Study and Development of Self Compacting Concrete using Particle Packing Approach

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Civil Engineering

by

PARESHKUMAR NARAYANSINH NIMODIYA

(Enrolment No. 139997106006)

Under supervision of

Dr. Harshvadan S. Patel

GUJARAT TECHNOLOGICAL UNIVERSITY

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ABSTRACT

The major concern with Self-compacting concrete (SCC) is the higher usage of binders even for low and medium resistance concrete (20-35 Mpa) to maintain rheological properties, which results in higher impact on environment and economy. The present research is intended to save binder content without compromising rheology of concrete mix having high volume of aggregates. The present research puts forward a simple statistical mix design method for SCC based on particle packing approach and targeted flow properties. To save binders in concrete production aggregates needs to be optimally packed. The available particle packing models are either complex or still need improvements. Therefore, an attempt is made to develop a new particle packing model for multi component angular aggregates which is unique and simple to use and saves extensive laboratory testing and trials. Using proposed particle packing model analytical packing density of blended coarse aggregate (20 mm and 10 mm) and fine aggregate is found, and the results are validated experimentally. Also, guideline for required particle size distribution for blended coarse and fine aggregate is given for optimum packing. The accuracy of the model is at par with the present efficient packing models. To validate the model, SCC mixes are casted using 20 mm and 10 mm size coarse aggregate for different cement content, w/c ratio and paste volume. It is found that slump flow has correlation with other fresh properties of SCC and it depends on excess paste volume available after filling the voids. Therefore, slump flow test alone can be performed at site for speedy determination of suitability of SCC mix for casting concrete. Based on various experimental results and statistical regression model, guideline is prepared for SCC mixes for targeted slump flow and compressive strength. Maximum slump flow for 10 mm MSA was 635 mm using 400 kg cementitious material, while 650 mm slump flow was observed using only 360 kg cementitious material when 20 mm MSA are used due to higher packing density. It was found that for SCC mixes with less paste volume, about 4% fines of total aggregate volume are necessary to make SCC mix cohesive. This Ph.D. thesis will help to design economical SCC mixes particularly for low to medium resistance concrete (20-35 Mpa) with least laboratory trials, so that advantage of SCC over conventional concrete can be extended to general construction in India.

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Pareshkumar Narayansinh Nimodiya

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List of Abbreviation

ACI	American Concrete Institute
AEA	Air Entraining Agent
CA	Coarse Aggregate
CS	Compressive Strength
CPM	Compression Packing Model
DCBD	Dry Compacted Bulk Density
DLBD	Dry Loose Bulk Density
ECO	Ecological
EFNARC	The European Federation of Specialist Construction Chemicals and Concrete Systems
FA	Fine Aggregate
GGBS	Ground Granulated Blast Slag
HRWRA	High Range Water Reducing Admixture
IS	Indian Standard
LPDM	Linear Packing Density Model
MSA	Maximum Size of Aggregate
MTM	Modified Toufar Model
PD	Packing Density
PCE	Poly Carboxylic Ether
PPC	Portland Pozzolona Cement
PSD	Particle Size Distribution
RCC	Reinforced Cement Concrete
SCC	Self Compacting Concrete
SF	Slump Flow
SP	Super plasticizer
SPGR	Specific Gravity
SSD	Saturated Surface Dry
USD	United States Dollar
VIF	Variance inflation Factor
VMA	Viscosity Modifying Agent
W/C	Water to Cementitious material ratio

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CHAPTER 1

Introduction

1.1 General

Japan was first country to introduce self-compacting concrete (SCC) prototype in 1988 and after that SCC was exploited in European countries [1]. Self-compacting concrete possesses many applications across the construction industry, due to its excellent properties such as self consolidation and flow under its own weight and fill up crowded sections and complex framework without any external compacting effort. Thus, it is used in constructing high rise reinforced concrete structures, long vertical elements in buildings etc. SCC possess excellent product properties such as exceptional flow rate, smaller amount of workforce necessities, restricted water use etc. are likely to help attain a positive viewpoint for the large-scale market in the estimated spell. However, even after long existence of thriving applications and despite its many benefits, the acceptance and application of SCC technology in broad construction have been sluggish. In India, demand for self-compacting concrete is increasing day by day, due to a shortage of skilled labours in the construction industry as well as due to the quality of finished concrete SCC possesses. SCC is better than conventional concrete in terms of fresh, mechanical and durability properties of concrete because voids due to lack of compaction are eliminated. As per market research done by Global market insight, the SCC market will be worth 30.2 Billion USD by 2024 worldwide.

The usage of SCC is lower in general construction in countries like India. Such a low usage was due to its high initial cost, and unavailability of proper mix design methods for SCC production. Due to higher use of Cementitious material comparing to conventional concrete, SCC is not economical particularly for medium grade of concrete (Compressive strength up to 35 N/mm^2),that are majorly used in India. So it is needed to develop a low cost SCC using simplified mix design approach.

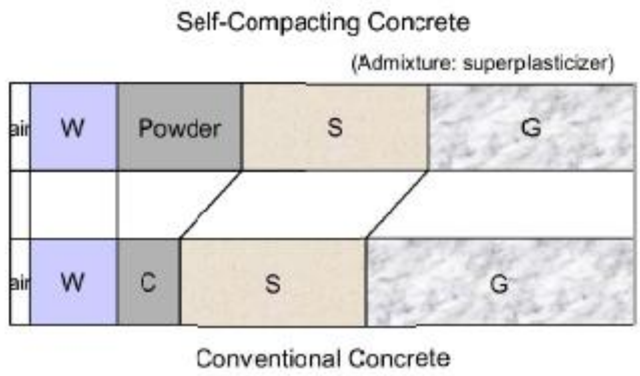


FIGURE 1.1 Comparison of material proportion for SCC and Conventional concrete (Okamura [1])

As shown in FIGURE 1.1 for SCC, the amount of cementitious material required is high compared to conventional concrete to achieve fresh properties, so that no vibration is required for compaction of concrete. For high strength concrete, it is comparatively easy to produce SCC, as high amount cementitious material and low amount of aggregate is required. In conventional concrete for medium-strength concrete i.e. 20 N/mm^2 to 35 N/mm^2, the paste volume required is about 30% to 35% of the total volume of concrete, i.e. in a conventional concrete mix, about 65% to 70% volume is occupied by aggregate. If we take the same proportion of paste and aggregate for SCC, as taken in conventional concrete for medium-strength concrete, it is very difficult to satisfy its fresh properties. So, to achieve these fresh properties of SCC, even though the target strength of concrete required is less, one has to use more cementitious material comparing to conventional concrete. Therefore, in countries like India in general construction where concrete strength required is 20 N/mm^2 to 35 N/mm^2; SCC is not prevalent over conventional concrete.

To amplify the demand of SCC in all-purpose construction, it is needed to find a way to decrease the high initial cost either by replacing the costly traditionally used materials with inexpensive local materials and by applying sustainable simplified mix design approach. For developing economical SCC mix i.e. SCC using less cementitious material the best approach is particle packing approach.

Packing density is defined as the ratio of the solid volume in a unit total volume. To reduce the paste volume it is necessary to achieve maximum packing of aggregate in a concrete mix. Superior packing density improves the workability as well as strength of concrete with lesser paste volume. Effect of packing density will be naturally more if the volume of aggregate is more in concrete mix or other words if the volume of paste is less. So for a medium grade of concrete in which paste required is less if one use fine and coarse aggregate combination with higher packing, it is possible to achieve good fresh and hardened properties even with less paste volume and economical SCC mix can be produced. For example, suppose the packing density of blended coarse and fine aggregate is said 0.85. And let in a concrete mix 650litre volume is of the aggregate and 350-litre volume is of a paste than out of 650litre aggregates considering 15% voids (due to 0.85 packing density), the volume of voids will be 97.5litre. So paste available for the flow after filling the voids of aggregate will be 252.5litre. This high amount of free paste will help to improve fresh properties, and even if paste volume and cementitious material are less, it is possible to achieve SCC. Also due to higher packing density concrete becomes less sensitive toward the little change in its ingredients.

Currently, for particle packing, different models are available like fuller, Andersen and Andersen, Modified Toufar method, compression packing model by De llaraad, Brouwers model etc. Out of all these models, compression packing model suggested by De llaraad is more useful for predicting packing density. However, to achieve higher packing density using this model, input data required is more and therefore cannot be adopted at the site easily. Therefore in the present research, a particle packing model is developed, which is easy to use. In the proposed particle packing model, packing density is easily achieved just based on the gradation and little exercise in Microsoft Excel.

The present study is carried out to optimize the packing density using gradation based particle packing model. Proposed particle packing model is verified by conducting laboratory experiment for a different combination of aggregates and different maximum size of aggregates. For this purpose coarse aggregates (size 20 mm and 10 mm) and fine aggregates (size 4.75 mm down) are combined in different proportions and packing density is calculated. For all such combination of the aggregate, the SCC mix is developed keeping paste content constant and only varying the aggregate proportion to verify the effect of packing density, aggregate size and other parameters related to aggregate. For fresh properties of SCC, slump flow, T500 time, V funnel, L box and sieve segregation tests are carried out and for hardened properties, compressive strength test is carried out for all mixes. The main aim of developing this gradation based model is to reduce the time and labour to derive the optimum packing density and also to reduce the trials required to develop SCC mix.

In present work, also SCC mix design is proposed based on particle packing approach. To develop SCC mix design, the effect of various parameters like aggregate volume, paste volume, Water to cementitious material ratio etc. are checked.

1.2 Definition of the Problem

Comparing to conventional concrete SCC requires more amounts of cementitious materials particularly for medium resistance concrete (20-35 Mpa) to achieve required rheological properties so that compaction can be achieved without any external effort. In country like India such concrete is widely used in rural as well as urban area. To make SCC economical and environment friendly, binder content needs to be reduced. Shi et.al.[2], has reviewed different mix design approach adopted by various researcher and concluded that particle packing approach most suitable and simpler to reduce the binders without compromising rheological properties. Therefore in present research attempt is made to develop mix design approach for medium resistance SCC mix (20-35 Mpa) using particle packing method.

In the concrete industry, the aggregates used are of different size and shape. So it is very difficult to predict the packing density of blended aggregates of different size and volume. Two types of particle packing models are available continuous and discrete, which are discussed in detail in literature review chapter. Continuous models are qualitative and does not give quantitative packing density and also require experimental trials. Some discrete models are applicable to binary particle only, and available multi-component discrete models possess complex equations and needs various experimental investigations. Therefore in present research an attempt is made to develop new particle packing model which simpler to use and has good accuracy in predicting quantitative packing density of blended multi-component aggregate.

So the problem of prediction of packing density for the different blending of fine and coarse aggregate is solved by developing new particle packing model, and to solve the problem of production of economical SCC mix for medium resistance concrete, with less cementitious material, a simplified mix design using particle packing approach is given. Also, many parameters affects the mix design of SCC like water-cement ratio, sand fines, size and volume of aggregate, admixture dosage, volume of binders etc., So to find the effect of various parameters and relationship between various parameters multiple regression model is developed in the present study.

1.3 Objective and Scope of the Research Work

The Objectives of the research work are listed below.

- To develop a particle packing model, that can predict packing density for a different combination of coarse and fine aggregate and simple to use in the concrete industry.
- To develop an economical and simple mix design approach for Self Compacting Concrete, using the proposed particle packing model.
- To give gradation range of fine and coarse aggregate suitable and optimum for developing self-compacting concrete.
- To develop relationships using multiple linear regression analysis for the estimation of compressive strength, slump flow and admixture dosage.

The Scope of the present study is as under.

- To develop a particle packing model using locally available material.
- To find out optimum packing density experimentally and its validation with proposed particle packing model.
- To study the effect of aggregate parameters like the maximum size of aggregate, fines in sand and packing density on properties of SCC.
- To study the effect of paste parameters like paste volume and its composition on the properties of SCC.
- To produce self-compacting concrete for four different cement content 400 kg, 380 kg, 360 kg and 340 kg with different water-cement ratio. The target strength of concrete is from 20 N/mm^2 to 35 N/mm^2, which is widely used in India.
- To evaluate fresh properties of SCC mix using slump flow, T500 time test and, hardened properties of SCC mix by cube compressive strength test.
- To identify factors affecting compressive strength, slump flow and Superplasticizer dosage using multiple linear regression analysis.

1.4 Research Methodology

FIGURE 1.2 shows the methodology adopted for current research work to achieve the objectives of the research. As shown in the figure the whole work is divided into two phases i.e. Aggregate phase and Paste phase. In the aggregate phase, particle packing model is developed to predict the packing density of blended coarse and fine aggregate. As coarse and fine aggregates have different sizes of aggregates, the amount of volume of each size of aggregate should be decided in such a way that it results in optimum packing. In present research the packing model is developed on same concept by studying different existing packing theories of solid physics and existing packing models. For calculation of packing density of blended aggregates using proposed model spreadsheet is developed. In aggregate phase, effect of size of aggregates, packing density and sand fines are evaluated. Different size of coarse aggregates when blended with fine aggregates result in different packing density and has different effects on the properties of SCC. Therefore, the effect of packing density is checked for SCC mix having different size of aggregate which are locally available in India. After phase 1, it will be possible to determine the best combination of fine and coarse aggregate and their gradation.~~.~~

Paste composed of cementitious material, water and admixture. As one of the objective is to develop linear regression model and mix design approach, extensive experiments covering effect of cement content, water-cement ratio, paste volume and composition is studied in paste phase. In the paste phase, the fine and coarse aggregate combination possessing optimum packing density are taken. So, in this phase, fine and coarse aggregate proportions in the total aggregate are kept the same for all mixes. Paste volume and composition is varied. Paste volume taken is in the range from 300 litres to 360 litres per cubic meter of concrete. SCC mixes are casted using 400 kg, 380 kg, 360 kg and 340 kg cementitious material per cubic meter of concrete. Water cement ratio and admixture dosage are also varied for each cementitious material used.

Based on the results of both the phases a guideline is prepared for design mix of self-compacting concrete. Also, regression models are prepared to predict compressive strength, slump flow and admixture dosage based on parameters affecting them.

1.5 Significance of Research

1. In the present research, a new gradation based particle packing model is developed which is very simple and easy to use. Using this model one can predict the packing density analytically for the different blending of coarse and fine aggregate. In the proposed particle packing model, the packing phenomenon of the multi-component mix is explained fundamentally. The model can universally be adopted for any size of the aggregate because it works on the size and amount of voids present in blended aggregate. The present model does not involve any complex mathematical equations, Spreadsheet is developed to perform calculations to find packing density.

2. Using particle packing approach economical SCC mixes are produced with minimum trial mixes. SCC mixes are produced using almost the same cementitious materials which are required for conventional concrete mixes. This leads to Sustainable SCC.
3. If SCC replaces conventional concrete, durability issues produced due to lack of compaction can be eliminated and thereby maintenance cost of concrete structures can be reduced and the age of structures can be increased.
4. Parameters affecting the compressive strength, slump flow and Superplasticizer dosage are found and the relationship is established using multiple linear regression analysis to predict them.
5. A simplified mix design method based on particle packing approach is developed by studying the effect of various parameters affecting the self-compacting concrete mix.
6. Gradation range of blended fine and coarse aggregate suitable for producing self-compacting concrete is given.

