International Journal of Informatics, Information System and Computer Engineering

Concrete Mix Design Using Particle Packing Method: Literature Review, Analysis, and Computation

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ABSTRACTS

Particle packing technology is used to reduce the amount of cement in concrete by optimizing the concrete mix, resulting in more sustainable concrete. In this study, four different methods were used to determine the distribution of the mixture presented; packing density method, packing density method, IS code method, and packing density method. The purpose of this study is to explain literature review, analysis, and data computation of the concrete mix design using particle packing method. In the packing density method, the paste content that exceeds the voids will increase along with the increase in the quality of the concrete. In cases of packing density, the cement-water ratio decreases with the quality of the concrete. In the packing of too many trials, trials and tribulations should be carried out to achieve the ratio of water-cement and paste content for a certain grade of concrete. This correlation curve helps reduce the experiments involved in determining the ratio of semen and paste content for a given concrete quality. The water and cement contents for the packing density and the IS code method are almost the same for each particular concrete class. The workability of concrete achieved was more in the packing density method than the IS code method for the same concrete quality, because the water-cement ratio was slightly higher in the packing density method than the IS code method. Therefore, more water and cement are required in terms of packing density. The correlation curve can be used to determine the ratio of water-cement and paste the content that exceeds the voids for a certain concrete quality.

ARTICLE INFO

Article History:
Received 01 May 2021
Revised 14 May 2021
Accepted 20 May 2021
Available Online 3 Jume 2021

Keywords:
Concrete Mix Design,
Mixtures Presented,
Packing Density Method,
Is Code Method

1. INTRODUCTION

There are various methods of proportioning for various types of concrete. The packing density method of mix design is the only mix design method used for proportioning normal concrete, high strength concrete, no-fines concrete, and self-compacting concrete (Raj et al., 2014).

The subject of optimizing the concrete composition by selecting the right amounts of various particles has already used interest for more than a century. To optimize the particle packing density of concrete, the particles should be selected to fill up the voids between large particles with smaller particles and so on, to obtain a dense and stiff particle structure. Most of the early researchers, working on the packing of aggregates, proposed methods to design an ideal particle size distribution. Geometrically based particle packing models can help to predict the water demand of concrete, and thus the material properties.

The cement paste has to fill up the voids between aggregate particles and the "excess" paste will then disperse the aggregate particles to produce a thin coating of paste surrounding each aggregate for lubricating the concrete mix. In general, the higher the packing density of the aggregate, the smaller will be the volume of voids to be filled and the larger will be the amount of paste in excess of void for lubrication (Yang et al., 2020).

The purpose of this study is to explain literature review, analysis, and data computation of the concrete mix design using particle packing method. In IS code method of mix design, we have curves to decide the water-cement ratio whereas in the packing density method we don't have such type of co-relation curves available. Here an attempt has been made to develop co-relation curves between compressive strength of concrete versus water-cement ratio and paste content versus Compressive strength. These co-relation curves help to reduce the trials and decide the water-cement ratio and paste content for the given grade of concrete.

Packing density is a new kind of mix design method used to design different types of concrete (Glavind, M., & Pedersen, E. 1999). To optimize the particle packing density of concrete, the particles should be selected to fill up the voids between large particles with smaller particles and so on, to obtain a dense and stiff particle structure. The higher degree of particle packing leads to minimum voids, maximum density, and requirement of cement and water will be less. In this work, the co-relation curves are developed for the packing density method between compression strength and water-cement ratio, paste content to reduce the time involved in the trial to decide water-cement ratio, and paste content for a particular grade of concrete (Rao, V. K., & Krishnamoothy, S. 1993).

An important property of multi-particle systems is the packing density. This is defined as the volume fraction of the system occupied by solids. For a given population of grains, it is well known that the packing density (Powers, 1968).

The packing density of the aggregate mixture is defined as the solid volume in a unit total volume (Hettiarachchi, C., & Mampearachchi, W. K. 2020). The aim of obtaining packing density is to combine aggregate particles to minimize the porosity, which allows the use of the least possible amount of binder (see Fig. 1).

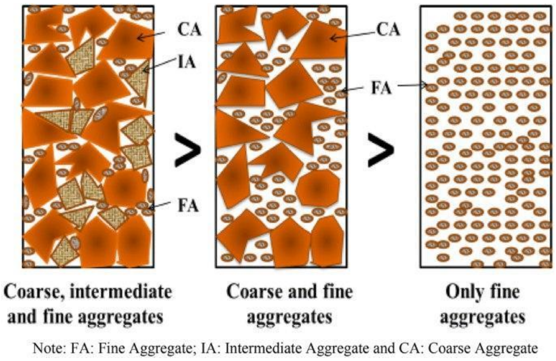

Fig. 1. Prediction of particle packing density (Source: http://link.springer.com/ accessed on 04/04/2021)

2. LITERATURE REVIEW

Wong and Kwan used the ordinary Portland cement complying with BS 12:1996. Fennis and Walraven used ordinary Portland cement and blast furnace slag cement. Wong and Kwan used aggregate particles smaller than 1.2mm for mortar and aggregate particles larger than 1.2mm for concrete mix. Kwan and Wong used pulverized fly ash as cementations material complying with BS 3892: Part 1: 1982. Kwan and Wong used the condensed silica fume complying with ASTM C 1240-03 as the cementation's material in their experiments. Kwan and Wong in their studies used two types of superplasticizers a polycarboxylate-based and cross-linked polymer and naphthalene-based formaldehyde condensate

1. Kwan and Wong measured the packing densities of cementations materials containing ordinary Portland cement, pulverized fly ash, and condensed silica fume. The results for non-blended materials revealed that the addition of a superplasticizer would always increase the packing densities of ordinary Portland cement and pulverized fly ash, the addition of a polycarboxylate-based superplasticizer could decrease the packing density of condensed silica fume.

