-61	**4.75-2.36**	5-6
2.36	46-55	**2.36-1.18**	10-11
1.18	36-44	**1.18-0.6**	5-7
0.6	31-37	**0.6-0.3**	17-20
0.3	14-17	**0.3-0.15**	11-13
0.15	3-4	**0.15-0.075**	3-4

Using the proposed PPM, **Table 10** suggests the gradation range of combined CA and FA for the ideal PD. After taking a trial mix of concrete on site, the combinedgradation of aggregate indicated in **Table 10** can be implemented; appropriate adjustments should be made for a satisfactory cohesive concrete mix. From the above particle packing analysis, general guideline and steps to achieve higher packing density of blended aggregate is mentioned below.

1. Perform gradation of CA and FA.
2. Combine the particles in different proportions based on wisdom depending on type of concrete to be produced. E.g. for conventional concrete keep more coarse aggregate than fine aggregate and for special concrete like Self compacting concrete keep more fine aggregate than the coarse aggregate.
3. Find out the retained aggregate between two consecutive sieves.
4. For each range of sieve size, find the size and volume of particles available which best fit into the voids of coarser particles. For the ternary packing size ratio is 1:7:77, for binary packing size ratio is

1:7. the ternary packing volume of particles required in descending order of their size is 66%, 24.7% and 9.3% respectively, and for binary packing volume of particle required is 72.7% and 27.3% respectively.

5. Try to match the volume of voids between the particles and volume of available particles which fit into these voids.
6. Try to maximize ternary and binary packed particles and minimize unpacked particles.
7. Try to minimize 10-4.75 mm and 4.75-2.36 mm particle size as these particles do not fit in any size.
8. Calculate packing density using the model, which can be programmed in Excel.

3.5 Comparison of results of proposed PPM with existing models

PSD curves for the continuous particle packing technique are shown in **Figure 3** and are attributed to Fuller [2], Andreasen and Andersen [3], and Funk and Dinger [4]. Additionally, using the sieving data provided by Radhika et al. [15], PSD curves for the discrete particle packing technique proposed by Toufar [11] and De Larrard [12–14] are visually shown. These PSD curves are compared with the PSD curve for ideal packing, which is shown in **Figure 3** and was created using the suggested model. It is evident that the suggested model's gradient has more tiny particles than the other models. For particle sizes between 0.6 and 20 mm, PSD obtained with the current PPMalmost matches that of the compression packing model; for particle sizes less than 0.6 mm, it fits the modified A&A model with a distribution modulus of 0.29. In contrast to the compression packing paradigm, the suggested method is straightforward and simple to implement on location.

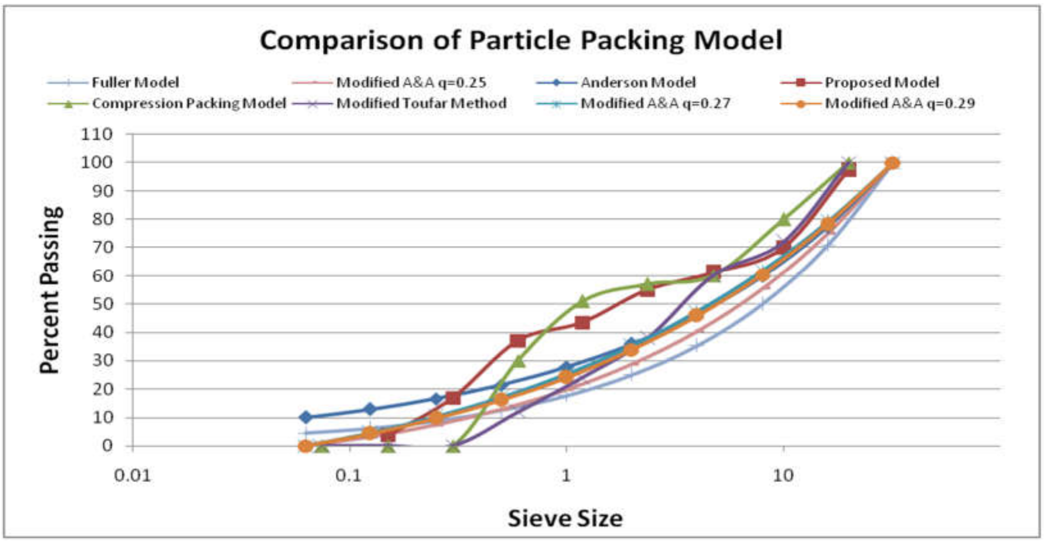


Figure 3 Comparison of PPM **based on PSD Curve**

Fine aggregates are retained greater than coarse aggregates in SCC because it has a cohesive and stable mix [3, 6, 31]. Excess fine particles, defined as those that are present in excess of what is required to fill voids, create a ball-bearing effect that can help move coarse particles and lessen their interlocking action [6].Compared to other models, more fine particles are available in PSD given by CPM for optimum packing; hence for developing SCC, CPM model is mostly used by the researchers [15-18]. Proposed PPM also suggests use of more fine particles in PSD for optimum packing density same as CPM, so it is useful for developing SCC mixes.

3.6 Assumptions of the Proposed Model

The theory of packing of spherical particles is expanded for angular particles in the current model.

The suggested approach is an analytical model that requires iterations in order to determine the ideal blended coarse and fine aggregate packing density. However, these analytical iterations are simply accomplished because the model is easily implemented in Excel. In order to cut down on iterations, guidelines for blended aggregate gradation are also provided.

Completely compacted aggregate is suitable for use with the suggested model. The suggested model makes the assumption that aggregates achieve optimal packing when compacted by mechanical vibration.