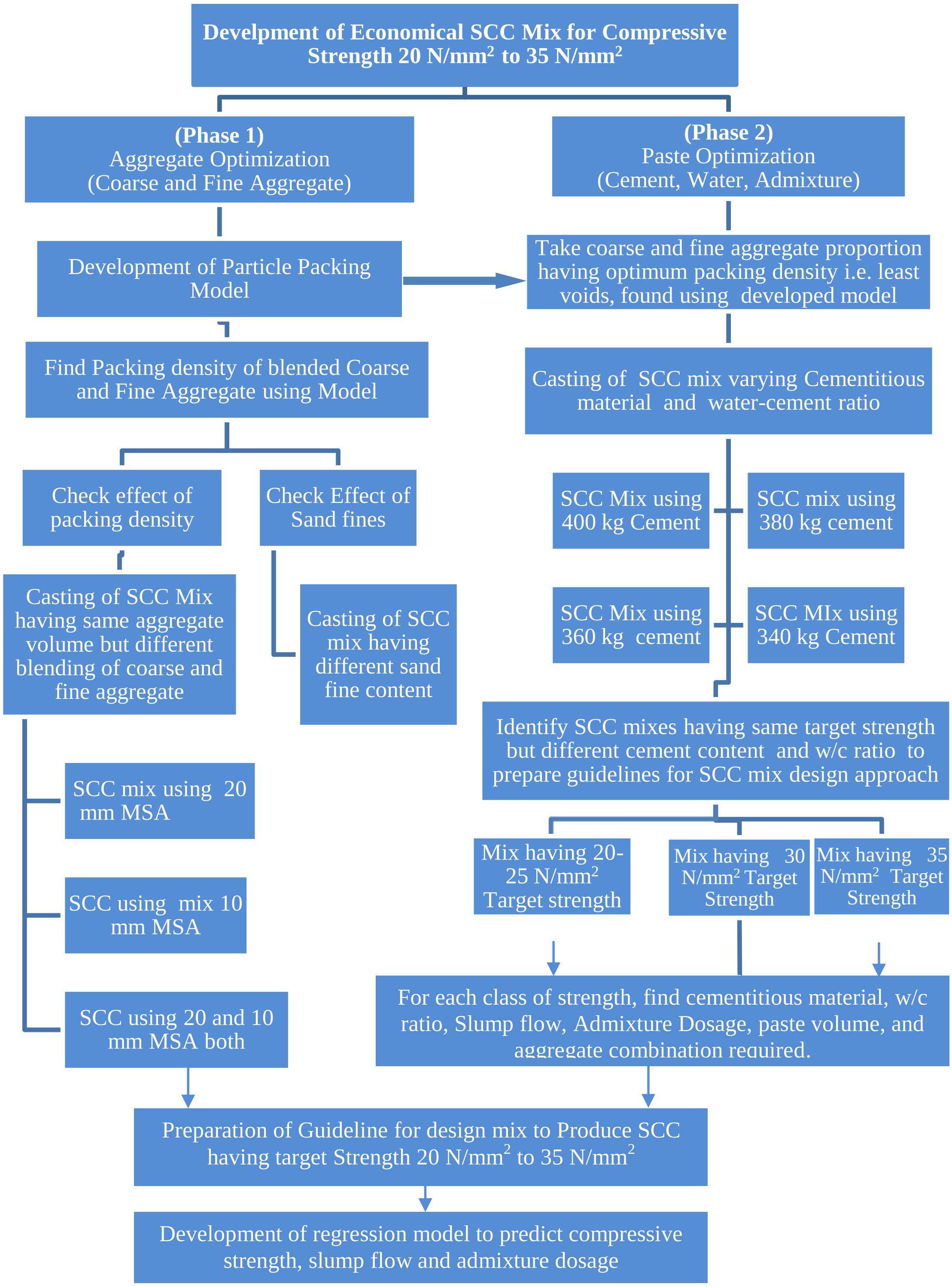


FIGURE 1.2 Flow Chart for Research Methodology

CHAPTER 2

Literature Review

2.1 General

The main focus for literature review was to study literature related to various types of available particle packing models, application of various particle packing models for producing self-compacting concrete, to study available guidelines, tests and acceptance criteria for mix proportioning of SCC and other important literature related to mix proportioning of SCC.

2.2 Literature on Particle Packing Model and Theory

On particle packing work is carried out since long and still, researchers are working on it to improve the existing model or to find new approaches. Particle packing model is divided into two categories, the continuous and discrete model.

The Continuous particle packing approach [3-5] assumes that all the sizes are available in particle gradation system, and between two adjacent sizes there is no gap exists. Continuous models give the particle size distribution (PSD) of the blended aggregate and not the quantitative packing density of the aggregates. Various researchers [3-5] gave the equations for PSD of aggregates. It is assumed that, if PSD of aggregate with certain distribution modulus (q) follows these equations, it will result in optimum packing of aggregates. Distribution modulus indicates the coarseness or fineness of the aggregate. Mixtures of particles with more values of q are going to be coarser, while less q values result in granular blends rich in fines.

In the discrete model, two or more sizes are available in particle gradation system. The discrete model is classified as binary, ternary and multi-component mixture model. In the discrete approach [11-21] the voids in coarser particles are filled by smaller particles, and further voids are filled by still smaller particles and so on. The discrete model is classified as binary, ternary and multi-component mixture model. Discrete models mainly work on the size ratio of the available particles [11-16].

2.2.1 Continuous Model and its application for SCC

Fuller et al. [3] have introduced the thought of composing an ideal particle size distribution (PSD) curve for aggregates. Fuller developed an empirical gradation curve termed as "Fuller curve", which shows the particle grading having optimum density. The idea behind the ideal PSD curve was to reduce the void present in the packed aggregate. As shown in equation 2.1 Fuller has used distribution modulus (q) value equal to 0.5. This empirically optimized gradation curve assumes particles of infinite finesses (i.e. $D_{min} = 0$). This assumption of Fuller curve with q = 0.5 can in no way be satisfied in real practice. In Fuller curve gradation of aggregate is the coarser side and therefore Fuller curve is less suitable for SCC.

$$\boldsymbol{P(D) = \left(\frac{d}{d_{max}}\right)^{0.5}} \qquad \textbf{(2.1)}$$

P(D): Cumulative particles passing from the sieve size D
d: Diameter of the particle being considered
d_{max}: Maximum size of the particles
Andersonet al. [4] reported that the voids between the particles depends on the value of q and can be expressed as ratio with this distribution modulus q as shown in equation 2.2. Andersen and Andersen suggested the value of q in the range of 0.33 – 0.50.

$$\boldsymbol{P(D) = \left(\frac{d}{d_{max}}\right)^{q}} \qquad \textbf{(2.2)}$$

q: Represents a parameter , which sets the trend of the gradation curve towards fineness or coarseness.
Funk and Dinger [5] realized that the imagination of existence of infinite size of aggregates is not possible in reality. Therefore, Funk and Dinger had modified the equation given by Anderson and introduced a lower size limit as shown in equation 2.3

$$\boldsymbol{P(D) = \left(\frac{d^q - dmin^q}{dmax^q - dmin^q}\right)} \qquad \textbf{(2.3)}$$

The granular mixture having with high values of q tends to have more coarse particles and mixtures with small value of q are rich in finer particles. A mixture with higher coarser particles have a high segregation tendency and blocking, while a mixture with higher fine particles poses a high apparent viscosity because of the high packing density.
Brouwers et al. [6] developed a mix design approach for SCC based on modified A&A model. The author has studied Japanese Method and Chinese method and extended their use for Dutch method. The Japanese method used the individual packing densities of

gravel and sand which results in SCC that contains higher amount of paste. Due to which SCC made using the Japanese method gives a higher strength than actually targeted. The Chinese Method considers combined packing density of sand and gravel, and assumes that the voids between the aggregates will be filled by paste. Brouwers had considered packing of all aggregates, filler and cement integrally in this study. Total three types of sand coarse, medium and fine and coarse aggregate of size having MSA 16 mm are taken for design mix. Experimentally results show that sand/gravel ratio of 60:40 in compacted condition results in maximum packing density. Modified A&A model with q=0.25 is followed for optimal PSD. SCC mixes are casted using 480 kg/m^3 powder content and results in concrete grade with compressive strength 35-45 Mpa. It is shown that more water is available for providing lubrication between the aggregates, when aggregates are optimally packed. Brouwers suggested that fines are very much necessary for developing cohesive SCC without segregation and bleeding.

Wang et al. [7] had modified the Brouwers particle packing based mix design procedure and applied it to produce SCC. He used q value ranging between 0.23 and 0.29 in modified A&A model depending on the application of mix and material selected. It was reported that distribution modulus from 0.23-0.29 is good for SCC and the optimum value is 0.28. He showed that due to particle packing approach, 20% binder is reduced. Various mix design methods were compared and it was shown that most of the methods are prescriptive and to finalize constituent materials no specific method is available.

Mehdipour et al. [8] had studied various literatures in this paper and shown that very limited study has been carried out to evaluate the correctness of the theoretical packing density models by performing experiments varying the type of the aggregates, the size of the aggregate and blending of the aggregate. The precision in predicting packing density by model is strongly depends on the ratio of particle size. Out of available continuous models, modified A&A approach with q value 0.22-0.29 is mostly used to optimize the PSD of granular skeleton. For selecting the best particle combination, various criteria like packing found using theory aggregate gradation, and volume of fine and coarse aggregate etc. should be used, . Fine aggregates are not only useful for filing the voids between the coarse aggregate but also the excess fine aggregate remained after filling voids of coarser aggregate ease the coarse aggregate movement by producing ball bearing effect. Due to this, the interlocking of coarse aggregates are reduced, which helps in achieving optimum packing density and reduce the particle interaction effect.

Esmaeilkhanian et al. [9] projected a new economical approach for the mix design of SCC based on particle packing approach. In this method, to develop Eco SCC, the water content is optimized to provide the required least paste volume to gain self-consolidating properties. High w/p ratio up to 0.67 is used to make SCC to ECO SCC by adding more water. The Funk and Dinger model was used for the optimization of the fine and coarse aggregate skeleton by finding grading curve that results in least voids. As, paste volume is less and aggregate fractions are more in Eco-SCC, the passing ability of such SCC mixes are less. The blocking of SCC mixes can be avoided by reducing coarse aggregate fraction in total aggregate but at the same time fine and coarse aggregate proportion should be selected so that it result in high packing density. In this paper a systematic approach to find q value for different combination of fine and coarse aggregate is given, because still no method is available to decide the correct value of q for a given combination of aggregates. In this new approach of selecting q value, if for the optimal packing density, coarse aggregate fraction is higher than that allowed for SCC, then q value for uppermost allowed coarse aggregate fraction shall be selected. Or, the q value corresponding to the optimum packing density should be chosen. Maximum CA volume fixed at 30%, and the corresponding q value is 0.23. Maximum coarse aggregate content is reached before the maximum packing density. The disadvantage of this method is that we have to find the experimental packing density of each combination of coarse and fine aggregate, and then the corresponding q value is found by drawing PSD. The total powder volume of SCC mixes was fixed to 10% of the total concrete volume. But, the total paste volume was fixed at 30%. So, in paste volume, 20% water volume is taken and 10% cementitious material is taken, and therefore w/cm material comes to 0.67, which is too high for structural concrete and not allowed by codes of many countries. The maximum slump flow achieved was 640 mm in a mix having w/p ratio 0.673 , SP dosage 1.32% and strength achieved at 28 days was 23 Mpa.

Muller et al. [10] had adopted a new approach in which the fillers that are non reactive is used to increase paste volume. Paste behaves as a lubricant for the movement of the aggregate blend. Due to better particle packing with an improved lattice effect can lower the lubricant need and also the cohesiveness of the concrete mix is improved. The author proposed a q value of about 0.27 for the PSD of whole mixture of solids in the Modified Andreasen & Andersen Model so that mixtures attains maximum packing and binders can be minimized. The SCC mixes were casted using FA:CA proportion of 75:25. Stone powder having particle size below 0.063 mm was used as filler material to enhance packing. Also, Silica fume is used to improve the strength as cementitious material is kept as low as 296 kg/m^3. W/C ratio is taken 0.60 for all mixes. Slump flow in the range of 550-650 mm was observed and It was concluded that the performance of Eco-SCC clearly depends on the aggregate packing characteristics.

2.2.2 Discrete Model and its application for SCC

Toufar et al. [11] had developed a packing model for binary packed particles. For binary packing the diameter ratio of two particles taken for mix should fall in the limit of 0.22 < d1/d2 < 1.0. If diameter ratio is larger than 0.22, the smaller particles (d1) will not able to to fit in the voids between larger particles (d2). For imbibing this effect in the model a factor k_d was introduced which relates the packing density to the diameter ratio of the two-particle classes. Also, the Toufar model considers that between the void of four closely spaced particles fine particles occupy the place which are used in factor ks. The packing density is described by the following equations.

$$\alpha t = \frac{1}{\frac{y1}{\alpha 1}+\frac{y2}{\alpha 2}-y2\left(\frac{1}{\alpha 2}-1\right)kdks} \tag{2.4}$$

$$kd = \frac{d2-d1}{d1+d2} \tag{2.5}$$

$$ks = 1-\frac{1+4x}{(1+x)^4} \tag{2.6}$$

$$x = \frac{y1\alpha 2}{y2\alpha 1(1-\alpha 2)} \tag{2.7}$$

Even though Toufar and modified Toufar models are comparatively easy to use but as the model is prepared for binary mixes it under estimate the packing density of multi-component systems and does not accurately predict the packing density.

De Larrard [12-14] had developed a compression packing model (CPM). CPM is one the most detailed and efficient multi-component particle packing models which utilize a polished version of linear packing density model (LPDM) for aggregate mixtures. The phenomenon of virtual packing is developed for calculating packing density. Virtual packing density is an imaginary packing density calculated by assuming that all thae particles are arranged in an optimal manner so that the voids between the packed particles are least. This imaginary density is always higher than the real achievable packing density. De Larrard has employed a factor called compaction index (K) to calculate the actual packing density. The value of K depends on the external energy used for compaction of particles and has the value of 4.1, 4.5, 4.75, and 9 for loose packing, rodding, vibration and vibration + compression respectively.

In addition to this, the CPM also considers the wall and loosening effect due to particle interaction. If a smaller particle is placed in the void of a coarse particle , coarse particles is dominant, and if available space is not enough to accommodate fine particle it will push the coarse particles apart to make space for fines to fit. This is termed as loosening effect. On the contrary if coarse particle are placed between large amount of fine particles, fine particle becomes dominant and voids are created in the vicinity of wall which is termed as wall effect. In present model it is shown that packing density is significantly affected by compaction. Wall effect and loosening effects are additive. It is observed that if container diameter is more than 10 times the aggregate diameter, there is no wall effect. The wall effect is significant only for coarser fractions. The major hypothesis of model is the granular interaction in any mixture is essentially binary in nature. Initially virtual packing density found using model was differing from the experimental packing density which is then corrected by using interaction coefficients found using developed equations. The interaction coefficient mainly controlled by size ratio of two fractions considered. From the packing density readings for binary particles, it is observed that there is only average 1% difference in error when interaction coefficients are considered. TABLE 2.1 represents effect of interaction of aggregate (interaction coefficient) on packing density of blended crushed angular aggregate. Experimental values of packing density is calculated for compacted aggregate through vibration and theoretical packing density is calculated using developed particle packing model by De Larrard. Here C8C05 show the pair of coarse (d_{min}= 8 mm and d_{max}=10mm) and fine (d_{min}= 0.5 mm and d_{max}=0.63mm) particle. Fine particles are increased by 10% in blending with coarse aggregate. It can be seen that, when interaction coefficients are considered the error in value in experimental and theoretical packing density is decreased. For maximum packing density for 30% FA blended with 70% CA, the difference in value of packing density with and without interaction is only 0.46%. for C8C05 combination and 0.85% for C8C2 combination. So, it can be observed that when packing density values are near optimum effect of particle interaction is negligible and this occurs may be due to compacting efforts.

TABLE 2.1 Effect of interaction coefficient on packing density of blended crushed angular aggregate

Size of Blended aggregate	FA %	Packing Density without Interaction effect (Compaction through vibration)			Packing Density with Interaction effect (Compaction through vibration)			Theoretical value difference with and w/o interaction effect i.e between column(2) and (5)
		Exp (1)	Theo (2)	Error (%) (3)	Exp (4)	Theo (5)	Error (%) (6)	
C8C05	10	0.642	0.6295	1.95	0.6392	0.651	-1.85	-3.42
	20	0.705	0.6779	3.84	0.6899	0.701	-1.61	-3.41
	30	**0.7365**	**0.7137**	**3.10**	**0.731**	**0.717**	**1.92**	**-0.46**
	40	0.723	0.6998	3.21	0.7248	0.721	0.52	-3.03
	50	0.6941	0.6666	3.96	0.6955	0.71	-2.08	-6.51
	60	0.6585	0.6331	3.86	0.6645	0.682	-2.63	-7.72
C8C2	10	0.611	0.6125	-0.25	0.6225	0.633	-1.69	-3.35
	20	0.634	0.6398	-0.91	0.6524	0.66	-1.16	-3.16
	30	**0.651**	**0.6594**	**-1.29**	**0.6758**	**0.665**	**1.60**	**-0.85**
	40	0.643	0.6554	-1.93	0.6769	0.66	2.50	-0.70
	50	0.6335	0.6349	-0.22	0.66	0.65	1.52	-2.38
	60	0.6245	0.6111	2.15	0.6386	0.638	0.09	-4.40

For multi-component aggregate mix, the virtual packing density of a mixture, containing n size classes with category i being dominant is expressed as:

$$\beta ti = \frac{\beta i}{1-\Sigma_{j=1}^{i-1}\left[1-\beta i+bij\beta i\left(1-\frac{1}{\beta j}\right)\right]yj-\Sigma_{j=i+1}^{n}\left[1-\frac{ai\beta i}{\beta j}\right]yj} \tag{2.8}$$

$$\alpha i = \frac{\beta i}{1-\frac{1}{k}} \tag{2.9}$$

Where βti is calculated virtual packing of a mixture when size class iis dominant. and βi and βj are virtual packing densities of size class i and j. For a monosized particle class βi can be determined by Equationof αiwhich is the experimentally determined packing density. It should be mentioned that as K value tends to infinity, the real packing density becomes closer to virtual packing density βti. Packing density αt is determined indirectly based on:

$$K = \sum_{i=1}^{n} Ki = \sum_{i=1}^{n} \frac{yi/\beta i}{\frac{1}{\alpha t}-\frac{1}{\beta ti}} \tag{2.10}$$

CPM is more superior than the formerly discussed models but the complexity of the calculation in model and the number of participation data makes it more difficult to use. Also, the experimental packing density of aggregates on each sieve needs to be found for calculating virtual packing density.