2. Kwan and Wong proposed a three-tier system design. The mix design would be divided into three stages. At the first stage, the packing density of the cementitious materials would determine the water demand, and at the second stage the aggregate particles smaller than 1.2mm would determine the paste demand and at the third stage, the aggregate particles larger than 1.2mm would determine the mortar demand.

3. Kwan and Wong used the mini-slump cone test to check the fresh state properties in their experimental studies. Fennis and Walraven carried out centrifugal consolidation to check the workability. Kwan and Wong obtained a curve between voids ratio and water-cement ratio for cementitious materials, where the ordinary Portland cement is blended with the pulverized fuel ash and condensed silica fume in different proportions.

From the above study, it is observed that the packing density mix design method is used to minimize voids to increase particle packing and to reduce the binder content.

3. METHOD

Ordinary Portland cement conforming to IS 12269-1987 locally available river sand belonging to zone II of IS 383-1970was used. The locally available crushed aggregate of size 12.5 mm and 20 mm downsize conforming to IS 383-1970 were used in the preparation of concrete. Potable water was used in the present investigation for both casting and curing of the concrete. Superplasticizer complies with IS 9103:1999 Sulphonated Napthelene based polymers are used. Bulk density and specific gravity test were carried out as per IS 2386(Part III)-1963 and the test results are presented in Table 1.

4. RESULTS AND DISCUSSION

4.1. Design of Concrete Mix Using Packing Density Method

1. Determination of aggregate fractions

The packing density of the aggregate mixture is defined as the solid volume in a unit total volume. The aim of obtaining packing density is to combine aggregate particles to minimize the porosity, which allows the use of the least possible amount of binder. Two size fractions of coarse aggregates were selected for the study i.e., 20 and 12.5 mm down a size. The values of bulk density of the coarse aggregates (20 and 12.5 mm in size) were first determined separately.

The coarse aggregate 20 and 12.5 mm were mixed in different proportions by mass, such as 90:10, 80:20, 70:30, and 60:40, etc., and the bulk density of each mixture is determined. The addition of a smaller size aggregate (12.5 mm downsize) increases the bulk density. However, a stage is reached when the bulk density of the coarse aggregate mixture, which instead of increasing, decreases again. The results of the Bulk density of coarse aggregate fractions (20 mm and 12.5 mm) are plotted in Fig. 1.

2. Determination of Packing Density

The packing density of individual aggregate in a volume fraction of total aggregate or overall aggregate is determined from its maximum bulk density of the mixture and specific gravity. Therefore, the total packing density of the mixture is the sum of the packing density of 20 mm, 12.5 mm, and fine aggregate i.e., equal to the ratio of bulk density of mixture to the specific gravity of individual aggregate (20 mm: 12.5 mm: fine aggregate). The value of specific gravity should be taken as average if the values are differing in the third decimal and if the values are differing in the second decimal, the individual values should be taken for calculating packing density and voids content.

3. Determination of Voids Contents and Voids ratio

The voids content in percentage volume of aggregate or mixture of three aggregate is determined from its bulk density.

From Figures 2, 3, and 4, it is observed that the bulk density, packing density are maximum and voids ratio is minimum for 70 % of coarse aggregate (20 mm) and 30 % of coarse aggregate (12.5 mm) respectively.

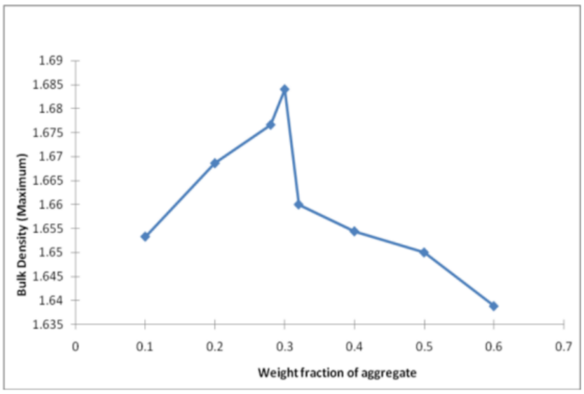

Fig. 2. maximum bulk density for 20 and 12.5 mm aggregates

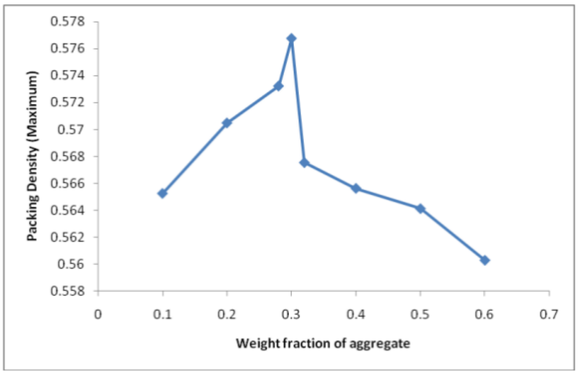

Fig. 3. maximum packing density for 20 and 12.5 mm aggregate

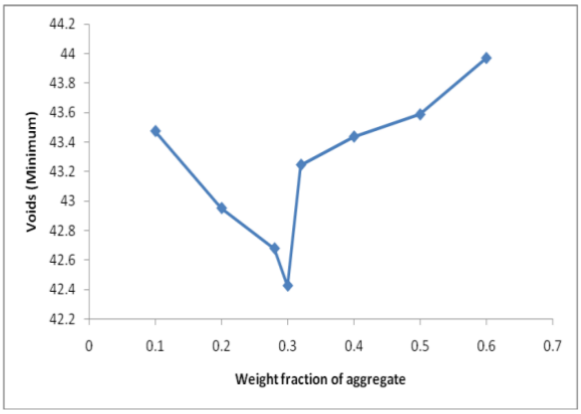

Fig. 4. minimum voids ratio for 20 and 12.5 mm aggregates

An increase in fine aggregate particles leads to a decrease in void content thus increases the bulk density. The replacement of fine aggregates in the total coarse aggregates (20 and 12.5 mm downsize in the proportion of 70:30) in the ratio of 90:10, 80:20, 70:30, 60:40, and 55:45. By increasing the finer content the bulk density increases up to a maximum extent after which it again reduces. Thus, the proportion obtained for maximum bulk density is fixed as total coarse aggregates: fine aggregates i.e., 60:40. Total coarse aggregate proportion i.e., 20 mm:12.5 mm is fixed as 70:30 as mentioned earlier. Therefore, proportions of these aggregates i.e., coarse aggregates 20 mm: coarse aggregates 12.5 mm: fine aggregates are 42:18:40. The bulk density, packing density, and voids ratio are plotted against the mass fraction of coarse aggregate are presented in Figures 5, 6, and 7, respectively. From Figures 5, 6, and 7, the maximum bulk density is 2.007 gm/cc, the maximum packing density is 0.722 gm/cc, and the minimum voids content is 0.2866.