Concrete with a higher volume of aggregate may normally benefit more from the particle packing method. Particle packing will have less 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/mm^2, 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.

4 Conclusion

The packing density can be computed with great efficiency using the suggested model. It also provides a fundamental explanation for the phenomenon of particle packing. The suggested paradigm is straightforward and simple to use; it contains no intricate mathematical equations.

The calculated PD closely matches the experimental PD with less than 5% error when the PPMis tested for two distinct sizes of coarse aggregate. As a result, the suggested paradigm is broadly applicable to aggregates of any size.

With this model, it is feasible to get the ideal packing density by varying the size and volume of the particles. Particles that are unpacked should be minimized and ternary and binary packed particles should be maximized in order to get the ideal packing density.

10 mm CA blended with FA, shows lesser packing density. From particle packing model, it is clear that 10-4.75 mm size particles are in more amount in 10 mm CA, which remains unpacked and results in lesser packing density.

References

1. Rodriguez S. G., Rodriguez V.I., Aguado A, Simple and rational methodology for the formulation of self-compacting concrete mixes, Journal of Materials in Civil Engineering, 28(2) (2015) 04015116-1-10.
2. W.B. Fuller, S.E. Thompson, The laws of proportioning concrete, Trans. ASCE. 33 (1907) 67–172.
3. A.H.M. Andreasen, J. Andersen, Relation between grain size and interstitial space in products of unconsolidated granules, Kolloid. 50 (1930) 217–228.
4. J.E. Funk, D.R. Dinger, Particle-packing phenomena and their application in materials processing, Mrs Bulletin, 22(12)(1997) 19-23.
5. F.V.Mueller, O.H.Wallevik, K.H.Khayat, Linking solid particle packing of Eco-SCC to material performance, Cement and Concrete Composites, 54 (2014)117-125.
6. K.H. Khayat, I. Mehdipour, Design and performance of crack-free environmentally friendly concrete “Crack-Free Eco-Crete”, No. NUTC 322 (2014).
7. X. Wang, K. Wang, P. Taylor, G. Morcous, Assessing particle packing based self consolidating concrete mix design Method, Constr. Build. Mater. 70 (2014) 439–452.
8. H.J.H. Brouwers, H.J. Radix, Self-compacting concrete: theoretical and experimental study, Cem. Concr. Res. 35 (11) (2005) 2116–2136.
9. RK McGeary, Mechanical packing of spherical particles, Journal of the American Ceramic Society. 44(10) (1961) 513-522.
10. JA Elliott, A Kelly, AH Windle, Recursive packing of dense particle mixtures, Journal of Materials Science Letters. 21(16) 2002 1249-1251.
11. W. Toufar, M. Born, E. Klose, Contribution of optimisation of components of different density in polydispersed particles systems, Freiberger Booklet A 558 (1976) 29–44.

12. De Larrard F, Concrete optimizationwith regard to packing density and rheology, 3rd RILEM International Symposium on Rheology of Cement Suspensions such as Fresh concrete. 2009.
13. F. De Larrard, Concrete Mixture Proportioning: A Scientific Approach, E&FN Spon, London and New York, 1999.
14. F De Larrard, Concrete mixture proportioning: a scientific approach, CRC Press. 2014.
15. KL Radhika, PR Kumar, Chand MS, Prasad B, Optimization of Mix Proportioning for Self Compacting Concrete using Particle Packing Theories, in 8th RILEM International Symposium on Self-Compacting Concrete,Washington DC, USA. (2016) 53-64.
16. W.Zuo, J.Li., Q.Tian, W.Xu,W.She,P.Feng,C.Miao, Optimum design of low-binder Self-Compacting Concrete based on particle packing theories, Constr. Build. Mater., 163 (2018) 938-948.
17. W.J. Long, Y. Gu, J. Liao, F. Xing, Sustainable design and ecological evaluation of low binder self-compacting concrete, J. Clean. Prod. 167 (2017) 317–325.
18. B.I.O.Koura, M.Hosseinpoor, A.Yahia, E.H.Kadri, A.Kaci, A new proportioning approach of low and normal binder self-consolidating concrete based on the characteristics of fine mortar and granular skeleton, Construction and Building Materials, 239 (2020) 117892.
19. A.K.H. Kwan, V. Wong, W.W.S.Fung, A 3-parameter packing density model for angular rock aggregate particles, Powder Technol. 274 (2015) 154–162.
20. P.N.Nimodiya, H.S.Patel, Effect of Packing Density on Properties of Self Compacting Concrete, Int. Journal of Civil Engg. and Tech.(IJCIET). 9(11) (2018) 2126-2131.
21. ACI 301, Specifications for structural concrete, American Concrete Institute. (2010).
22. BIS 9103, Concrete Admixtures: Specification, Bureau of Indian Standard, Delhi. (1999).
23. BIS 1489, Portland pozzolona cement-specifications, Part 1–Fly ash based, Bureau of Indian Standards. (1991).
24. BIS 383, Specification for coarse and fine aggregates from natural sources for concrete. (2016).
25. BIS 2386 (Part I), Methods of test for aggregate for concrete Part I Particle Size and Shape, Bureau of Indian Standards. (2002).
26. BIS 2386 (Part III), Methods of test for aggregate for concrete Part III Specific Gravity, Density, Voids, Absorption and Buckling, Bureau of Indian Standards. (2002).
27. ASTM C29. Standard test method for bulk density ('unit weight') and voids in aggregate. American Society for Testing and Materials. 2003.
28. P.N.Nimodiya, H.S.Patel, Experimental Investigation of Effect of Sand Fines on Properties of Self Compacting Concrete, Int. Journal ofEmer. Tech. and Inno.Res.(JETIR), **5** (9), (2018), 980-985.