J. D. Dewar [15] considered packing density in loose condition of aggregates. Instead of packing density the void ratio is calculated in this method. The voids ratio and the log mean size of each individual material are utilized to calculate the voids ratio for given combination of aggregates. For multi-component mixtures, an analogous process, as discussed above is used. The Dewar method requires that initially two most fine materials should be combined and later the next coarser material is added. Finding experimental void ratio for each material to be combined makes this method time consuming and difficult to use.

R.K.McGeary [16] did a study on spherical particles and found that mono sized particles can be packed to the density of 62.5%. He found that to achieve higher packing density for multi-component particles, it requires $1/7^{th}$ difference between sphere size of the individual component. This size of void is the void size between the three closely spaced particles forming a triangular void, which is filled by migration of the other smaller size particle. For binary packing volume composition required is 72.7% and 27.3% for coarser and finer particle respectively and achieved packing density is 85.9%. A ternary packing with a density of 94.7% was achieved from the sphere of volume composition 66%, 24.7% and 9.3 % for the size of particles coarser to finer respectively. Packing was achieved by axial vibration. Also, the best method to achieve high packing density is multi-component packing in which preceding component or components act as a stationary filter bed for the next finer component, and the whole assembly is mechanically vibrated for entry of fines into the bed.

Elliott et al. [17] gave the mathematical model to prove the work done by R.K.McGeary. For mono sized, binary, ternary and quaternary particles packing density was checked. In following TABLE 2.2 comparison of experimental value obtained by McGeary [16] and theoretical values derived from the models are compared. It satisfies the work done by R.K.McGeary.

TABLE 2.2 Comparison of theoretical result with McGeary's experimental data

Type of Packing and Size ratio	Particle 1 (Volume)		Particle 2 (Volume)		Particle 3 (Volume)		Particle 4 (Volume)		Packing Density	
	Theory	Expt.	Theory	Expt.	Theory	Expt.	Theory	Expt.	Theory	Expt.
Mono size (1)	1.00	1.00	--	--	--	--	--	--	0.625	0.625
Binary (1:7)	0.727	0.723	0.273	0.277	--	--	--	--	0.859	0.840
Ternary (1`:7:77)	0.660	0.670	0.247	0.230	0.093	0.100	--	--	0.947	0.900
Quaternary (1:7:38:316)	0.638	0.607	0.239	0.230	0.090	0.102	0.034	0.061	0.980	0.951

The recursive mathematical model was developed without considering the shape of the particle, therefore it was concluded that the same model can be extended for the angular aggregate which packed randomly with different volume of particles.

Radhika K.L.et al. [18] had studied three types of discrete packing models and found packing density of multi-component angular aggregates using each model. It was found that the compression packing model contains more amount of fine aggregate and is most suitable for producing self-compacting concrete. In this research paper, aggregate proportions were optimized using modified Toufar model (MTM), J.D.Dewar model and Compression packing model (CPM).

The steps for optimization of aggregate proportion are as below.

Step-1 Physical properties of mono sized aggregate proportions

Step-2 Binary blending of single-sized aggregates

Step-3 Poly-dispersed blending of well-graded aggregates

It was observed that when two groups of coarse aggregates are combined in different proportions packing density is not increased, this happens due to smaller void size comparing to particle size available for fitting into voids. Maximum packing is observed when coarse aggregate is combined with fine aggregate. TABLE 2.3, TABLE 2.4 and TABLE 2.5 shows the size wise combination of coarse and fine aggregate that results in optimum packing density for MDM, J.D.Dewar model and CPM respectively.

TABLE 2.3 Optimized aggregate proportions for poly dispersed mixes (MTM)

Size	CA/FA	20-16	16-12.5	12.5-10	10-4.75	4.75-2.36	2.36-1.18	1.18-0.6	0.6-0.15	Ø
20 mm	40/60	0.14	0.06	0.08	0.12	0.22	0.14	0.12	0.12	0.807
16 mm	40/60	-	0.16	0.10	0.14	0.22	0.14	0.12	0.12	0.798
12.5 mm	35/65	-	-	0.23	0.12	0.24	0.13	0.15	0.13	0.791

TABLE 2.4 Optimized aggregate proportions for poly dispersed mixes (J.D.Dewar**)**

Size	CA/FA	20-16	16-12.5	12.5-10	10-4.75	4.75-2.36	2.36-1.18	1.18-0.6	0.6-0.15	Ø
20 mm	35/65	0.12	0.07	0.09	0.07	0.36	0.15	0.06	0.08	0.777
16 mm	31/69	-	0.10	0.12	0.09	0.38	0.16	0.08	0.07	0.769
12.5 mm	28/72	-	-	0.16	0.12	0.39	0.17	0.09	0.07	0.762

TABLE 2.5 Optimized aggregate proportions for poly dispersed mixes (CPM**)**

Size	CA/FA	20-16	16-12.5	12.5-10	10-4.75	4.75-2.36	2.36-1.18	1.18-0.6	0.6-0.15	Ø
20 mm	40/60	0.04	0.04	0.12	0.20	0.03	0.06	0.21	0.30	0.872
16 mm	40/60	-	0.05	0.05	0.3	0.03	0.06	0.21	0.30	0.870
12.5 mm	40/60	-	-	0.05	0.35	0.03	0.06	0.21	0.30	0.870

It can be seen that combination of 60% fine aggregate with 40% coarse aggregate results in maximum packing density for MTM and CPM, while 35% FA blended with 65% FA results in optimum packing density for J.D.Dewar model. SCC mixes were prepared using an optimum blending of FA and CA, using CPM and all the mixes were showing satisfactory performance. It was concluded that CPM is the best-suited model for developing SCC mix.

Kwan [19] had developed a new particle packing model for binary mixes of angular aggregate. The model has considered 3-parameters loosening, wedging and wall effect. It was shown that the spherical particle packing model can be extended for angular aggregate. In the kwan model, no study is shown on packing of multi component angular aggregate. Author has compared the packing model with the de Larrard model [12-14] and fung and kwan model for binary mixes, and shown that their the results are more in agreement with the fung and kwan model. Overall, when applied to predict the packing densities of the binary mixes tested by Fung and Kwan, the 3-parameter model is accurate to within an absolute error of 5.9%. They consider this error small for the applicability of the model. It is very difficult to predict wall and loosening effect mathematically, and the author also speculated the effect and suggests further study in the phenomenon is recommended.

Long et al. [20] had used a CPM to find packing densities of the mixture of powder and aggregates for SCC. The mix design is proposed based on aggregate and powder optimization. Fine aggregates were sieved in five different sizes and coarse aggregate sieved in two different sizes. The packing density of aggregate and powder was found separately, then for optimum sand/total aggregate (S/a) ratio powder is mixed with aggregate and optimum packing density was found. The minimum void content was attained when the S/A is 0.45 and when the aggregate/binder volume ratio is approximately 6. The packing density for S/A=0.45 was 0.8301. The proposed design saves around 16% binder content for SCC mix. Total 9 mixes were casted using cement content 320, 350 and 380 kg/m^3, with 3 variations of fly ash content. The slump flow is significantly increased by adding fly ash to the concrete. It is shown that the mixtures with total binder content ranging from 320 to 380 kg/m3 exhibit slump flow in the range of 545-620 mm and 28-day compressive strengths in the range of 30-40 MPa, which are suited for construction applications

W.Zuo et al. [21] had used gyratory Compactor to test the dense packing density (PD) of solid particles. First optimum PD of FA and CA proportion is found, which is at 40%FA and 60% CA, then PD of aggregate and powder found which is optimum for 15% Cementitious material and 85% Aggregate in which 50% FA is kept constant. Using CPM and 3-Parameter model PD was found and compared with actual PD. Before the densest state, the 3-Parameter agrees with the test results better than that of the CPM, while after that the CPM is much closer to the test results. Analytical and experimental PD is compared. The slump flow spreads are higher as the increase of the sand to aggregates ratio in all cases. Also, V funnel time decreases. Compressive strength decreases with higher sand content. Limestone powder increases self-compacting property. Also, it was concluded that based on the PSD curve drawn using modified A&A model, q values of 0.5 and 0.275–0.300 should be considered for the ca and FA optimization and aggregate-powder optimization respectively.

2.2.3 Experimental Particle Packing and its application in SCC

Rodriguez S. G. et al. [22] reported that much work is emerging for the design and application of SCC with 25-35 Mpa strength. In SCC mix design it was assumed that paste governs the fluidity of concrete. A natural characteristic of SCC, because it has a larger amount of cementitious material, is that its mechanical properties tend to be higher than those of normal concrete. Mix design was divided into 3 phase. In first phase FA and CA content are optimized manually, which results in minimum void content, the volume of the void is used to initially estimate paste volume. Aggregate packing was optimized by varying CA size (19 mm and 12.5 mm MSA) and keeping FA content constant at 50%. 50% CA having19 mm MSA with 50% FA gives minimum voids. The powder content was taken ranging from 530 kg/m3 to 640 kg/m3, which is very high and does not fulfil the objective.

The salient point for mix design of SCC, adopted by the author is as below.

1. By mixing several combinations of fine and coarse aggregate the volume of the void content can be determined and based on that estimate the volume of paste.
2. The admixture dosage is influenced by the aggregate-cement and addition-cement ratio and ultimately affects the segregation resistance and the flowability of the SCC mix. Therefore both properties are determined to optimize the paste composition for stable concrete mic.

Pelisser et al. [23] had used experimental method to find optimum PD of aggregates by changing the proportion of fine sand, coarse sand and coarse aggregate. For Optimum PD different SCC mixes were cast using different cement to the aggregate ratio (C/A) and with a different combination of cement, metakaolin and fly ash. For Cement to total aggregate ratio 3, w/b ratio is taken 0.46 and binders were taken 582 kg/m3. To make eco-SCC, C/A ratio was increased to 7, but to maintain the paste volume w/b ratio was increased up to 0.9. W/b ratio 0.9 is too high for durability perspective and is not allowed for structural concrete.

P.Ghoddousi et al. [24] had investigated the packing density of aggregate mixture with addition of mineral admixture. For this wet method is used to determine the packing density of SCC mixtures. The PSD of all the solids in an SCC mixture is considered. The addition of mineral admixture tends to reduce the packing density. Generally, mineral admixtures are finer than cement and they increase the packing density of total solids. It was shown that addition of silica fume and metakaoline increases the yield stress while GGBFS decreases the yield stress. Author concluded that for optimum combination of fine and coarse particles not only reduce the voids but also minimize loosening and wall effects.

P Nanthgopalan et.al. [25] has developed experimental set up to determine partially compacted packing density in which blended aggregates are allowed to fall in a cylinder through bucket kept at 200 mm height. Total 24 various combinations of fine and coarse aggregate were tested for packing density. Fine aggregate is blended with 12.5 mm and 20 mm coarse aggregate in various proportions to find packing density. Using MATLAB packing density of other combinations were found using available 24 data points. It is observed that for binary packing 70% fine aggregate in combination with 30% 20 mm size coarse aggregate gives maximum packing density. While for ternary packing combination of 60% fine aggregate in combination with 20% 12.5mm CA and 20% 20 mm CA results in maximum packing density. The result shows that the hardened properties are not much affected by the variation of fine and coarse aggregate combination for same packing density but the fresh property is substantially affected. To check the effect of packing density on SCC mix, total 10 mixes were casted keeping paste volume and composition constant and varying fine and coarse aggregate blending. The cementitious material 495 kg/m3, w/c ratio 0.37, admixture dosage 0.16 is kept constant for all mixes. FA:CA proportion is varied from 48:52 to 63:37 for 10 mixes. The coarse aggregate size 20 mm is kept almost 85% and 12.5 mm size is kept about 15%. The slump flow is varying in range of 445-720 mm and compressive strength is varying in range of 43.8-44.9 mm. The results suggest that packing density has significant effect on fresh properties while little effect on mechanical properties. Also, for FA:CA ratio 48:52 segregation is observed, which suggest that fine aggregate should be kept more for obtaining cohesive mix. Mixes with more fine aggregate were showing decrease in slump flow, due to less admixture dosage.

P Nanthgopalan et.al. [26] investigated the effect of paste composition and paste content on properties of SCC. Total 19 mixes were casted. 15 mixes were casted without VMA and 4 mixes were casted using VMA. The study is used to empirically predict paste volume for targeted slump flow for SCC mixes with compressive strength ranging between 20-70 Mpa. For casting SCC mixes combinations of fine and coarse aggregate having optimum packing density was chosen. Paste volume was taken in range of 388 l/m3 to 503 l/m3 with different paste composition. Excess paste was in the range of 68 l to 183 l. To achieve minimum requirement of slump flow of 550 mm, at least 50–70 l of free paste over and above the void content of the loosely packed aggregates was found essential for achieving SCC. It is concluded that for SCC only slump flow and J ring test is sufficient to understand fresh properties. It is also observed that segregation tendency is reduced by maximizing packing density.

2.3 Other literature Related to SCC

C.Bibm et.al. [27] gave the guideline for mix design of SCC. Salient Point of Mix Design is listed below.

1. Water/powder ratio equal to 0.85 to 1.1 by Volume
2. Total powder content 160 to 240 litres (380-600 kg) per cubic meter.
3. Total Paste Content- 300 to 380 litre
4. Coarse aggregate content 27 to 36 % by volume of the mix. (750-1000 kg)
5. Water Content 150-210 litre/m3
6. The sand content 48-55 % of the total aggregate weight.

As per EFNARC guideline, self-compacting concrete needs superplasticizer in addition to conventionally required materials like cement, fine and coarse aggregate, water etc. The purpose of using chemical and mineral admixtures are mentioned below..

- ❖ In high strength concrete mineral admixtures are used as replacement of cement to improve fresh and hardened properties.
- ❖ Superplasticizer increases the free water and thereby imprves workability
- ❖ For the movement of coarse aggregate in SCC mix, powder content plays the role of lubricant.
- ❖ VMA to increase the viscosity and segregation resistance of the concrete.

A good SCC should possess characteristics like filling ability, passing ability, viscosity and resistance to segregation and bleeding. In EFNARC guideline, for measurement of fresh properties of SCC, different tests are suggested and for each test acceptable limit is given. The tests for fresh SCC and acceptable limits are summarized in TABLE 2.6**.** Acceptable limit for slump flow is 550 mm to 850 mm depending on the application of concrete mix. SCC requirements are specific to site condition e.g. if reinforcement is little or no, no need to perform passing ability test and slump flow of 550-650 mm is sufficient.

TABLE 2.6 Requirements of SCC mix in Fresh State [25]

Test	Classes	Range (mm)	Application	Purpose	Remarks
Slump Flow	SF-1	550-650	Unreinorced	To check segregation, filling ability, viscosity	If paste extend several millimetres from the C.A. and if C.A. segregated at central area
	SF-2	660-750	Normal		
	SF-3	760-850	Very Congested Stru.		
T 500 time	VS-1	<=2	Good Filling,Surace finish	Viscosity	Prone to bleeding and segregation
	VS-2	>2	High segregation Resistance		Lake in Surface finish
V Funnel	VF-1	<=8	Same as T500	Viscosity	Same as T500
	VF-2	9 to 25			
L-Box	PA-1	>=0.80 with 2 rebars	Housing/Vertical Structures (Gap 80 mm to 100 mm)	Passing Ability-Flow without blocking	No need when gap is more than 100 mm
	PA-2	>=0.80 with 3 rebars	Civil Engineering Stru (Gap 60 mm to 80 mm)		
Sieve Segregation Test	SR-1	<=20%	For thin slabs & Vertical Application	Segregation resistance for higher slump flow	Flow Distance<5m Confinement Gap >80mm
	SR-2	<=15%	Tall Vertical Application		Flow Distance>5m Confinement Gap <80mm

Shi C et al. [2] had studied and evaluated various design mix approaches suitable for SCC He concluded that, the method based on targeted compressive strength represents a lucid and exact method to find precise amount of ingredients and decrease the number of trials required for final mix. He also concluded that method based on particle packing strongly depends on the characteristics of paste and aggregate skeleton. It needs to optimize blending of aggregates so as to achieve optimally packed particle system. Hence, this method is simpler and requires a smaller amount of binders.

Nan Su et al. [28] mix design method was easy comparing to Japanese method and consume less binders. Concept of packing factor was used for mix design. Packing factor is the ratio of packing density of loosely packed aggregate to compacted aggregate. Aggregate amount is kept around 59-68% in SCC. The ratio of FA to Total aggregate was kept 50-57%. In this method actual packing of blended coarse and fine aggregate was not found. Packing factor of individual aggregate was used to determine amount of aggregate in mix. Amount of cement was not based on fresh property required for SCC, rather it solely based on the strength. But, using this method not much saving in binder was noticed and more binders were required for SCC mix than conventional concrete.

M.R.Jones et al. [29] and Mangulkar et al. [30] had compared various particle packing models. Particle packing model was applied to both aggregate and cement phase and it is shown that the aggregate phase has more impact on void ratio. Modified CPM estimates void ration close to the experimental value. Different particle model works very well for different particle size group but Still, much work is needed to develop a fundamental model.

D'Souza et al. [31] had developed an economical SCC, which is termed as smart dynamic concrete (SDC). SDC is an SCC that possesses lesser amount of paste fraction. To develop SDC a new generation VMA is used. SCC having compressive strength M40 was manufactured by utilizing only 425 kg of cementitious material and the granular fraction contains 48% coarse aggregate in total aggregate.