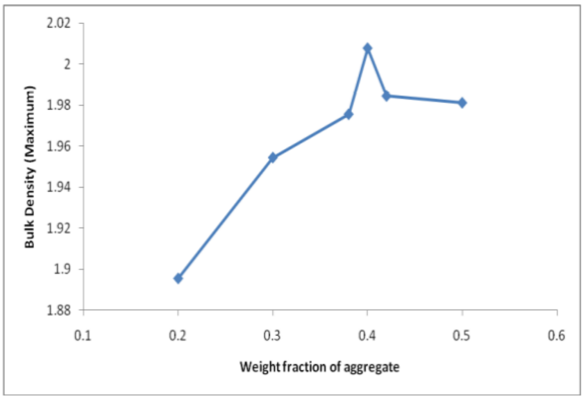

Fig. 5. Maximum bulk density for 20 mm and 12.5 mm and fine aggregates

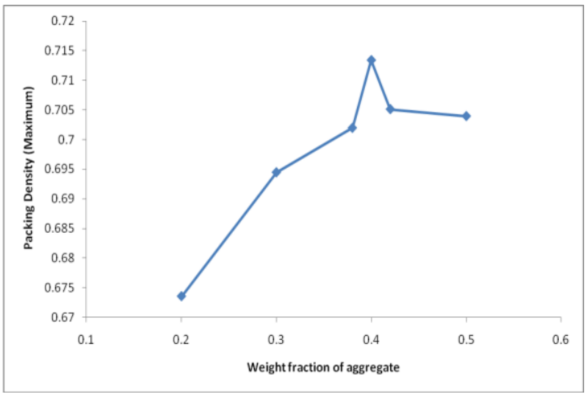

Fig. 6. Maximum packing density for 20 mm and 12.5 mm and fine aggregate

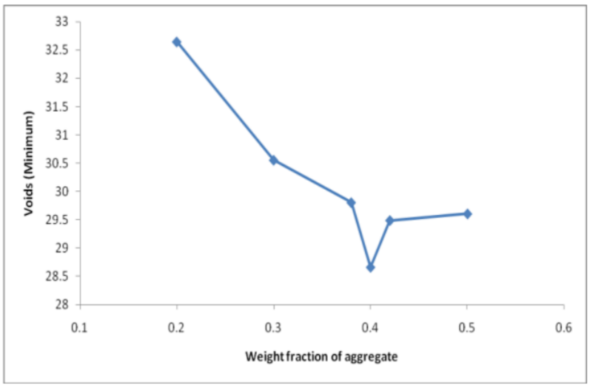

Fig. 7. Minimum voids for 20 mm, 12.5 mm and fine aggregate

Using the above concept, design of concrete mix is carried out for M20, M25, M30, M35 and M40 concrete mixes. A detailed sample calculation for M20 grade of concrete is presented below. The ingredients of concrete for M20 grade were obtained for 5%, 10% and 15% in excess of paste content and water-cement ratio 0.56 and 0.58 the values are presented in Table 2.

4.2. Mix Design for M20 Grade Concrete (Packing Density Method)

The calculations are presented in the following paragraph for bulk density, voids ratio and packing density.

1. Bulk density of combined coarse aggregate 20 and 12.5 mm in the proportion 70:30.

$$\text{Bulk density} = \frac{W_2 - W_1}{\text{Volume of mould}}$$

Where,

W_1= empty weight of mould

W_2= weight of mould + aggregate filled

Bulk density (Maximum)

$$= \frac{35066\text{-}9800}{15000}$$

$= 1.6840$ gm / cm^3

2. Bulk density of three aggregates i.e., CA 20mm : CA 12.5mm : FA is 42 : 18 : 40. (coarse aggregate 20 mm : 12.5 mm i.e., 70 : 30 as fixed earlier).

Bulk density (Maximum)

$$= \frac{39916\text{-}9800}{15000}$$

$= 2.0077$ gm / cm^3

3. Voids content:

Voids content in percent volume

$$= \frac{2.8143\text{-}2.0077}{2.8143} \times 100$$

$= 28.660\%$

4. Packing density (P.D.):

Packing density (maximum)

$$= \frac{\text{Bulk density x weight fraction}}{\text{Specific gravity}}$$

Packing density of 20mm aggregates

$$= \frac{2.00778 \times 0.420}{2.9122}$$

$= 0.2896$ gm/cm^3

Packing density of 12.5 mm aggregates

$$= \frac{2.0078 \times 0.180}{2.9376}$$

$= 0.1230$ gm/cm^3

Packing density of fine aggregates

$$= \frac{2.00778 \times 0.400}{2.5931}$$

$= 0.3097$ gm/cm^3

Total Packing Density = Packing Density of CA (20 mm) + Packing Density of CA (12.5 mm) + Packing Density of Fine Aggregate.

PD = 0.7223 gm / cm^3

This packing density value is fixed for further calculations.

4.3. Determination of Paste content for M20 Grade Concrete

Minimum paste content is the sum of the void content in combined aggregate and excess paste over and above it to coat the aggregate particle. The meaning of minimum paste content can be explained as, a concrete mix containing minimum paste content should be cohesive, free from segregation and bleeding. Flow table tests were carried out to decide the minimum paste contents required to form the workable mix for different W/C ratios and different paste content in excess of void content.

Voids content = 1 – 0.7223 = 0.2777

Assuming paste content as 10% more than void content, detailed calculations to obtain all. Ingredients of concrete such as coarse aggregate 20 mm, 12.5 mm, fine aggregate, cement, and water content are given below.

Paste content 10% more than void content

Paste content = 0.2777 + 0.1x 0.2777

= 0.3054

Volume of aggregates = 1 – 0.3054

= 0.6945 cc

Total solid volume of aggregates

$$= \frac{\text{Weight fraction of 20 mm}}{\text{Specific gravity}} + \frac{\text{Weight fraction of 12.5 mm}}{\text{Specific gravity}} + \frac{\text{Weight fraction of fine aggregate}}{\text{Specific gravity}}$$

Total solid volume of aggregates

$$= \frac{0.420}{2.9122} + \frac{0.180}{2.9376} + \frac{0.400}{2.5931}$$

= 0.3598 cc

Weight of 20 mm aggregates

$$= \frac{0.6945}{0.3598} \text{ x } 0.420 \text{ x } 1000 = 810.7354 \text{ kg/cum}$$

Weight of 12.5 mm aggregates

$$= \frac{0.6945}{0.3598} \text{ x } 0.180 \text{ x } 1000 = 347.4580 \text{ kg/cum}$$

Weight of fine aggregates

$$= \frac{0.6945}{0.3598} \text{ x } 0.400 \text{ x } 1000 = 722.1290 \text{ kg/cum}$$

For M20 grade concrete keeping in mind the target mean strength suitable water-cement ratio is fixed as per trial mixes.

W/C ratio = 0.56; W = 0.56C.

$$\text{Total Paste} = C + W = \frac{C}{3.15} + \frac{0.56C}{1} = 0.8775 \text{ C}$$

$$\text{Cement content} = \frac{0.3054}{0.8775} \text{ x } 1000$$

=348.1140 kg/cum

Water content = 0.56 x 348.1140

= 194.9438 Kg/cum

Following the above procedure, all the ingredients of concrete were obtained for 5%, 10%, and 15% in excess of paste content and water-cement ratio 0.56 and 0.58, the values are presented in Table 2.

To decide the paste content and water cement ratio among three paste content and two water cement ratios, using the above ingredients Flow Table tests were carried out. Flow Table test is carried out as per IS 1199-1959 (Indian Standard). Results of Flow table tests for M20 grade concrete indicated that water cement ratio 0.58 and all the three-paste content (i.e., 5%, 10% and 15 %) and water cement ratio 0.56 with 5% paste content were rejected because of segregation and bleeding. Water cement ratio 0.56 with paste content of 10% and 15% in excess of void content resulted in good flow percent of 133 and 134 respectively without segregation and bleeding. For water cement ratio 0.56 in order to decide the paste content i.e., 10% and 15% in excess of void content, trial cube casting was carried out for 7 days cube compressive strength.

The average compressive strength (3 cubes) obtained at the end of 7 days curing was 22.88 N/mm and 23.666 N/mm for 10% and 15% paste content respectively. Keeping economy in mind paste content of 10% for water-cement ratio 0.56 was finalized for further casting. Mix design is carried for M25, M30, M35, and M40 grade concrete as mentioned in mix design steps for M20 grade concrete. The value of packing density remains the same irrespective of the grade of concrete because coarse aggregate 20 mm, 12.5 mm and fine aggregate used is the same for all grades of concrete. Depending on the grade of concrete paste content will vary, increases with an increase in grade of concrete. The Water-cement ratio for different grades of concrete (M25, M30, M35, and M40) is fixed as per trial mixes. Paste contents for different grades of concrete were determined using flow table tests as mentioned earlier for an individual grade of concrete finalized mix proportions are presented in Table 3.

4.4. Design of Concrete Mix Using IS Code Method

Mix design is also carried out using IS code 10262-2009 (Indian Standard). The objective of IS code method of mix design is to compare the ingredients of concrete (mix proportions) with the packing density method and also to compare the compressive strength at 28 days in these two cases and relevant observations were discussed. Here also the final mix proportions were obtained for M20, M25, M30, M35, and M40 grade of concrete using IS method with the different trial mixes. The trial mix design for different grades of concrete was carried for different water-cement ratios and workability is checked using Flow Table tests. Accepted trial mixes were further used to cast the trial cube specimens and were tested for compressive strength at the 7 days curing age. Observing the results of trial casting the appropriate mix is finalized. This finalized mix proportion is used for further casting. Finalized mix proportions for different grades of concrete designed by IS code method are presented in Table 4.

4.5. Comparing the Mix Proportion of Concrete by IS Code Method and Particle Packing Method

1. Mix Proportions and Compressive Strength

Finalized mix proportions for M20, M25, M30, M35, and M40 grade concrete using packing density and IS code method are presented in the following tables. Using these finalized mix proportions for different grades of concrete final casting was carried out as mentioned in the following section.

In the packing density method, finalized mix proportions were used for final casting. Six cube specimens were cast (3 cube specimens for 7 days curing and 3 cube specimens for 28 days curing). Similarly, in IS method for each grade of concrete six cube specimens were cast (3 cube specimens for 7 days curing and 3 cube specimens for 28 days curing). The casting, curing, and compressive strength testing procedure was followed according to IS 516-1959 (see Figs. 8 and 9).

The average test result of 3 cube specimens is considered for the final test result. The results of the final casting are presented (Tables 5 and 6).

2. Workability

The variation in workability of concrete mixes designed by different methods with different water-cement ratios is presented in table 7 (KORE, S. D., & Vyas, A. K. 2017).