Bhattacharya et al. [32] studied the influence of particle packing on mix design and properties of SCC. They showed that Particle packing concept improves the fresh and hardened properties of the concrete with the economy. Total 10 SCC mixes were prepared by varying coarse aggregate sizes in total aggregate keeping fine aggregate constant. Also, Paste composition was kept constant. The cementitious material was taken in the range of 386-424 kg/m^3. Maximum size of aggregate used was 25mm. Slump flow was observed in the range of 600-710 mm and compressive strength was in the range of 47.2-61.8 Mpa. It was concluded that Water/powder ratio and paste volume have more effects on SCC than a water-cementitious material ratio and the equal distribution of 25 mm and 9.5 mm aggregate for SCC helped to achieve higher slump-flow.

Guru Jawahar et al. [33] did the study about the effect of the blending of two size of coarse aggregate i.e. 20 mm and 10 mm in ratio of 40:60 and 60:40. Also, the coarse aggregate volume was taken 32% and 28% respectively, and the effect of these variations of coarse aggregate on the mechanical properties of SCC was evaluated. The variation in the coarse aggregate proportions and content particularly affects the modulus of elasticity and density of SCC mix, and a little or no effect is observed on the compressive strength of SCC mixes at all ages, From the test results it can be seen that for same paste volume and composition but different combination of fine and coarse aggregate compressive strength is nearly same but fresh properties are changing. So, it was concluded that compressive strength is mainly influenced by the composition of the binders.

Ana C.P. Santos et.al. [34] has found the effect of continuous and discontinuous aggregate skeleton on hardened properties of SCC. Continuous distribution contains, a high volume of sand, a average contribution of medium aggregate and smaller amount of coarse aggregate. While discontinuous distribution contains, a high volume of sand, a lower contribution of average aggregate and medium proportion of coarse aggregate. It is shown that fines have significant effect on cohesion, fluidity and water retention. SCC mixes are casted targeting 35 Mpa and 60 Mpa compressive strength. The results shows that SCC mixes having continuous distribution of aggregates shows better rheological properties with nearly same compressive strength, due to higher amount of paste available for coating of coarser particles. In all mixes fine aggregate amount is taken around 55% of total aggregate.

Mikbin I.M. et.al.[35] has investigated the effect of coarse aggregate size and volume on properties of SCC. Total 12 mixes were casted using three types of coarse aggregate 9.5 mm, 12.7 mm and 19 mm. In series 1 different combination of coarse aggregate sizes were used keeping all other ingredients constant. Two different strength levels were considered in series1, for which 3 mixes were casted using 422 kg cement with 0.38 w/c ratio and 3 mixes were casted using 352.8 kg cement with 0.53 w/c ratio keeping paste volume constant. It is observed that for 352.8 kg cement, maximum slump flow of was observed when 19 mm size coarse aggregates are used and similarly compressive strength also slightly increased. For 422 kg cement mixes, maximum slump flow was achieved with 12.7 mm size coarse aggregate. In series 2 and 3, coarse aggregate size was kept constant at 12.7 mm and by varying volume from 30% to 60% in increment of 10%. In series 2 mixes , maximum slump flow was lesser than series 1 mixes, even with higher cement content of 373.9 kg due to use of only 12.7 mm size coarse aggregate, which indicates that aggregate skeleton has significant effect on fresh properties of SCC. Author has concluded that with increase in size of coarse aggregate all the mechanical properties like compressive strength, modulus of elasticity, tensile strength etc. are improved.

2.4 Summary of Literature

In following TABLE 2.7, a summary of all the literature studied is presented. Various parameters like type of particle packing approach used, mix design method adopted, amount of cementitious material and water to powder ratio used for mix proportioning of SCC and fresh and hardened properties in terms of slump flow and compressive strength is presented in the table.

TABLE 2.7 Summary of Literature

Author	Year	Packing density approach	Verification of Packing Density	Cementitious material(kg/m3) / Water/Powder	Comp.Stre. (MPa)/ Slump Flow (mm)	Remarks
Application of Continuous Model for SCC						
Brouwers [6]	2005	Modified A&A q=0.25	Experiment	473-499 kg 0.34-0.37	50.7-53.6 720-745	
Wang [7]	2014	Modified A&A q= 0.23-0.29 0.23,0.25,0.29	Curve fitting through spread sheet and VB	380-448 kg 0.40	39-56 597-762	Required iteration to find optimum q value
Esmaeilkhanian [9]	2017	Mod A&A q=0.23	Experiment	278-312 kg w/p=0.67	23-27 560-640	w/p=0.67
Muller [10]	2014	Mod A&A q=0.27	Gyratory ICT	450-637 w/p=030-0.47	55-70 550-650	
Application of Discrete Model for SCC						
K L Radhika [18]	2016	CPM, MDM and JDD	Manual	400-605 kg 0.49-0.31	31.27-72.5 653-685	CPM is good for SCC
Long [20]	2017	CPM	Experiment	320-380 kg 0.40	24.6-43.4 545-620	
W.Zuo [21]	2018	CPM&3-PM	Gyratory ICT	361-520 kg 0.35-0.49	30-50 550-700	
Kwan [19]	2015	3-PM model with wedge effect for binary mixes.	NA	NA	NA	
Experimental particle packing for SCC						
G. Rodriguez [22]	2015	Quantitative, voids calculated	Experiment	530-640 kg 0.36-0.45	38-63 640-803	
Pellisser [23]	2018	None	Experiment	582 w/p 0.46 294 w/p 0.9	68.5/750 28.6/670	w/p=0.9
Ghoddousi [24]	2014	Wet packing	Experiment	400 0.45	42 670	
Nanthgopalan [25]	2012	New Experimental method	Experiment	495 0.37	720 44.9	
Other literature related to SCC						
Nan su [28]	2001	Packing not found for blended aggr.Individual PF found.	Experiment ASTM C29	424-553 0.42-0.31	48.3-52 600-710	

Disuza [31]		Packing not found for blended aggr	Not found	360-450 0.38-0.47	20-40 550-650	
Arka Bhattacharya [32]	2008	Not adopted	Not found	424-498 kg 0.40	47.2-61.8 650-710	
Guru Jawahar [33]	2013	No PD Found Random mixing of FA and CA	Not found	384-495 0.5-0.36	31.12-32.26 695-710	

Based on the literature, it can be seen that out of all available continuous models, modified A&A model given by Funk and Dinger [5] is widely used to develop ECO-SCC. In the modified A&A model if distribution modulus is kept between 0.21-0.29, it gives optimum packing density and it is the best suitable range for SCC [6-10].

The mono sized spherical particles can be packed to the density of 62.5% [16-17]. For binary packing volume composition required is 72.7% and 27.3% for coarser and finer particle respectively and achieved packing density is 85.9% [16-17]. A ternary packing with a density of 94.7% was achieved from the sphere of volume composition 66%, 24.7% and 9.3 % for the size of particles coarser to finer respectively [16-17]. Toufar Model [11] calculates packing density for binary mixes and does not give an accurate result for a multi-component mix. For multi-component mixes, compression packing model (CPM) given by De Larrard [12-14] gives a better prediction of packing density compared to other models [18-21], but the process of finding packing density is complex and cannot easily be adopted at the site. For SCC, possessing a stable and cohesive mix, fine aggregates are kept more than the coarse aggregate [6, 9]. Fine aggregates are not only useful for filing the voids between the coarse aggregate but also the excess fine aggregate remained after filling voids of coarser aggregate ease the coarse aggregate movement by producing ball bearing effect. Due to this, the interlocking of coarse aggregates are reduced, which helps in achieving optimum packing density and reduce the particle interaction effect [8]. Therefore, for developing SCC, the CPM model is mostly used by the researchers [18-21], as it gives more fine particles comparing to coarse particles for optimum packing.

Due to complex equations and uncertainty in the result of existing models, the still-experimental method is used to find optimal packing of aggregates for proportioning of self-compacting concrete [22-26]. The experimental method is tedious and needs more efforts to arrive at the optimal packing of aggregates.

Particle packing approach is more useful, particularly for ECO-SCC in which aggregate volume is about 65-70% and therefore aggregate phase has more impact on the performance of SCC [30]. For ECO-SCC, Wallevik et.al. [9] has kept total powder content limited to 315 kg/$m^3$and the volume of powder around 10-15%. In Eco-SCC, paste volume is limited to 30-35%, out of which around 10-15% is a powder, so, the water volume will be around 20%. As cementitious material is lower in Eco-SCC, to provide the necessary minimum paste volume of around 30-35% to obtain self-consolidating properties, high w/p ratio up to 0.65-0.90 [9,23] is used to make SCC to Eco-SCC. Also, with this much less binders, mineral admixtures like silica fume need to be used to increase the strength and chemical admixture like AEA needs to be used to increase flowability, which ultimately increases the cost of the final mix. Indian standard IS: 456-2000 [36] allows maximum w/p ratio up to 0.55 for structural concrete. Similarly, as per ACI-301 [37] maximum w/p ratio allowed for durability requirement is 0.50. Therefore in the present study w/p ratio is kept limited up to 0.5.

2.5 Research Gap from Literature

Literature indicates that still researchers are trying to develop new particle packing models and theories and still fundamental model needs to be developed. For continuous models various researchers have given different distribution modulus (q) values ranging from 0.21-0.29 for optimum packing of aggregate. So, one should need to find the q value that suits their aggregates performing experimental iterations to find the best combination of fine and coarse aggregates. In addition to that, continuous models do not give quantitative value of packing density, so it is not possible to find exact paste volume required to make SCC mix economical. In addition to that, as the continuous model assumes that all the sizes are available in the aggregate, it never matches with the actual PSD curve of blended aggregate.

In the discrete approach, compression packing model suggested by De llaraad is more useful for predicting packing density, but the complexity of the model and the number of input data makes it more difficult to use.

Therefore, research is needed to develop a new logical and simplified approach to find a packing density of blended aggregate, which overcomes the ambiguity of existing models. The analytical procedure should be without any complex calculations and can be easily used at a construction site to find optimum packing density.

Also, it can be seen that, not much work is done for medium grades of concrete, which are widely used in India. To make economical medium resistance concrete, less paste needs to be used. When less paste is used, effect of aggregate skeleton is predominant on behavior of SCC. Therefore it is necessary to optimize aggregate skeleton and paste composition. Effects of Parameters like aggregate gradation, fine aggregate volume, fines in fine aggregate, size of aggregate, w/c ratio, cementitious material volume and admixture dosage needs to be carried out to develop mix design approach for economical SCC mix. So, further research is needed to develop a simplified mix design approach, which requires lesser cementitious material to produce SCC mix and can be used for structural concrete.

2.6 Major Conclusions from literature

Following major conclusion are drawn from the literature:

- Out of available continuous models, the modified Anderson model with distribution modulus between 0.21-0.29 is result in optimum packing of aggregates and best suited for self-compacting concrete mixes.
- Wall effects can be ignored if the container size is 10 times the diameter of the particle.[12-14,16]
- By considering interaction effect of particles, packing density differs about 2% as compared to packing density without interaction effect, and this error is decreased as packing density goes near to optimum level and become a negligible when optimum packing is achieved. [12-14,24]
- Compaction through vibration is the best method for optimum packing of multi-component particles.
- As packing density of aggregate skeleton is increased the fresh properties of SCC mix is significantly improved while the mechanical properties are less affected.
- For good cohesive mixes fine aggregate should be kept more than the coarse aggregate in total aggregate. Also, fines are very necessary for good cohesive mixes.
- Aggregate skeleton, Paste volume and composition needs to be optimized for medium resistance concrete to get better fresh properties of SCC.

CHAPTER 3

Material Testing Data

3.1 General

In INDIA, in the majority of the concrete mix, the coarse aggregates having a maximum size of aggregate (MSA) 20 mm and 10 mm are used in combination with fine aggregate having MSA 4.75 mm. In present study material used are 20 mm and 10 mm down coarse aggregate, 4.75 mm down fine aggregate, Portland Pozzolona Cement (PPC) and PCE based superplasticizer Master Glenium Sky BASF 8549. All materials taken are easily available locally. All important properties of these materials like specific gravity, water absorption, gradation, etc. are found and presented. Master Glenium SKY 8549 comply with all the requirements of IS: 9103:1999 [38]. PPC cement taken satisfies all the requirements of IS: 1489-2015 [39]. The test certificate of the Portland pozzolona cement taken in this research is provided by the manufacturer. The fly ash percentage in cement is 32.60%. Sieve analysis of fine and coarse aggregate is performed as per the requirement of IS: 383-2016 [40] and IS 2386-2002 (Part-1) [41]. TABLE 3.3, TABLE 3.4 and TABLE 3.5 shows the sieve analysis results of the coarse and fine aggregate taken in this study. Specific gravity and water absorption tests are performed as per the requirement of IS: 2386-2002 (Part-III) [42] and the results are presented in TABLE 3.1 and TABLE 3.2.

Master Glenium SKY 8549 is an advanced super plasticizer of a latest age group based on modified PCE, has a diverse chemical arrangement from the conventional super plasticizers. The side chains of this PCE are long, due to which cement particles achieve more stability and able to disperse with more capacity comparing to conventional admixture. This advance admixture release more water and therefore superior flowability is obtained with least water content. Fine aggregate used in this study falls in Zone-II. The result of Sieve analysis of fine and coarse aggregate satisfies the given codal guidelines.

3.2 Specific Gravity and Water Absorption

Specific gravity and water absorption tests are performed as per the requirement of IS:2386-1963 (Part-III) [42].

TABLE 3.1 Specific gravity and Water Absorption of Aggregate

Sr. No	Weight	Fine Aggregate (Sand)	Coarse Aggregate (20 mm)	Coarse Aggregate (10 mm)
1	wt. of bottle + sample + water (A) (g)	1833	1742	1860
2	wt. of bottle + water (B) (g)	1533	430	1531
3	wt. of surface saturated sample in water (C)	485	2011	503
4	wt. of oven dried sample (D) (g)	476	1996	497
5	Bulk Specific Gravity [D/ (C-(A-B))]	2.57	2.86	2.86
6	Water Absorption [((C-D)/ D)x100] (%)	1.89	1.11	1.41

TABLE 3.2 Specific gravity and Water Absorption of all materials

Material	Specific Gravity	Water Absorption
Cement	2.9	-----
Coarse Aggregate (20 mm)	2.86	1.11
Coarse Aggregate (10 mm)	2.86	1.41
Fine Aggregate	2.57	1.89
PCE based Super Plasticizer Master Glenium Sky 8549	1.1	-----

FIGURE 3.1 **Specific Gravity and Water Absorption of Aggregate**

3.3 Sieve Analysis

Sieve analysis is performed as per the requirement of IS: 383-2016 [40] and IS 2386-2002 (Part-1) [41]. Both coarse and fine aggregate satisfies the requirements of the codes.