It can be seen from table 7, all the concrete mixes achieved their target slump of 75-100 mm. While achieving the target slump the dose of the super-plasticizer is increased. In the case of the packing density method at all water-cement ratios, the dose of super-plasticizer required is more than that of the BIS code method. This increase is caused by the increased sand content in concrete mixes designed by the packing density method as seen in Table. On average sand, content increased by 14% in the packing density method as compared to that of the BIS code method. The increased sand content absorbs more water from the mix resulted in a stiff mix. Hence, a higher dose of super-plasticizers is required to achieve the desired workability.

3. Saving in cement content and cost comparison

Table 8 saving in cement content (KORE, S. D., & Vyas, A. K. 2017).

Table 9 shows the saving in cement content in concrete mixes designed by the packing method. From this table, it was observed that the concrete mixes designed by the packing density method are economical because of saving in cement content. The maximum saving of 18% was achieved at a 0.45 water-cement ratio. The concrete mixes designed by the packing density method showed an average 12% reduction in cement content as compared to that of the BIS code method. It depicts that the concrete mixes designed by the packing density method are economical (KORE, S. D., & Vyas, A. K. 2017).

The table shows the cost analysis of the concrete mixes. From this analysis, it was observed that the concrete mixes designed by the packing density method show a saving in the material cost of concrete. The average cost of material to produce concrete can be reduced by 11% by adopting the packing density method for the design of concrete mixes. Hence it indicates that the concrete mixes designed by the packing density method are cost-effective and economical.

4. CO2 production

The cement manufacturing industry is a major contributor to CO2 emissions in the world. The contribution of the cement industry in greenhouse gas emission is around 3.95 billion tons annually and that is 7% of the total greenhouse gas emissions on the earth's surface. The global annual production of concrete in the year 2014 was 4.2 billion tons and it is expected that this figure may increase by 2.9 % by 2018. In India, around 275 MT of cement was produced during the year 2014 which accounts for the generation of an equal amount of CO2. To produce 1 Ton of cement around 0.94 Ton of CO2 is released. The CO2 emission factor for road transport, i.e., trucks or lorries is considered as 512.2 g/km. Table 10 reduction in carbon di oxide emission.

Table 1. The technology used in the device of virtual voting system

Sl. No	Materials	Bulk density Kg/m3 (Compacted condition)	Bulk density Kg/m3 (Loose condition)	Specific gravity
1.	Fine aggregates	1600.133	1718.063	2.593
2.	Coarse aggregate 12.5 mm	1387.777	1542.222	2.937
3.	Coarse aggregate 20 mm	1525.555	1660.000	2.912

Table 2. Trial mix proportions for M20 grade concrete

Grade of concrete	W/C ratio	Excess paste content (%)	Water content (Kg/m^3)	Cement content (Kg/m^3)	Wt. Of Fine aggregate (Kg/m^3)	Wt. Of 12 mm Coarse aggregate (Kg/m^3)	Wt. Of 20 mm Coarse aggregate (Kg/m^3)
M20	0.58	5	188.4416	324.8994	787.6736	354.4531	827.0573
			0.58	1	2.4243	1.0817	2.5455
	0.58	10	197.4151	340.3708	772.2352	347.5058	810.8469
			0.58	1	2.2688	1.0209	2.3822
	0.58	15	206.3885	355.8422	756.7967	340.5585	794.6366
			0.58	1	2.1268	0.9570	2.2331
	0.56	5	186.0907	332.3048	787.6736	354.4531	827.0573
			0.56	1	2.3703	1.0667	2.4889
	0.56	10	194.9522	348.1289	772.2352	347.5058	810.8469
			0.56	1	2.2182	0.9982	2.3292
	0.56	15	203.8136	363.9529	756.7967	340.5585	794.6366
			0.56	1	2.0794	0.9357	2.1834

Table 3. Finalized mix proportions designed by packing density method

Grade of concrete	W/C ratio	Excess paste content (%)	Water content (Kg/m³)	Cement content (Kg/m³)	Wt. Of Fine aggregate (Kg/m³)	Wt. Of 12 mm Coarse aggregate (Kg/m³)	Wt. Of 20 mm Coarse aggregate (Kg/m³)
M20	0.56	10	194.9522	348.1289	772.2352	347.5058	810.8469
			0.56	1	2.2182	0.9982	2.3292
M25	0.54	15	201.1187	372.4420	756.7967	340.5585	794.6366
			0.54	1	2.0320	0.9144	2.1336
M30	0.50	20	203.8259	407.6518	741.3583	333.6112	778.4262
			0.50	1	1.8186	0.8184	1.9095
M35	0.48	25	208.9378	435.2871	725.9199	326.6639	762.2159
			0.48	1	1.6677	0.7505	1.751
M40	0.44	30	209.7061	476.6047	710.4815	319.7167	746.0055
			0.44	1	1.4907	0.6708	1.5653

Table 4. Finalized mix proportions designed by IS code method

Grade of concrete	W/C ratio	Water content (Kg/m³)	Cement content (Kg/m³)	Wt. Of Fine aggregate (Kg/m³)	Wt. Of 12 mm Coarse aggregate (Kg/m³)	Wt. Of 20 mm Coarse aggregate (Kg/m³)
M20	0.55	192	349	669	609.7	609.7
		0.55	1	1.9169	1.7470	1.7470
M25	0.52	192	369.23	662.786	633.70	633.70
		0.52	1	1.7950	1.7162	1.7162
M30	0.48	197	410	646	617	617
		0.48	1	1.5756	1.5048	1.5048
M35	0.46	197	428	638	610.5	610.5
		0.46	1	1.4907	1.4264	1.4264
M40	0.42	197	469	625	598	598
		0.42	1	1.3326	1.2750	1.2750

Table 5. Compressive strength of cube cast using IS code method

Grade of concrete	W/C ratio	Paste content	Strength of cube (Mpa) (7 days)	Strength of cube (Mpa) (28 days)
M20	0.56	10 %	22.8889	33.7037
M25	0.54	15 %	26.9629	38.7407
M30	0.5	20 %	30.3333	44.4444
M35	0.48	25 %	36.6667	50.6667
M40	0.44	30 %	40.8519	54.8048

Table 6. Compressive strength of cube cast using packing density method

Grade of concrete	W/C ratio	Strength of cube (Mpa) (7 days)	Strength of cube (Mpa) (28 days)
M20	0.55	22.6667	31.5555
M25	0.52	26.2222	37.7037
M30	0.48	31.8518	45.6296
M35	0.46	34.0741	48.8889
M40	0.42	38.2222	54.5184

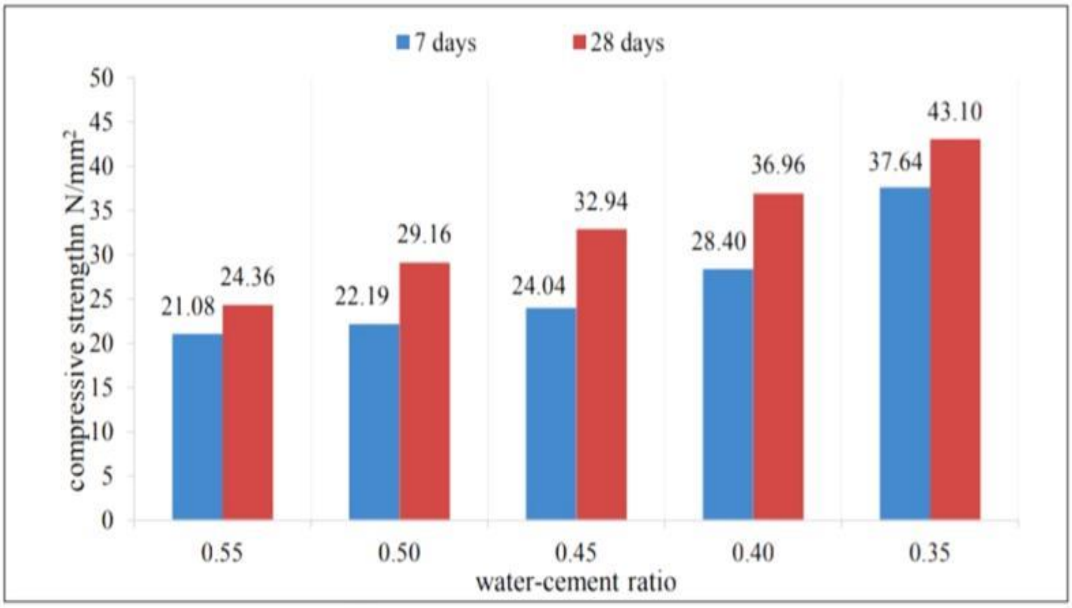

Fig. 8. Variation in compressive strength of concrete mixes designed by packing density method

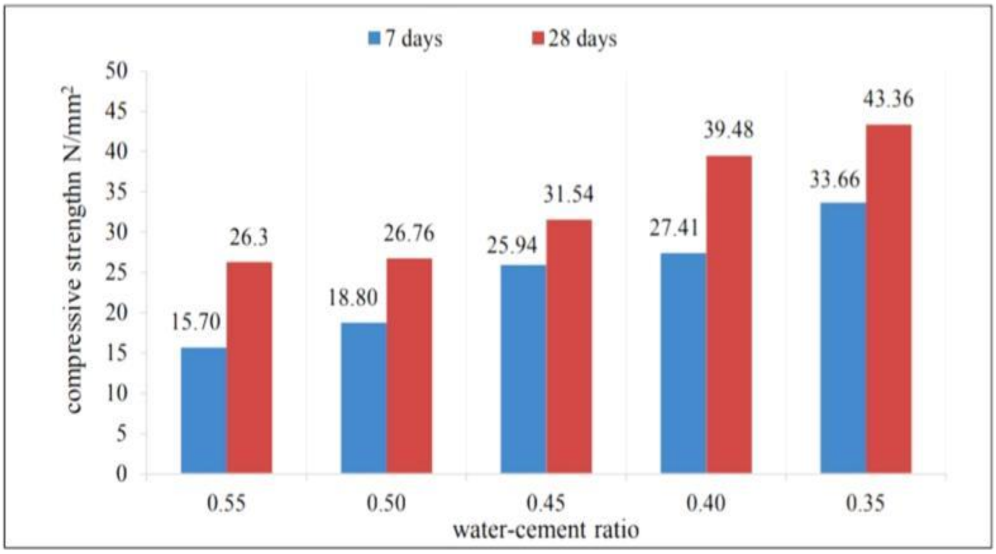

Fig. 9. Variation in compressive strength of concrete mixes designed by BIS code method

Table 7. Variation in Workability of Concrete Mixes

WC	**BIS code method**		**Packing Density Method**	
	Dose of Super-plasticizer by weight of cement (%)	**Slump (mm)**	**Dose of Super-plasticizer by weight of cement (%)**	**Slump (mm)**
0,55	0,25	80	0,50	100
0,50	0,25	90	0,65	90
0,45	0,50	100	0,90	90
0,40	0,70	90	1,0	90
0,35	0,25	80	2,3	100

Table 8. Saving in Cement Content

Cement Content in Kg/m³				
W/C ratio	**BIS code method**	**Packing density method**	**Saving in cement by PDM (kg)**	**% Saving in cement**
0,55	348	308	40	11,49
0,5	383	327	56	14,62
0,45	425	348	77	18,12
0,40	400	372	28	7,00
0,35	435	400	35	8,05

Table 9. Cost of Material for Production of 1m3 of Concrete

Cost of material in Rs. For 1m³ of concentrate				
w/c ratio	**BIS code method**	**Packing density method**	**Saving in cost**	**Percentage saving**
0,55	2817	2640	177	6
0,50	2995	2746	149	8
0,45	3217	2864	353	11
0,42	3295	2998	297	9
0,35	3311	3155	156	5