TABLE 3.3 Sieve Analysis of 20 mm Aggregate

Sr. No.	IS. Sieve Size	Weight Retained			Passing Weight (%)	Required Passing weight as Per IS. Specifications (%)
		Weight (g)	Weight (%).	Cumulative Weight (%)		
1	40	0	0	0	100	100%
2	20	150	7.50	7.50	92.50	85-100%
3	10	1570	78.50	86.00	14	0-20 %
4	4.75	280	14.00	100.00	0.00	0-5 %
5	Pan	0	0.00	100.00	0.00	NA

TABLE 3.4 Sieve Analysis of 10 mm Aggregate

Sr. No.	IS. Sieve Size	Weight Retained			Passing Weight (%)	Required Passing weight as Per IS. Specifications (%)
		Weight (g)	Weight (%).	Cumulative Weight (%)		
1	12.5	0	0	0	100	100%
2	10	190	9.50	9.50	90.50	85-100%
3	4.75	1680	84.00	93.50	6.50	0-20 %
4	2.36	110	5.50	99.00	1.	0-5 %
5	Pan	20	1.00	100.00	0.00	NA

TABLE 3.5 Sieve Analysis of Fine Aggregate

Sr. No.	IS. Sieve Size	Weight Retained			Passing Weight (%)	Required Passing weight for Zone-II as per IS-383 (%)	Required Passing weight for Zone-III as per IS-383 (%)
		Weight (g)	Weight (%).	Cumulative Weight (%)			
1	10	0	0	0.00	100	100	100
2	4.75	116	5.8	5.80	94.2	90 to100	90 to100
3	2.36	193	9.65	15.45	84.55	75 to 100	85 to 100
4	1.18	355	17.75	33.20	66.80	55 to 90	55 to 90
5	0.6	195.0	9.75	42.95	57.05	**35 to 59**	**60 to 79**
6	0.3	621	31.05	74.00	26	8 to 30	12 to 40
7	0.15	409	20.45	94.45	5.55	0 to 10	0 to 10
8	0.075	95.0	4.75	99.20	0.8	0 to 3	0 to 3
9	Pan	16.0	0.8	100.00			

3.4 Marsh Cone Test

Marsh Cone test [44-47] is performed to check the compatibility of admixture with the cement. Using this test it is also possible to determine the Optimum dosage of admixture (Super plasticizer) for given water-cement ratio. In the present study, marsh cone test set up used is shown in FIGURE 3.3**.** For Marsh cone test, cement paste is prepared by adding the water, initially w/c ratio was kept of 0.45, and dosage of admixture is increased step by step by percentage weight of cement. Time taken by Marsh cone apparatus to flow out 1000 cc of cement paste is calculated in seconds, which is termed as marsh cone time in seconds. The process is continued until the decrease in marsh cone time is observed, which reflects that now further addition of admixture dosage is not improving the flowability of cement slurry. So, the dosage at which saturation of cement paste is obtained is called optimal dosage. The similar test is repeated after time gap of 5 minute and 60 minute to recognize the slump withholding potential of the admixture. The optimal dosage of admixture found for various w/c ratio like 0.5, 0.45, 0.40 and 0.35 and the test results are shown in TABLE 3.6 and FIGURE 3.2**.**

TABLE 3.6 Optimum Dosage of Super plasticizer using Marsh Cone Test

Sr.No.	W/C Ratio	Optimum Dosage (%)
1	0.35	1.1
2	0.40	0.9
3	0.45	0.8
4	0.50	0.7

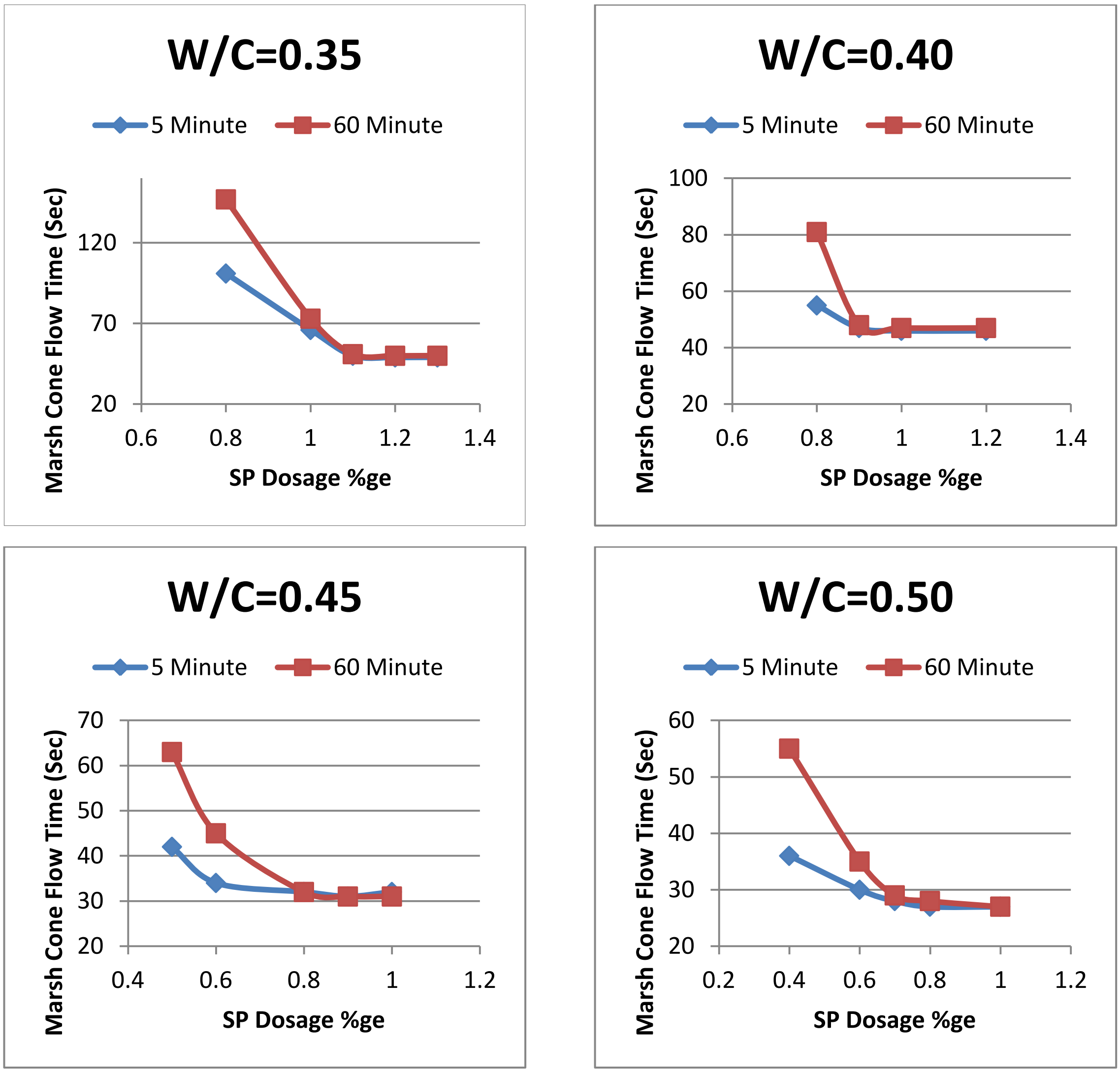


FIGURE 3.2 Optimum Admixture Dosage using Marsh Cone Test

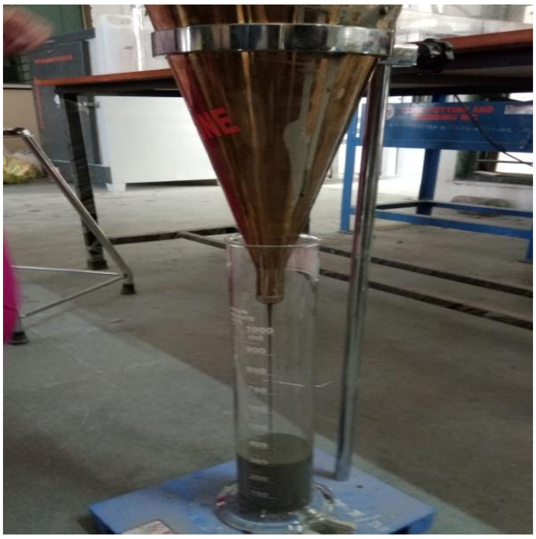


FIGURE 3.3 Marsh Cone Test

3.5 Bulk Density, Void Volume and Packing Density

Bulk density is calculated as per the procedure given in IS: 2386-2002 (Part-3) [42]. Bulk density, voids and packing density is calculated for fine aggregate, 10 mm coarse aggregate and 20 mm coarse aggregate and presented in TABLE 3.7. Also, to find the best combination of 10 mm and 20 mm coarse aggregate, which results in optimum packing density, packing density of different combination is investigated and presented in TABLE 3.8. Combination of 75% 20 mm coarse aggregate with 25% 10 mm coarse aggregate results in optimum packing density.

TABLE 3.7 Bulk Density, Volume of Voids and Packing Density of Coarse and fine Aggregate

Sr. No	Weight	Fine Aggregate (Sand)	Coarse Aggregate (10 mm)	Coarse Aggregate (20 mm)
	Specific Gravity	**2.57**	**2.86**	**2.86**
1	Wt. of container (w1) kg	6.8	6.8	6.8
2	Volume of container in m3 (v)	0.010474	0.010474	0.010474
3	Wt. of Container + Wt. of Compacted Aggr. (w3) (kg)	26.55	24.8	23.95
4	Dry Compacted Bulk density =(w3-w1)/v (kg/m^3)	1885.62	1718.54	1637.39
5	Voids as per SPGR based on DCBD=[(Gs-DCBD)/Gs]*100	26.63	39.91	42.75
6	Packing Density for DCBD	0.734	0.601	0.573

FIGURE 3.4 Bulk and Packing Density of Aggregate

TABLE 3.8 Bulk Density, Volume of Voids and Packing Density of Graded Coarse Aggregate

Sr. No	Weight (kg)	50%(20 mm) + 50%(10 mm)	60%(20 mm) + 40%(10 mm)	75%(20 mm) + 25%(10 mm)
1	Wt. of container (w1) kg	8.69	8.69	8.69
2	Wt. of Container + Wt. of compacted Aggr.(w2) kg	34.46	34.79	36
3	Volume of container in m3 (v) m3	0.015	0.015	0.015
4	Compacted Bulk Density = (w2-w1)/v	1718.00	1740.00	1820.67
5	Volume of Voids in Compacted State of Aggregate (%) =	39.93	39.16	36.34
6	Packing Density(DCBD)= (Bulk Density/(Specific Gravity*1000)	0.601	0.608	0.637

3.6 Procedure to find Specific gravity and packing density of blended coarse and fine aggregate:

As, aggregates of different specific gravities are blended together, it is important find the combined specific gravity of blended aggregate. To find combined specific gravity equation, the procedure is explained below for blend of fine and coarse aggregate.

The weight of the blended fine and coarse aggregate is given by

$$W_{blend} = W_{CA} + W_{FA}$$

Let the volume occupied by the individual particles of the blend is given by

$$V_{blend} = V_{CA} + V_{FA}$$

The weight and volume of the aggregate particles are related through specific gravity:

$$V_{aggr} = \frac{W_{aggr}}{G_s \cdot \gamma_w}$$

Let G_{CA}, G_{FA}, and G_{blend} be the specific gravities of materials CA and FA and the blend. Then the

volume equation above can be rewritten as

$$\frac{W_{blend}}{G_{blend} \cdot \gamma_w} = \frac{W_{CA}}{G_{CA} \cdot \gamma_w} + \frac{W_{FA}}{G_{FA} \cdot \gamma_w}$$

$$\frac{1}{G_{blend}} = \frac{{W_{CA}}/{W_{blend}}}{G_{CA}} + \frac{{W_{FA}}/{W_{blend}}}{G_{FA}}$$

$$\frac{1}{G_{blend}} = \frac{F_{CA}}{G_{CA}} + \frac{F_{FA}}{G_{FA}} \tag{3.1}$$

Let if F_{CA} and F_{FA} are the fraction of total blended aggregate. If F_{CA} and F_{FA} are 0.35 and 0.65 respectively and G_{CA} and G_{FA} are 2.86 and 2.57 respectively.

$$\frac{1}{G_{blend}} = \frac{0.35}{2.86} + \frac{0.65}{2.57}$$

$$G_{blend} = 2.664$$

The other formula can be derived as below

We know that $$\frac{W_{blend}}{G_{blend}.\gamma_w} = \frac{W_{CA}}{G_{CA}.\gamma_w} + \frac{W_{FA}}{G_{FA}.\gamma_w}$$

Let if P_{CA} and P_{FA} are the proportion of total blended aggregate for material CA and FA respectively and If F_{CA} and F_{FA} are 0.35 and 0.65 respectively and G_{CA} and G_{FA} are 2.86 and 2.57 respectively.

$$\frac{W_{blend}}{G_{blend}.} = \frac{P_{CA}.W_{blend}}{G_{CA}.} + \frac{P_{FA}W_{blend}}{G_{FA}.}$$

$$\frac{1}{G_{blend}.} = \frac{P_{CA}}{G_{CA}.} + \frac{P_{FA}}{G_{FA}.}$$

$$G_{blend} = \frac{1}{\frac{P_{CA}}{G_{CA}} + \frac{P_{FA}}{G_{FA}}}$$

$$\boldsymbol{G_{blend}} = \frac{\boldsymbol{P_{CA}+P_{FA}}}{\frac{\boldsymbol{P_{CA}}}{\boldsymbol{G_{CA}}} + \frac{\boldsymbol{P_{FA}}}{\boldsymbol{G_{FA}}}} \tag{3.2}$$

Taking same example as above

$$G_{blend} = \frac{0.35 + 0.65}{\frac{0.35}{2.86} + \frac{0.65}{2.57}}$$

$$G_{blend} = 2.664$$

Specific gravity for different blending of fine aggregate, 10 mm coarse aggregate and 20 mm coarse aggregate are presented in TABLE 3.9**.** As per the procedure given in IS:2386-2002 (Part-3) [42], experimental value of bulk density and voids are calculated using the specific gravity of blended aggregates. And, knowing the volume of voids, packing density of blended aggregates are calculated and presented in TABLE 3.9**.**

TABLE 3.9 Experimental Volume of voids and Packing Density of blended coarse and fine aggregate

Combination			Dry Compacted Bulk Density (kg/m^3)	Specific Gravity of Blended Aggregate	Volume of Voids (%)	Packing Density= 1-Vv
FA	10 mm	20 mm				
100:00:00			1885.62	2.57	26.63	0.734
00:100:00			1716	2.86	40	0.601
00:00:100			1638.78	2.86	42.7	0.573
65:00:35			2247.7	2.66	15.5	0.845
60:00:40			2237.8	2.68	16.5	0.835
55:00:45			2238.08	2.69	16.8	0.832
52:00:48			2214	2.70	18	0.820
60:10:30			2194.92	2.68	18.1	0.819
55:11:34			2181.59	2.69	18.9	0.811
52:12:36			2157.3	2.70	20.1	0.799
65:35:00			2098.74	2.66	21.1	0.791
60:40:00			2114.52	2.68	21.1	0.788
55:45:00			2108.96	2.69	21.6	0.778
52:48:00			2081.7	2.70	22.9	0.771
48:52:00			2062.31	2.71	23.9	0.761

3.7 Major Conclusions from the Chapter

Following conclusions are derived based on data obtained from testing materials used in this study.

- 75% 20 mm coarse aggregate in combination with 25% 10 mm coarse aggregate gives maximum experimental packing density equal to 0.637.
- Comparing to any combination of 10mm CA with FA, 65% fine aggregate in combination with 20 mm coarse aggregate results in maximum experimental packing density equal to 0.845.

CHAPTER 4

Development of Particle Packing Theory& Model

4.1 General

While finding out the packing density of the aggregate i.e. fine aggregate (sand), 10 mm aggregate and 20 mm aggregate and their combination, some interesting observations were found.

1. The packing density of individual aggregate that of sand, 10 mm and 20 mm is 0.734, 0.601 and 0.573 respectively.
2. Combination of fine aggregate with 20mm aggregate gives more packing density than its combination with 10 mm.
3. For a combination of 65% sand with 35% of 20 mm aggregate gives maximum packing density and packing density for this combination was 0.845. And for the same combination of sand with 10 mm aggregate i.e 65% sand and 35% 10 mm aggregate packing density is 0.789

Also packing density for other combination is

Proportion of FA & CA	Packing Density	
	With 20 mm CA	With 10 mm CA
65:35	0.845	0.791
60:40	0.835	0.788
55:45	0.832	0.778
52:48	0.820	0.771

Looking at the above results of packing density it was quite clear that packing density depends on the gradation of individual aggregate and also on the number of particles passing from various sieves.

To select the fine and coarse aggregate proportion that results in optimal packing density or least voids, can be done in different ways. One of the ways is that the PSD curve of the aggregates follows an ideal curve as given by continuous models. The other way is to use discrete empirical models. In this study a new discrete approach is attempted as below.

4.2 Properties of Aggregates needed for Particle packing theory and Model

The major ingredient in concrete manufacturing is coarse and fine aggregates, which occupy almost 70% of the total volume. To produce concrete, coarse size aggregates are blended with finer size aggregate to fill the voids and to achieve maximum packing. The coarse and fine aggregates used in concrete production do not have mono size particles; instead, they have different size of particles in different proportions.

In INDIA, in the majority of the concrete mix, the coarse aggregates having a maximum size of aggregate (MSA) 20 mm and 10 mm are used in combination with fine aggregate having MSA 4.75 mm. Particles having different sizes and proportions may have different packing phenomena like single component, binary and ternary packing etc. So it is very difficult to predict the packing density of blended aggregate as the interaction between particles is very complex. In the proposed packing model, packing density is predicted for a different amount of blending of coarse and fine aggregates by analyzing this complex particle packing phenomena.

To find the packing density using the proposed model, the main properties of the materials required are gradation and voids of coarse and fine aggregates**.** TABLE 4.1 and TABLE 4.2 summaries these properties of coarse and fine aggregate taken in this study.

TABLE 4.1 Sieve Analysis of Coarse and Fine Aggregate

Sr. No.	Sieve Size	Passing Percentage through Sieve		
		Fine Aggregate	Coarse Aggregate 10 mm MSA	Coarse Aggregate 20 mm MSA
1	40	-	-	100
2	20	-	-	92.50
3	12.5	-	100	-
4	10	100	90.50	14
5	4.75	94.2	6.50	0
6	2.36	84.55	1	-
7	1.18	66.80	-	-
8	0.6	57.05	-	-
9	0.3	26	-	-
10	0.15	5.55	-	-
11	0.075	0.8	-	-
12	Pan	-	-	-

TABLE 4.2 Bulk density and voids of aggregate

Material	Bulk Density (kg/m3)	Voids (%)	Packing Density=(100-Voids)/100
Coarse Aggregate (20 mm)	1637.39	42.75	0.573
Coarse Aggregate (10 mm)	1718.54	39.91	0.601
Fine Aggregate	1885.62	26.63	0.734

4.2.1 Fundamentals of Model

For high-density multi-component packing, at least a sevenfold difference between sizes of individual component is required [16-17]. To verify this, an AutoCAD drawing is drawn as shown in FIGURE 4.1, the densest packing is possible when three particles are close to each other, and finer particle occupies the voids in between.

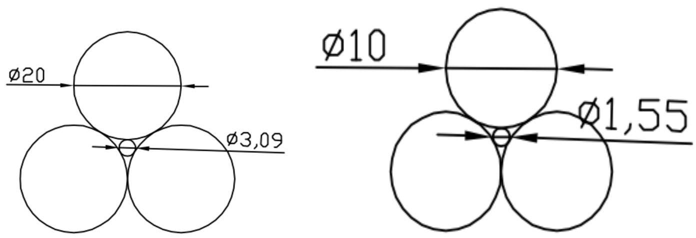


FIGURE 4.1 AutoCAD drawing showing void size between 20 mm and 10 mm MSA

It can be seen in FIGURE 4.1, that between closely packed 20 mm and 10 mm size particles, it is possible to fit particles of size 3.09 mm and 1.55 mm respectively, which is nearly 1/7 size of respective aggregate size. Actual packing of particles is three dimensional, and it is proved in past research [16,17] that the void size between the closely spaced spherical particles is nearly 1/7 of size of particle. So, size of void remain constant about 1/7 of size of particle for any size of particle.

Here, the packing concept of spherical particles is extended for angular aggregates [17]. For angular aggregates particle interaction in form of wall effect and loosening effect affects the packing density [12-14, 15, 17]. But, as discussed in literature review chapter, wall effect can be neglected if container diameter is 10 times the diameter of the particle [12-14, 17]. Also, interaction effect is very less when particles are optimally packed [12-14]. In the proposed particle packing model, the interaction effect is taken care by using initial voids of coarse aggregate that are found experimentally. The packing density of mono size spherical particles is 0.625 [16-17], so mono size spherical particles when closely packed have 37.5% voids. As shown in TABLE 4.2, experimental packing densities of angular coarse aggregates taken in this study are 0.601 and 0.573 for 10 mm MSA and 20 mm MSA respectively, so voids present in these aggregates are 40% and 42.7% respectively. Due to interaction effect, voids in angular aggregates are more than the spherical aggregates. In the proposed model, these experimental voids in the angular coarse aggregates are used to calculate packing density, hence partially interaction effect is considered and therefore, in proposed particle packing model, interaction effect is not considered separately in the calculation of packing density.

The present particle packing model is based on two parameters.

1. Available finer size of particles which fits into voids of coarser size particles.
2. Volume fraction required for packing particles

To explain the effect of different coarse aggregate sizes on packing density, 20 mm and 10 mm coarse aggregates are blended with fine aggregates separately. TABLE 4.3 shows the particle size and volume required for ternary, binary and single component (Mono Size) packing of rounded aggregates.

TABLE 4.3 Volume and size of particles required for single component, binary and ternary packing for rounded aggregate [16-17]

Packing of blended aggregate	**Aggregate Volume and Size required for packing**				**Theoretical Packing Density**
	Description of Volume and Size of Particle	**Particle P_1**	**Particle P_2**	**Particle 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	
	Required size of particles for ternary packing in 20 mm MSA Gradation	20 mm	<2.86 mm	< 0.260 mm	
	Required size of particles for ternary packing in 10 mm MSA Gradation	10 mm	< 1.43 mm	< 0.200 mm	
Binary Packing	Volume (%)	72.7%	27.3%	---	0.859
	Size Ratio (P1:P2:P3) (1:7:0)	1	< 1/7 of P_1	---	
	Aggregate sizes required 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	---	
Single Component	Volume (%)	100%	---	---	0.625
	Size Ratio (P1:P2:P3) (1:0:0)	1	---	---	

Note: P1, P2 and P3 are particles required for packing in descending order of their size.

Depending on the sizes of particles available in gradation test as shown in TABLE 4.1, in 20 mm MSA two ternary packing of particles in size ratio of 1:7:77 is possible i.e. (I) 20 mm: 2.86 mm: 0.260 mm and (II) 10 mm: 1.43 mm: 0.130 mm. For first ternary packing, in voids of 20 mm particle, particles smaller than 2.86 mm will occupy the space and further smaller voids will be filled up by particles of size 0.260 mm and less. Similarly, when 10 mm MSA are blended with fine aggregate, one ternary packing is possible i.e. (I) 10 mm: 1.43 mm: 0.130 mm. For ternary packed particles packing density achieved is 94.7%.

After ternary packing, remaining particles will be binary packed depending on available sizes. For binary packing available particle sizes in size ratio of 1:7 are (i) 20 mm: 2.86 mm (ii) 10 mm: 1.43 mm (iii) 4.75 mm: 0.680 mm (iv) 2.36 mm: 0.340 mm and (v) 1.18 mm: 0.170 mm. For binary packing, the corresponding volume of particle required is 72.7 %, 27.3% respectively. For binary packed particles packing density achieved is 85.9%.

The particles, which are neither ternary nor binary packed, will remain unpacked, i.e. remain single component. Such single component particles have a maximum packing density of 62.5%.

To achieve maximum packing density, one should balance the proportion of different sizes and different volumes of aggregate. This can be done by varying the proportion of the coarse and fine aggregates in total aggregate.

Using the packing concept explained above, how probable ternary, binary and single component packing takes place in blended coarse and fine aggregate is explained logically in TABLE 4.4, TABLE 4.5 and TABLE 4.6 for 20 mm MSA and in TABLE 4.7, TABLE 4.8 and TABLE 4.9 for10 mm MSA separately. For explanation purpose packing density of 35% CA blended with 65% FA is shown.

4.2.2 Analytical Packing Density Calculation using proposed approach for 20 mm MSA blended with fine aggregate (FA)

TABLE 4.4 shows combined gradation result for 65% FA blended with 35% CA of 20 mm size.

TABLE 4.4 Combined Gradation and particle availability for 20 mm MSA (35%) blended with FA (65%)

Sieve Size (mm) (1)	Passing of particles (%) (2)	Available Size range of Particles (mm) (3)	Particle retained between two consecutive sieves (%) (4)	Size of voids between particles of column 3 (mm) (5)	Available volume of particles for filling voids (%) (6)
20	97.38	20-10	30.10	2.36-1.18	11.54
10	69.90	10-4.75	8.67	1.18-0.6	6.34
4.75	61.23	4.75-2.36	6.27	0.6-0.3	20.18
2.36	54.96	2.36-1.18	11.54	0.3-0.15	13.29
1.18	43.42	1.18-0.6	6.34	0.15-0.075	3.09
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		
0.075	0.52		0.52		

The percentage of aggregate retained between two sieves is calculated in column 4 of TABLE 4.4. In column 6 of TABLE 4.4, the volume of particles available for filling voids between coarser particles is calculated. E.g. between 20 mm and 10 mm sieve, available particles are 30.10%. The size of the void between 20 mm is 1/7th means 2.86 mm, and in 10 mm sieve is 1.43 mm. So between voids of 20 mm – 10 mm particles, the particles of size 2.36 mm – 1.18 mm will fit easily. The amount of 2.36 mm – 1.18 mm particle is 11.54%. A similar calculation is given for other range of particle. Green and yellow colours in TABLE 4.4 show the particle sizes available for ternary packing.

4.2.2.1 Ternary packing of blended aggregate

TABLE 4.5 shows the calculation of ternary packed particles. In the first possible ternary packing between voids of 10-4.75 mm particles, 1.18-0.6 mm particles will fit, and in further smaller voids, 0.15-0.075 mm particles will occupy the space. As shown in column 4, the volume of 10-4.75 mm particles is 8.67% and volume of their voids is 3.70%, which are filled by 1.18-0.6 mm particles, and further smaller voids will be filled by 0.15-0.075 mm particles having volume 1.58%. So, a total of ternary packed particles will be 13.95%. The excess particles remained after filling voids are shown in column 5. Similarly, for second Ternary packing, ternary packed particles are 45.31%. Therefore, total ternary packed particles for 65% FA blended with 35% 20 mm CA, will be 59.26%.The theoretical volume of particles required for ternary packing is 66%, 24.7% and 9.3% respectively, and the packing density achieved is 0.947**.** Here as 42.7%, voids are considered between angular aggregates, the volume of particles for ternary packing comes to 62.1%, 26.5% and 11.3% respectively (column 6), which is near to the theoretical value as shown in TABLE 4.3. The theoretical values are for 37.5% voids and volume fractions of particles for ternary packing are 66%, 24.7% and 9.3%.

TABLE 4.5 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 4.4)	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 4.4)	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 %**		

4.2.2.2 Binary and Single Component packing of blended aggregate

TABLE 4.6 shows the binary and single component (mono size) packing of particles. After achieving ternary packing, remaining particles were binary packed, and after achieving binary packing remaining particles are unpacked (single component). E.g. as shown in TABLE 4.4, 4.75-2.36 mm particles are 6.27% in total aggregate, and these particles are not utilized in ternary packing. The particles which will fit in the voids between these particles are 0.6-0.3 mm. Now considering 42.7% voids between 6.27% particles, the required 0.6-0.3 mm size particles to fill the voids are 2.68%. Remaining 0.6-0.3 mm particles will be unpacked (Single component). So binary packed particles for this range of particle is 8.95%. As per theory [16-17], the volume of particles required for binary packing is 72.7% and 27.3% and packing density achieved is 0.859. As per the model volume of the binary packed particle are 71.4% and 28.6%, which is near to the theoretical value. The total volume of binary packed and single-component particles is 12.71% and 28.03% respectively.

TABLE 4.6 Binary and single component packing of particles for 20 mm MSA (35%) blended with FA (65%)

Size Range of particle (%)	Particle left after ternary packing (%)	42.7% Voids	Particle range available for void filling (mm)	Available particle for packing (%)	Used Particle for packing (%)	Binary packed particles (%)	Volume of coarser particle (%)	Volume of finer particle (%)	Unpacked (Single Component) Particle (%)
20-10	1.26	0.54	2.36-1.18	0.00	0.00	0.00			1.26
10-4.75	0.00	0.00	1.18-0.6	2.64	0.00	0.00			0.00
4.75-2.36	6.27	2.68	0.6-0.3	20.18	2.68	8.95	**70.1%**	**29.9%**	-2.68
2.36-1.18	0.00	0.00	0.30-0.15	8.37	0.00	0.00			0.00
1.18-0.6	2.64	1.13	0.15-0.075	1.51	1.13	3.76	**70.1%**	**29.9%**	-1.13
0.6-0.3	20.18	----	----	0.00	0.00	0.00			20.18
0.3-0.15	8.37	----	----	0.00	0.00	0.00			8.37
0.15-0.075	1.51	----	----	0.00	0.00	0.00			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

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

Similar calculation of packing density is shown in TABLE 4.7, TABLE 4.8 and TABLE 4.9 for 10 mm size 35% coarse aggregate blended with 65% fine aggregate.

4.2.3 Packing Density Calculation for 10 mm MSA blended with FA

TABLE 4.7 Gradation Calculation for 10 mm MSA (35%) blended with FA (65%)

Sieve Size (mm) (1)	Passing of particles (%) (2)	Available Size range of Particles (mm) (3)	Particle retained between two consecutive sieves (%) (4)	Size of voids between particles of column 3 (mm) (5)	Available volume of particles for filling voids (%) (6)
20	100.00	20-10	3.33	2.36-1.18	11.89
10	96.68	10-4.75	33.17	1.18-0.6	6.34
4.75	63.51	4.75-2.36	8.20	0.6-0.3	20.18
2.36	55.31	2.36-1.18	11.89	0.3-0.15	13.29
1.18	43.42	1.18-0.6	6.34	0.15-0.075	3.09
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		
0.075	0.52		0.52		

TABLE 4.8 Ternary packing of particles for 10 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	10-4.75	33.17	13.27	15.84	17.33	**64.1%**
	1.18-0.6	6.34	2.54	6.34	0.00	**25.6%**
	0.15-0.075	3.09	----	2.54	0.55	**10.3%**
	Total	42.60		**24.72**	17.88	100%
Ternary Packing 2	20-10	3.32	1.33	3.33	0.00	**64.1%**
	2.36-1.18	11.89	0.53	1.33	10.56	**25.6%**
	0.30-0.15	13.29	----	0.53	12.76	**10.3%**
	Total	28.50		**5.19**	23.32	100%
Total Ternary Packed Particles=				24.72+5.19= 29.91		

TABLE 4.9 Binary and single component packing of particles for 10 mm MSA (35%) blended with FA (65%)

Size Range of particle (%)	**Particle left after ternary packing (%)**	**42.7% Voids**	**Particle range available for void filling (mm)**	**Available particle for packing (%)**	**Used Particle for packing (%)**	**Binary packed particles (%)**	**Volume of coarser particle (%)**	**Volume of finer particle (%)**	**Unpacked (Single Component) Particle (%)**
20-10	0.00	0.00	2.36-1.18	10.56	0.00	0.00			0.00
10-4.75	17.33	6.93	1.18-0.6	0.00	6.93	0.00			17.33
4.75-2.36	8.20	3.28	0.6-0.3	20.18	3.28	11.48	**0.714**	**0.286**	-3.28
2.36-1.18	10.56	4.22	0.30-0.15	12.76	4.22	14.78	**0.714**	**0.286**	-4.22
1.18-0.6	0.00	0.00	0.15-0.075	0.55	0.00	0.00			0.00
0.6-0.3	20.18	----	----	0.00	0.00	0.00			20.18
0.3-0.15	12.76	----	----	0	0.00	0.00			12.76
0.15-0.075	0.55	----	----	0	0.00	0.00			0.55
0.075-Pan	0.52								0.52
Total	**69.58**					**26.26**			**43.84**

Total Ternary packed particle.	29.90
Total Binary packed particle	26.26
Total Unpacked particle	43.84
Total	100.00

Packing Density = 0.784

4.2.4 Experimental Packing Density calculation to verify Analytical packing density calculated using proposed model

FIGURE 4.2 Test procedures to calculate experimental packing density

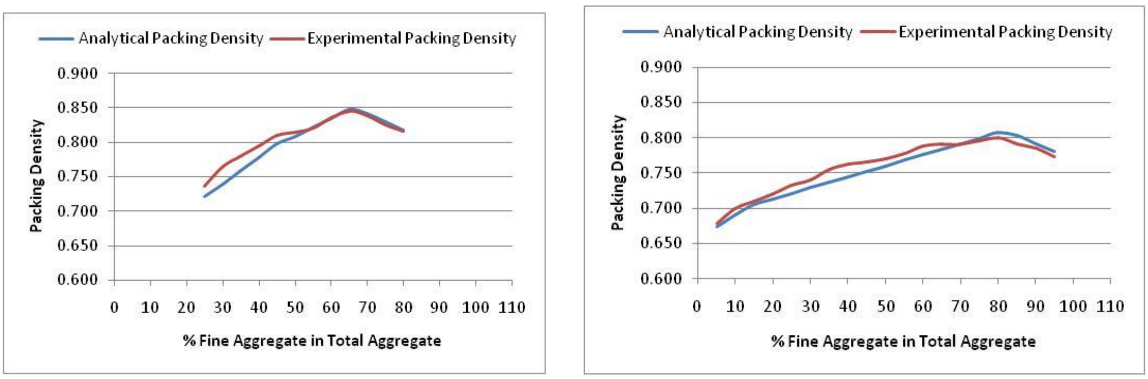
As shown in FIGURE 4.2, experimental packing density is found using cylindrical container in accordance with ASTM C29 [43] and IS; 2386-2002 (Part-III) [42]; the only change is the way of compaction. Coarse and fine aggregate is first to be dry mixed in the required proportion. Then these blended aggregates are poured into a cylinder of known volume in three layers. The filled cylinder is then compacted on table vibrator. The bulk density of the blended aggregate is measured. At last, based on bulk density, packing density (PD) is measured. This process is repeated three times, and the average value is considered as the packing density of blended aggregate.

R.McGeary [16] reported that mechanical vibration is the best way of compaction for blended particles of different sizes so that fine particles can enter into the voids of coarser particles and maximum compaction can be achieved. When compacted packing density of aggregate is found using mechanical vibration, the amount of compacting effort will remain same and same value of PD will be achieved at any place, on the contrary, if loose PD is found, PD varies with amount of compacting effort and the way it is found. In compacted packing density achieved by mechanical vibration, the value of PD will remain almost the same for same aggregate for any variation of laboratory conditions. Mix design of SCC based on compacted PD is more easy and universal as the amount of paste required to fill the voids can exactly be found and free paste required for flow can be estimated. TABLE 4.10, shows the comparison of analytical packing density calculated using the proposed model and experimental packing density. It can be seen that the proposed model is very effective in estimating the packing density of blended aggregate.

TABLE 4.10 Comparison of Analytical Packing density calculated through model and Experimental Packing Density

Combination of Aggregate	Analytical Packing Density	Experimental Packing Density	Error (%)
35% 20 mm CA + 65% FA	0.847	0.845	0.292
35% 10 mm CA + 65% FA	0.784	0.791	0.899

In FIGURE 4.3 graph is plotted by increasing fine aggregate content in total aggregate at an interval of 5% and, for each 5% increase of fine aggregate, packing density is calculated analytically using the proposed model and experimentally too. The packing density is calculated for both 20 mm and 10 mm MSA blended with fine aggregate. As shown in figure analytical packing density calculated using proposed model matches with the experimental packing density.