Table 10. Reduction in Carbon di Oxide Emission

Cement Content in Kg/m³			CO_2 emission (Kg/m³)		Percentage reduction in CO_2 emission by packing density method
W/C ratio	**BIS code method**	**Packing density method**	**BIS code method**	**Packing Density**	
0,55	348	308	327	289	11
0,5	383	327	360	307	15
0,45	425	348	400	327	18
0,40	400	372	376	350	7
0,35	435	400	409	376	8

From the above Table, it can be observed that the cement content required for the design of concrete mixes by using the packing density method reduced by 12%. On the other hand, from Table 8, it can be observed that the reduced usage of cement content for concrete mix resulted in an average 12% reduction in carbon dioxide emission as compared to that of the BIS code method. Adopting a packing density approach for the design of concrete mixes would reduce the annual global cement production from 4.2 billion tons by 0.51 billion tons and CO2 release from 3.95 billion tons to 3.47 billion tons. The concrete produced using the packing density approach is not only a cost-effective and sustainable product mitigating environmental pollution to a large extent.

4.6. Applications of the mixture design approach using particle packing model

To demonstrate the application of the particle packing models to the mixture design of various concretes, the software LISA 20 is considered because of its relevance, simplicity, and availability. A detailed description of the method of a mixed design using this software is given in the user manual of LISA. For this study, the modified Andreassen model was chosen.

1. Application in mortar

To demonstrate the modified Andreassen model for the concrete application, a pilot trial on cement mortar was conducted. The proportions used for the testing of compressive strength of cement mortar as per IS 4031: 1996 21 were used to design the reference mix and denoted as Mix A. Then the missing zones of particles in the particle gradation were adjusted using crushed sand, quartz powder, and micro silica and denoted as Mix B. The mixture design details are given in Table 3. The flow table spread diameter value at 25 blows was kept constant at 60 percent by adding polycarboxylic ether (PCE) based admixture.

The appearance of the ideal gradation curve against the actual overall gradation curve for Mix A and Mix B is shown in Fig 5. It can be seen in Fig 5 that the reference gradation curve (smooth curve) is the modified Andreassen curve, and the actual overall particle size distribution curve is the irregular curve. This is adjusted to fit the reference curve to the closest extent possible by altering the inputs by trial and error. The results of the compressive strength of the two mortar mixtures are shown in Fig 7. The value shown is the average strength of three 7 cm cube specimens.

It may be noted that from Table 3, the w/c of 0.4 is kept constant for both Mix A and Mix B; only the gradation of Mix B is adjusted to fit the Andreassen curve. It is observed from Fig 6 that a strength increase of about 28-30 percent could be achieved at all ages for Mix B. A comparison of Figs 5 (a) and (b) and the examination of the increase in compressive strengths, Fig 6, due to the altered proportions of the mortar by filling the missing fractions showed that the model by and reason may lead to optimal mixture proportions (See Fig. 10 and Table 11).

2. Application in concrete

The mixture designs for high strength, high performance, and self-compacting concrete are illustrated below.

- High strength concrete (HSC)

High-strength concrete could be designed at low cement content with a proper selection of ingredients. A typical mixture proportion of high-strength concrete is given in column 2 of Table 4. The modified Andreassen ideal gradation curve for q = 0.26 and the actual overall gradation are shown in Fig 7(a).

- High-performance concrete (HPC)

High-performance concrete requires the usage of supplementary cementations materials. A typical mixture proportioning using micro silica with the aid of the modified Andreassen model with exponent q = 0.27 and the combined gradation that could be managed with given materials are shown in Fig 7(b). The details of the mixture proportions are given in column 3 of Table 4.

- Self-compacting concrete (SCC)

Self-compacting concrete is highly flowable and is very sensitive to overall gradation and water content. A typical mixture proportion of SCC is given in column 4 of Table 4. The ideal gradation for q = 0.22 and the combined grading obtained with available material are shown in Fig 7(c) (see Fig. 11 and Table 12).

Table 11. Mixture design details of mortar mixtures used for validation of the model

Ingredients, kg/m³	*Mix A*	*Mix B*
Standard sand (G-1)	541	341
Standard sand (G-2)	541	341
Standard sand (G-3)	541	341
Crushed sand (correction)	-	341
Cement, (OPC)	541	541
Quartz powder (insert filler)	-	150
Micro Silica	-	60
Water	216	216
SP (PCE)	2	4
w/c	0,40	0,40
w/p	0,40	0,29
Flow spread, percent	60	60