(a) 20 mm MSA blended with FA **(b) 10 mm MSA blended with FA**

FIGURE 4.3 Comparison of Experimental and Analytical packing density

4.3 Discussion on Particle Packing Model

As shown in TABLE 4.11 from packing pattern of 20 mm and 10 mm particles, it is seen that when 20 mm aggregate is used, ternary packed particles are more and unpacked particles are less compared to 10 mm particles. Due to higher packing density, 6% less voids are generated when 20 mm MSA is used.

TABLE 4.11 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	Unpacked 10-4.75 (%)	0.00	17.33	-17.33
5	Voids (%)	15.5%	21.6%	6.1%

Also, out of all unpacked particles, 10-4.75 mm particles (Yellow colour in TABLE 4.9) are more when 10 mm MSA are blended with fine aggregate comparing to 20 mm. All other unpacked particles are similar in both 20 mm MSA and 10 mm MSA. So 10-4.75 mm particles are responsible for lesser packing density in 10 mm MSA.

After close analysis of particle packing phenomenon, it can be concluded that for higher packing one should set size and volume of blended coarse and fine aggregate such that ternary packed particles are maximized and unpacked (Single Component) particles are minimized.

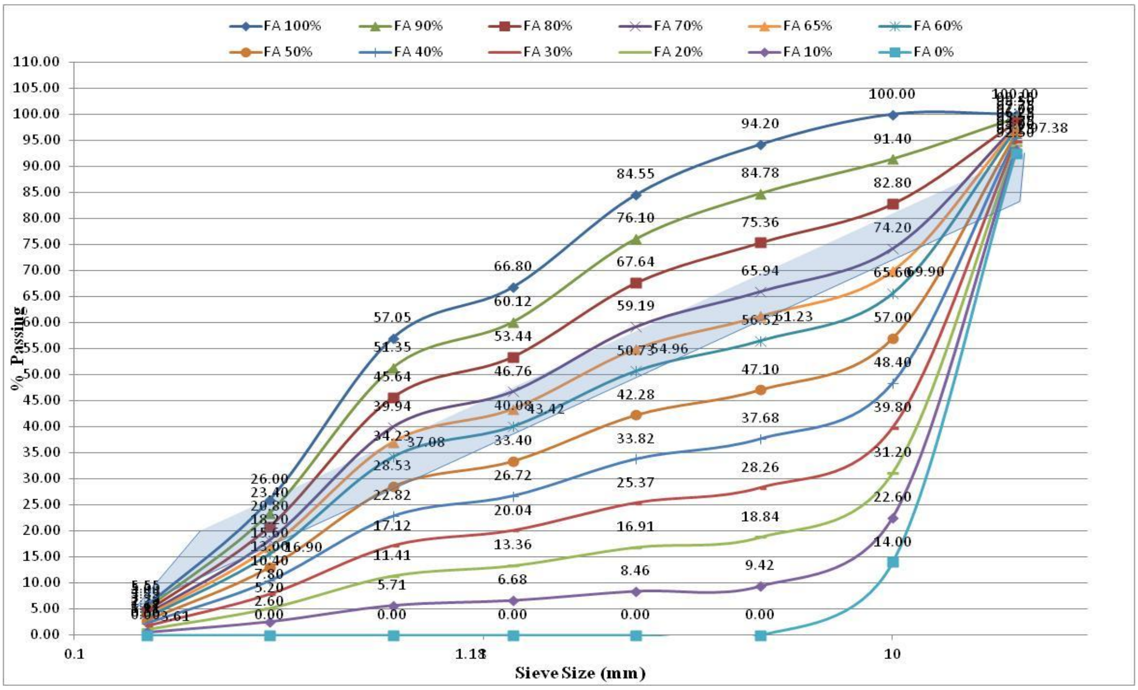


FIGURE 4.4 Gradation Curve for blended coarse and fine aggregate

FIGURE 4.4, shows the gradation curve for the 20 mm MSA blended with fine aggregate by increasing fine aggregate content at an interval of 10 % in total aggregate. The shaded portion shows the gradation curve for the combination of coarse and fine aggregate having optimum packing density.

In TABLE 4.12, the gradation range of combined coarse and fine aggregate is suggested for optimum packing density using the proposed particle packing model. The size and volume of particles are balanced in such a way that maximum packing density can be achieved by maximizing ternary and binary packing and minimizing unpacked (single Component) particles. The combined gradation of aggregates shown in TABLE 4.12 can be adopted after taking a trial mix of concrete at site, and necessary changes should be made for good cohesive concrete mix.

TABLE 4.12 Suggested combined gradation for optimum packing density based on the model

Suggested gradation for SCC			
Sieve	**Percentage passing**	**Range of sieve**	**Percentage 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

Steps involved in Particle packing model can be summarized as below. Proposed particle packing needs programming in Microsoft Excel, to perform the stepwise procedure.

1. Find voids and packing density of individual coarse and fine aggregate experimentally. These voids are taken in particle packing model for void calculation of aggregates.
2. Perform gradation of coarse and fine aggregate individually.
3. Insert the gradation in Microsoft Excel sheet. Combine the coarse and fine aggregates in different proportion based on the available size and volume of particles on different sieves, so that combined gradation of fine and coarse aggregates follows guideline given in TABLE 4.12.
4. Try to maximize ternary and binary packed particles and minimize unpacked particle through the calculation in Microsoft Excel.
5. Calculate packing density using the model, using programming in Microsoft Excel.

4.4 Comparison of results of proposed particle packing model with existing models

In FIGURE 4.5, grading curves for continuous particle packing approach given by Fuller 3], Andreasen and Andersen [4] and Funk and Dinger [5] are depicted. Also, grading curves for discrete particle packing approach given by Toufar [11] and De Larrard [12-14] is graphically depicted based on the sieving data of the aggregates given by KL Radhika et.al. [18].

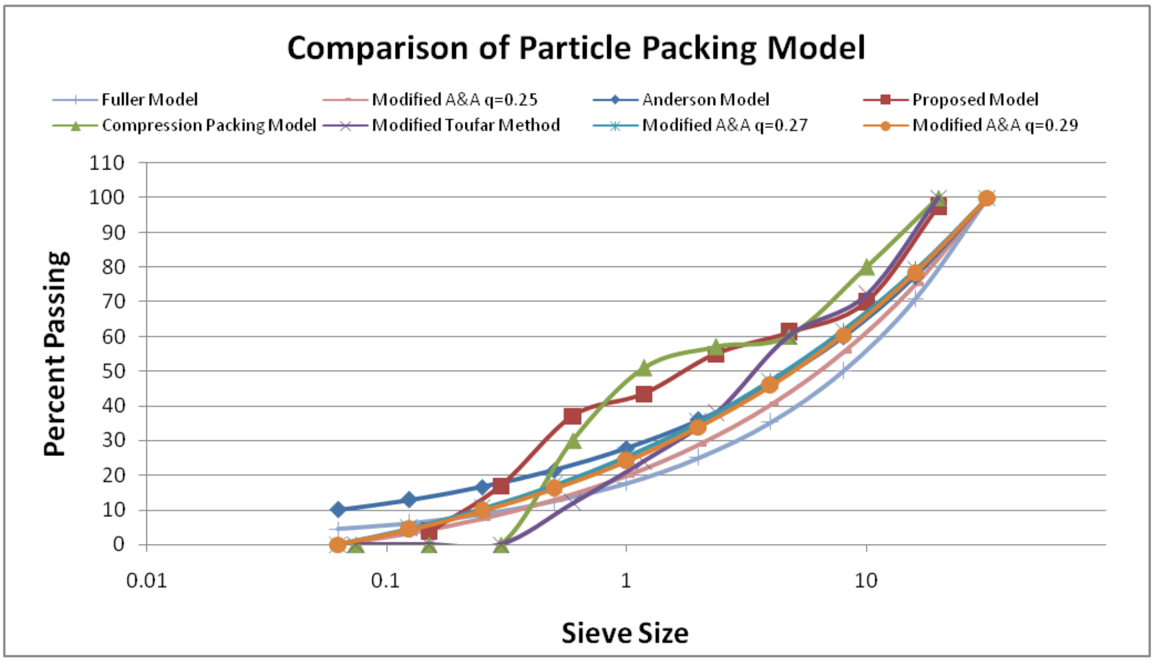


FIGURE 4.5 Comparison of proposed Particle packing model with other models

These grading curves of the other models are compared with the grading curve drawn for optimum packing obtained using the proposed model in FIGURE 4.5. It can be seen that gradation by the proposed model is having more fine particles comparing to other models. The particle size distribution obtained through present particle packing model closely matches with compression packing model for particle size 0.6-20 mm and with modified A&A model having distribution modulus 0.29 for particle size smaller than 0.6 mm. Comparing to the compression packing model, the proposed approach is very simple and easy to adopt at the site.

The gradation data given by KL Radhika [18] for optimum packing density of compression packing model and modified Toufar model are used in the proposed model and packing density is found. In Table 4.13 packing density obtained using proposed model is compared with that given by KL Radhika [18] for MTM and CPM. It is not possible to find packing densities of continuous models quantitatively, as it assumes infinite number of particles with aggregate sizes not matching with the sizes of aggregate taken in study.

Optimal packing density obtained by proposed model is varies by about 3.5% then the packing density achieved by other models. As discussed in literature [12], modified Toufar model is for binary mixtures and it under estimates the packing density for multi-component mixtures. Similarly de Larrard [12-14] has mentioned that virtual packing density by CPM over estimates the packing density, and same results are observed here comparing to proposed particle model.

Table 4.13 Comparison of packing density achieved by proposed model based on data [18] of other models

Particle packing model	Optimum Packing Density	PD using Proposed Model	Error (%)
Modified Toufar model	0.807	0.834	3.34
Compression packing model	0.872	0.841	3.55

The proposed model adds many advantages as given below over the existing models in terms of ease, logic, accuracy etc.

1. In the proposed particle packing model, the packing phenomenon of the multi-component mix is explained fundamentally.
2. The model can universally be adopted for any size of the aggregate because it works on the size and amount of voids actually present in blended aggregate.
3. The present model does not involve any complex mathematical calculations.
4. Using the proposed particle packing model experimental efforts to find optimum packing density can be eliminated. The new particle packing model is very simple and easy to use. Using this model one can predict the packing density analytically for the different blending of coarse and fine aggregate.
5. Gradation range of blended fine and coarse aggregate suitable for producing economical self-compacting concrete is given using the proposed model.
6. Using particle packing approach economical SCC mixes are produced with minimum trial mixes. SCC mixes are produced using almost the same cementitious materials which are required for conventional concrete mixes. This leads to Sustainable SCC.

4.5 Assumptions of the Proposed Model

- For the present model, the theory of packing of spherical particles is extended for angular particles.
- The proposed model is empirical and needs iterations to arrive at the optimum packing density of blended coarse and fine aggregate. But, as a model can be easily

programmed in Excel these analytical iterations can easily be done. Also, the guideline is given for gradation of blended aggregate, which can be followed to reduce iterations.

- The proposed model is applicable for fully compacted aggregate. The proposed model assumes that when aggregates are compacted through mechanical vibration, optimum packing is attained by the aggregates.
- The particle packing approach may generally be more useful for concrete having more amount of aggregate volume. If the aggregate volume is decreased and paste volume is increased, the effect of particle packing will be less significant on fresh and hardened properties of SCC. So, this particle packing model is more useful for concrete compressive strength up to 35 N/mm2, i.e. concrete in which aggregate volume is around 60% to 70%.
- When the present model is applied to produce SCC, it is assumed that voids between aggregates will completely be filled by the paste, and free paste will help to improve the rheological properties of SCC.

4.6 Major Conclusions from the chapter

- It is possible to find the optimum packing density by adjusting volume and size of different fractions obtained from the sieve analysis of fine and coarse aggregate.
- Therefore, in Indian perspective to produce economical SCC mix with compressive strength up to 35 N/mm^2 and having more slump flow with less cementitious material, it is recommended to use 20 mm MSA due to more packing density comparing to 10 mm MSA.
- The interaction effect on particle packing is taken care by considering experimental voids of maximum size of coarse aggregate as voids to be filled by finer particles. The size and volume of fine particle are adjusted such a way that maximum voids of coarse aggregate are filled by ternary packing. The efficiency of the proposed model is verified by comparing with the experimental packing densities for various combinations of fine and coarse aggregate and also by comparing the packing density found using other models with the results of packing density calculated using proposed model.
- The gradation range of blended coarse and fine aggregate for optimum packing density found using proposed particle packing model closely matches with the gradation range given by KL Radhika [18].

CHAPTER 5

Experimental Program and Result Analysis

5.1 General

The experimental program is prepared to develop the economical SCC mix having compressive strength up to 20-35 N/mm^2 using locally available material. In present research, coarse aggregate (20 mm and 10 mm), fine aggregate, Portland pozzolona cement (PPC), PCE based admixture (BASF 8549) are used to manufacture SCC mix.

To make SCC mix design as simple as conventional concrete mix, locally available materials are used which can easily be procured. As a chemical admixture, only PCE based superplasticizer is used. As fly ash is considered necessary for the production of SCC, due to its rounded particle shape, which improves the fresh properties, Portland pozzolona cement (PPC) is used having 32.6% fly ash content. No other chemical or mineral admixture like air-entraining agent (AEA), viscosity modifying agent (VMA), silica fume, GGBFS etc are used to keep mix design as simple as conventional concrete mix design.

To verify the rheological properties of SCC like flowability, passing ability, and segregation resistance, the tests like Slump flow, T500 time, V funnel, L Box and Sieve segregation are carried out following the EFNARC guidelines [27]. As per IS:456-2000 [36] , tensile and flexure strength has definite relationship with compressive strength for conventional concrete. In present study same materials are used like conventional concrete, therefore only cube compressive strength test is performed to find mechanical properties of hardened concrete as per the guidelines given in IS: 516 [48].

The experimental program is prepared to find out the effect of various parameters on the mix design of self-compacting concrete. An experimental program for SCC mix design is divided into two-phase (1) Aggregate Phase and (2) Paste Phase.

1. **Aggregate Phase:** In aggregate phase experimental program is prepared to check the effect of parameters like the maximum size of aggregate, aggregate packing i.e. packing density, fines in sand and effect of paste composition for same aggregate volume. To check the aggregate effect, only aggregate proportions are changed, while all other material proportion kept constant

2. **Paste Phase:** Paste includes Cement, water, admixture and air. So, in paste phase SCC mixes are casted by varying cement content, water-cement ratio, and admixture dosage to verify their effect on concrete mix for target compressive strength of 20-35 Mpa.

5.2 Design Mixes for Aggregate Phase

It is already mentioned that present research is aimed to study low to medium resistance concrete (20-35 Mpa). Such concrete contains high volume of aggregates; therefore Granular skeleton has significant effect on fresh properties of SCC. Therefore, in this phase, effect of various fine and coarse aggregates related properties like maximum size of aggregate, packing density and sand fines are studied. For this purpose in all mixes paste volume and composition is kept same. The aggregate volume is also kept same but their size and blending proportions are changed.

5.2.1 Calculation and test matrix of design mixes for Aggregate phase

For medium resistance concrete, aggregate volume in conventional concrete is around 60-70%. So, paste volume is in the range of 30-40%. Therefore, in aggregate phase to keep paste volume between 30-40%, for initial casting SCC mixes are prepared using 400 kg/m^3 of cement. Once guideline of mix design will be prepared, the cementitious material can be chosen based on target strength and targeted fresh properties. Here, for all mixes, water to the cementitious material ratio (w/c) is kept constant and is taken 0.5. Also, PPC cement 400 kg/m^3 is taken for all mixes and therefore water is taken 200 litre/m^3. SP dosage is kept constant at 0.8% of cement weight, so it comes 3.2 kg/m3. Considering 2% air content, the total volume of paste for these mixes in aggregate phase comes 360.84 litre/m^3 of concrete. Hence, the volume of aggregate will be 639.16 litre/m^3 of concrete.

If the volume of aggregates and aggregate proportion in total aggregate is known, their weights can be worked out as below.

Let assume that in a given volume of total aggregates, the volume of fine aggregates is V_{FA}, Volume of Coarse aggregate having size 10 mm and 20 mm is V_{10mm} and V_{20mm} respectively and volume of filler material if any is V_F.