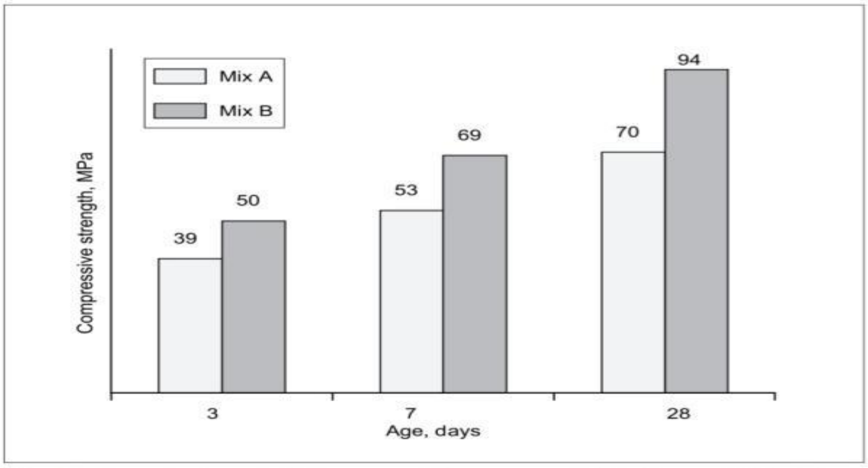

Fig. 10. Comparison of strength between Mix A and Mix B

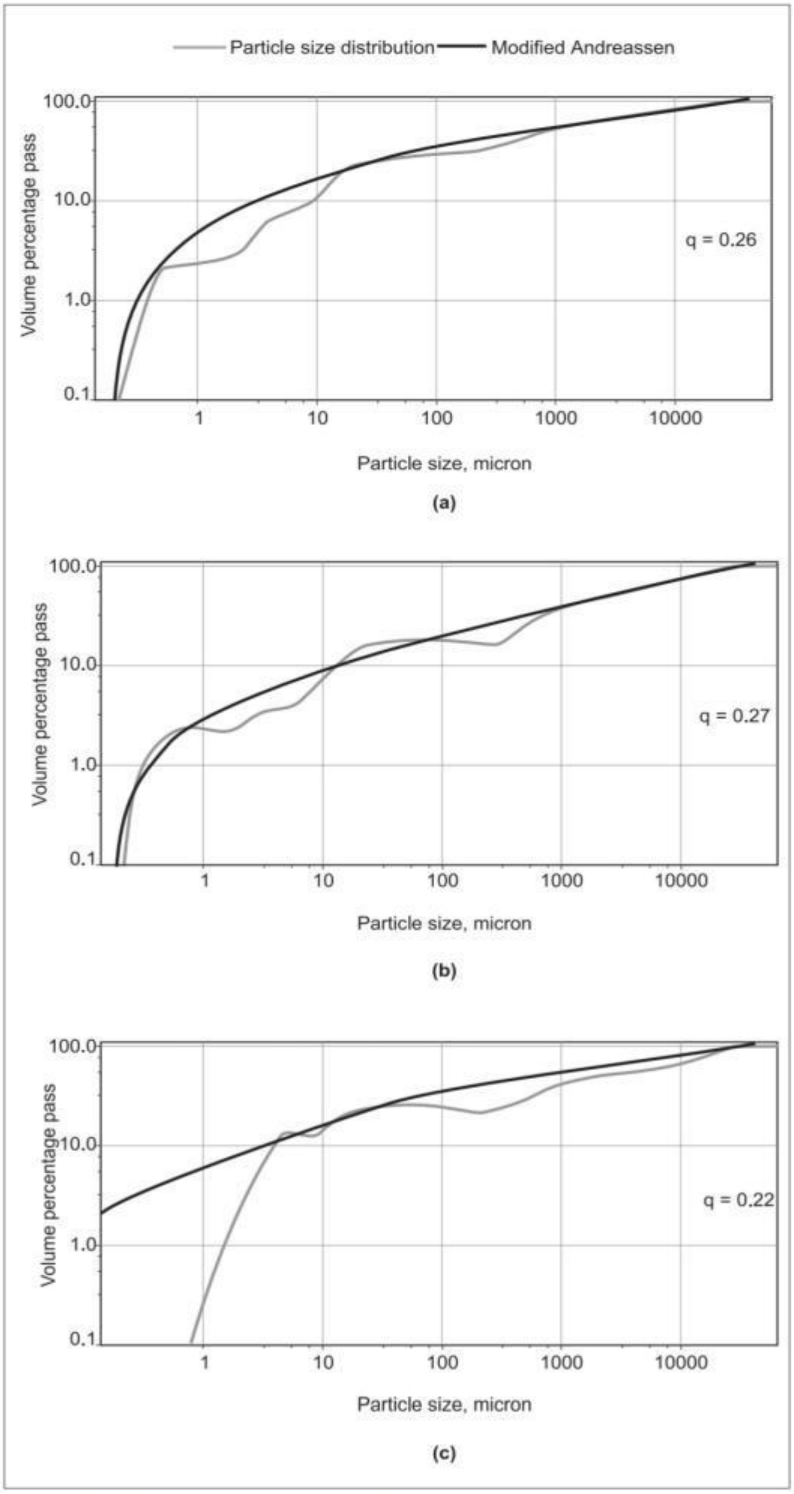

Fig. 11. Ideal grading curve and actual overall particle size distribution for (a) high strength concrete (b) high-performance concrete (c) self-compacting concrete

Table 12. Proportions of various particulate ingredients

Ingredients, kg/m³	HSC	HPC	SCC
Coarse aggregate (<20 mm)	565	520	-
Coarse aggregate (<10 mm)	545	530	748
Fine aggregate (<4,75 mm)	900	868	870
Cement (OPC 53 grade)	270	360	320
Inert filler (quartz)	55	-	-
Fly ash	-	-	220
Micro silica	30	42	-
water	12	144	180
Superplasticizer, PCE, /	5	8.25(SNF)2.12	2.12
Viscosity modifier. /	-	-	0,375
Exponent (q)	0,26	0,27	0,22
Workability – slump, mm	100	100	690 (flow)
Test result			
Compressive strength, Mpa			
3-day	42	47	14
7-day	63	63	21
28-day	83	78	41
RCPT coulombs	-	350	1296

HSC: high strength concentrate, HPC: High Performance Concentrate, SCG: Self compacting concentrate, RCPT: Rapid chloride permeability test.

5. CONCLUSION

The packing density value will remain the same irrespective of the grade of concrete. In the packing density method, paste content more than void content will increase with the increase in the grade of concrete. In the case of the packing density method, the water-cement ratio decreases with an increase in the grade of concrete. In packing density too many trial calculations, trial tests, and trial casting are to be done to arrive at water-cement ratio and paste content for a particular grade of concrete. These co-relation curves help to reduce the trials involved in determining the water-cement ratio and paste content for the given grade of concrete. The water and cement content for packing density and IS code method is nearly the same for any grade of concrete. The workability of concrete achieved is more in packing density method compared to IS code method for the same grade of concrete, as the water-cement ratio is slightly higher in packing density method than IS code method. The fine aggregate particles required are more in the case of the packing density method compared to IS code method. Therefore, water and cement required in case of packing density are more. Co-relation curves can be used to decide the water-cement ratio and paste content more than void content for the given grade of concrete.

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