Then total volume of aggregate is given by

$$V_{FA} + V_{10mm} + V_{20mm} + V_F = V$$

$$\frac{W_{FA}}{G_{FA}} + \frac{W_{10mm}}{G_{10mm}} + \frac{W_{20mm}}{G_{20mm}} + \frac{W_F}{G_F} = V$$

$$\frac{P_{FA}.W}{G_{FA}} + \frac{P_{10mm}.W}{G_{10mm}} + \frac{P_{20mm}.W}{G_{20mm}} + \frac{P_F.W}{G_F} = V$$

Where V= Total Volume of blended aggregate

W= Total weight of blended aggregate

G= Specific gravity of material

P= Percentage proportion of aggregate in total aggregate

$$\boldsymbol{W} = \frac{\boldsymbol{V}}{\frac{\boldsymbol{P_{FA}}}{\boldsymbol{G_{FA}}} + \frac{\boldsymbol{P_{10mm}}}{\boldsymbol{G_{10mm}}} + \frac{\boldsymbol{P_{20mm}}}{\boldsymbol{G_{20mm}}} + \frac{\boldsymbol{P_F}}{\boldsymbol{G_F}}} \qquad (\mathbf{5.1})$$

For example in a blended aggregate, if Fine aggregate is 65% and 20 mm aggregate is 35% and the total volume of blended aggregate is 639.16 litre then the total weight of aggregate

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

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

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

Proportions finalized for SCC mix per cubic meter of concrete:

	Paste (360.84 liter)				Aggregates (639.16 liter)			
	Water	Cement	Admixture	Air	Sand	10 mm	20 mm	Filler
Volume (liter)	200	137.93	2.91	20	639.16			
Weight (Kg)	200	400	3.2	0	1107	0	596.08	0
	Paste Volume and Composition (fix)				Aggregate volume is fixed but proportion of			

TABLE 5.1 shows the test matrix of the experimental program planned for aggregate phase. The experiments are grouped on basis of purpose of testing.

TABLE 5.1 Test Matrix of Aggregate Phase

Mix Designation	Mechanical Properties No. of Specimen		Fresh Properties No. of Specimen				Size of CA	FA:CA ratio
	Cube Compressive Strength		Slump Flow and T-500	V-Funnel	L-Box	Sieve Segregation		
	7 Days	28 Days						
Effect of aggregate size and packing Density due to different blending of Coarse and Fine Aggregate								
Mix A1 to A4	12	12	4	4	4	4	20 mm	Varying
Mix A5 to A9	15	15	5	5	5	5	10 mm	Varying
Mix A10 to A12	9	9	3	3	3	3	20+10 mm	Varying
Effect of Sand Fines on SCC mixes by varying particles finer than 150 micron								
Mix A13 to A15	9	9	3	3	3	3	20 mm	60:40
Mix A16 to A18	9	9	3	3	3	3	20 mm	55:45
Effect of Paste Composition on SCC mixes having same aggregate volume								
Mix A19 to A21	9	9	3	3	3	3	20 mm	60:40
Mix A22 to A24	9	9	3	3	3	3	20 mm	55:45
Total Sample	144		24	24	24	24		
Note: For all above mixes paste volume (360.8 litre) and Aggregate Volume (639.2 litre) is kept constant.								

5.2.2 Design mixes to find effect of aggregate size and packing density

EFNARC guideline [27] suggests that to produce SCC, fine aggregate content can be taken up to 48% to 55% of the total aggregate. As per particle packing model, for aggregates used in this study, packing density is maximum for 65% FA blended with 35% CA, also for FA: CA proportion 60:40, 55:45 and 52:48 packing density is good. Therefore, to check the effect of packing density and the effect of volume of coarse and fine aggregate, total 12 mixes using above FA:CA proportions are designed keeping paste volume and paste composition same. Three types of aggregate variation are taken. Four mixes are prepared using 20 mm MSA, five mixes are prepared using 10 mm MSA and in 3 mixes are prepared using a combination of both 20 mm and 10 mm in the ratio of 75% 20mm and 25% 10mm. As shown in TABLE 3.8 , the combination of 75% 20mm and 25% 10mm CA gives optimum packing density when they blended together. For 20 mm MSA, fine and coarse aggregate proportions of 65:35, 60:40, 55:45 and 52:48 were taken. For10 mm MSA, fine and coarse aggregate proportions of 65:35, 60:40, 55:45, 52:48 and 48:52 were taken. For a combination of 20 mm and 10 mm CA with FA, FA: CA (10mm): CA

(20mm) proportions of 60:10:30, 55:11:34 and 52:12:36 were taken. Mix proportions of all these mixes are presented in TABLE 5.2**,** TABLE 5.3 and TABLE 5.4.

TABLE 5.2 Mix Proportion per m3 using Maximum Size of aggregate 20 mm

Mix Designation	Combination of Aggregate			20 mm (kg)	10 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (kg)
	FA	10 mm	20 mm						
Mix A1	65:00:35			596.08	0.00	1107.00	400.00	200.00	3.2
Mix A2	60:00:40			684.83	0.00	1027.25	400.00	200.00	3.2
Mix A3	55:00:45			774.53	0.00	946.65	400.00	200.00	3.2
Mix A4	52:00:48			828.81	0.00	897.87	400.00	200.00	3.2

TABLE 5.3 Mix Proportion per m3 using Maximum Size of aggregate 10 mm

Mix Designation	Combination of Aggregate			20 mm (kg)	10 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (kg)
	FA	10 mm	20 mm						
Mix A5	65:35:00			0.00	596.08	1107.00	400.00	200.00	3.2
Mix A6	60:40:00			0.00	684.83	1027.25	400.00	200.00	3.2
Mix A7	55:45:00			0.00	774.53	946.65	400.00	200.00	3.2
Mix A8	52:48:00			0.00	828.81	897.87	400.00	200.00	3.2
Mix A9	48:52:00			0.00	901.72	832.36	400.00	200.00	3.2

TABLE 5.4 Mix Proportion per m3 using blending of 20 mm and 10 mm MSA

Mix Designation	Combination of Aggregate			20 mm (kg)	10 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (kg)
	FA	10 mm	20 mm						
Mix A10	60:10:30			513.62	171.21	1027.25	400.00	200.00	3.200
Mix A11	55:11:34			585.20	189.33	946.65	400.00	200.00	3.200
Mix A12	52:12:36			621.61	207.20	897.87	400.00	200.00	3.200

5.2.2.1 Result and discussion on effect of aggregate size and packing density on SCC mix

The fresh and hardened properties of all the mixes are presented in TABLE 5.5, TABLE 5.6 and TABLE 5.7. In SCC mixes, fine aggregate is gradually decreased unless the bleeding is observed. Once bleeding is observed, no further reduction of FA is made.

TABLE 5.5 Compressive strength and fresh properties of design mix with MSA 20 mm

Mix Designation	Combination of Aggregate			Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	L-Box (H2/H1)	Sieve Segregation Portion (%)	Compressive Strength		Remarks/Observation
	FA	10 mm	20 mm						7 Days	28 Days	
Mix A1	65:00:35			700	1.72	4.8	1.0	5.82	23.29	39.19	Cohesive Mix
Mix A2	60:00:40			680	1.59	4.4	0.95	6.65	21.3	39.36	Cohesive Mix
Mix A3	55:00:45			650	3	2.4	0.95	10.35	23.46	39.92	Cohesive Mix
Mix A4	52:00:48			640	3.12	1.66	1.0	13.25	26.9	41.37	Bleeding

TABLE 5.6 Compressive strength and fresh properties of design mix with MSA 10 mm

Mix Designation	Combination of Aggregate			Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	L-Box (H2/H1)	Sieve Segregation Portion (%)	Compressive Strength		Remarks/Observation
	FA	10 mm	20 mm						7 Days	28 Days	
Mix A5	65:35:00			635	2.4	3.86	0.95	4.36	21.77	39.55	Cohesive Mix
Mix A6	60:40:00			630	2.57	4.84	0.95	5.25	22.33	39.09	Cohesive Mix
Mix A7	55:45:00			620	3.6	5.99	0.95	5.80	21.59	41.38	Cohesive Mix
Mix A8	52:48:00			610	2.68	9.47	0.95	6.95	20.66	38.18	Cohesive Mix
Mix A9	48:52:00			600	2.42	10.5	0.90	9.75	19.96	38.93	Bleeding

TABLE 5.7 Compressive strength and fresh properties of design mix with MSA 20 mm+10 mm

Mix Designation	Combination of Aggregate			Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	L-Box (H2/H1)	Sieve Segregation Portion (%)	Compressive Strength		Remarks/Observation
	FA	10 mm	20 mm						7 Days	28 Days	
Mix A10	60:10:30			700	1.77	4.51	0.98	5.46	18.72	36.68	Cohesive Mix
Mix A11	55:11:34			640	1.9	11	0.95	5.98	19.09	37.46	Cohesive Mix
Mix A12	52:12:36			620	3.39	9.28	0.95	7.03	25.27	38.03	Cohesive Mix

For the same FA: CA ratio, 20 mm aggregate gives more packing density comparing to 10 mm aggregates. Due to higher packing density, SCC mixes with 20 mm MSA has more free paste volume and hence gives better fresh properties comparing to 10 mm MSA, which is portrayed in FIGURE 5.1 and FIGURE 5.2. Compressive strength and slump flow are represented in FIGURE 5.3 and FIGURE 5.4 respectively. SCC mix with 20 mm MSA gives more slump flow without compromising compressive strength comparing to SCC mix with 10 mm MSA. As paste composition and paste volume are kept same, the compressive strength is nearly the same for all mixes.

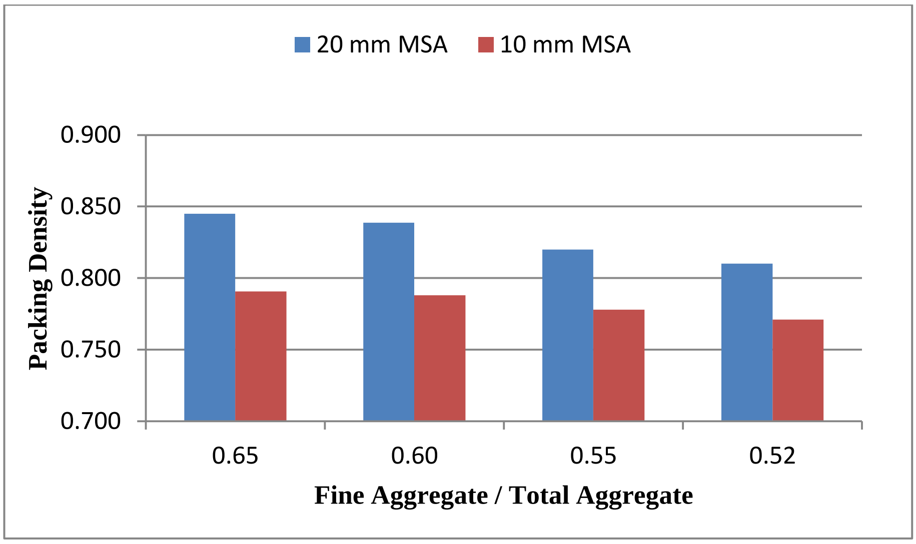


FIGURE 5.1 Packing Density for 20 mm and 10 mm MSA SCC mix

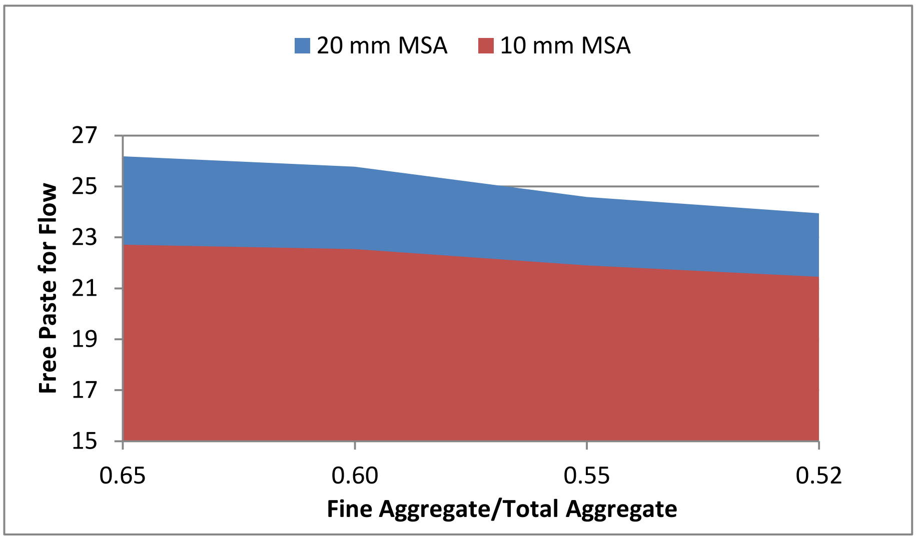


FIGURE 5.2 Free paste for flow for 20 mm and 10 mm MSA SCC mix

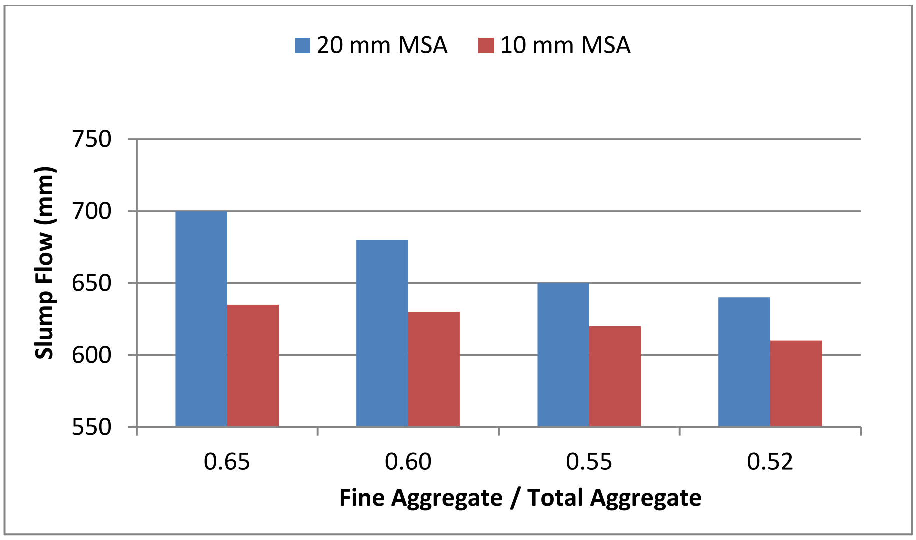


FIGURE 5.3 Slump Flow of 20 mm and 10 mm MSA SCC mix

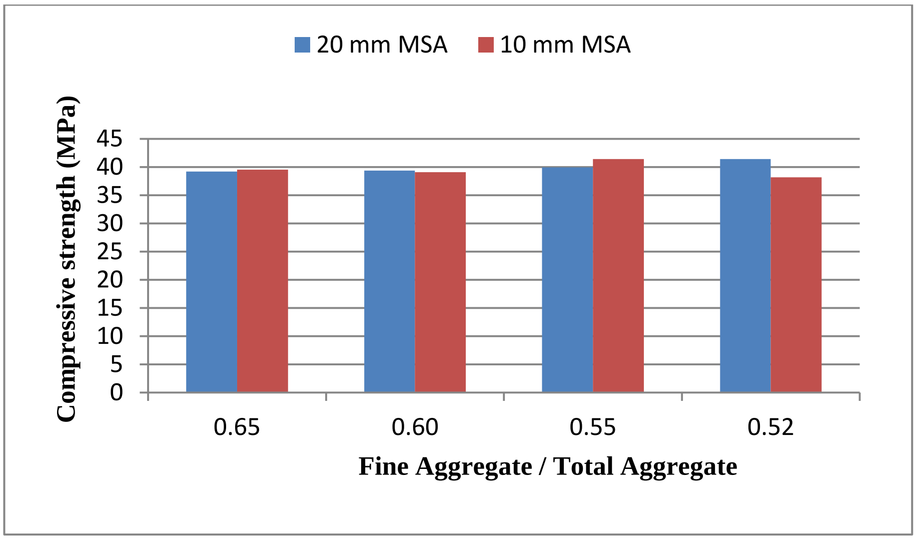


FIGURE 5.4 Compressive Strength of 20 mm and 10 mm MSA SCC mix

FIGURE 5.5, FIGURE 5.6 and FIGURE 5.7 are represented to visualize the quality of SCC mix produced in terms of segregation and bleeding. FIGURE 5.5 and FIGURE 5.6 represents the slump flow of SCC mix prepared using 10 mm MSA and 20 mm MSA respectively. All the mixes are cohesive. It is observed that as the volume of fine aggregate decreased, chances of segregation and bleeding increase. As shown in FIGURE 5.5, when 10 mm aggregate is increased to 52% in total aggregate, bleeding and segregation have started. Similarly as shown in FIGURE 5.6, when 20 mm aggregate is increased to 48% of total aggregate bleeding was observed.

FIGURE 5.5 Slump flow of 10mm MSA mix for FA to CA ratio 65:35, 60:40, 55:45, 52:48 and 48:52 respectively

FIGURE 5.6 Slump flow of 20mm MSA mix for FA to CA ratio 65:35, 60:40, 55:45 and 52:48 respectively

Here one can observe that mixes are quite cohesive when 10 mm aggregates are used comparing to SCC mix with 20 mm aggregate are used. There is no sign of bleeding and segregation when 10 mm aggregate is used but slump flow is decreased compared to mix with MSA 20 mm for the same proportion of aggregate. This is due to the less paste available for flow, also as in 10 mm aggregate, 6.5% particles are finer than 4.75 mm, due to which total fine aggregate volume is increased which makes mortar more cohesive simultaneously more viscous too. So, fine aggregates are very much necessary for good cohesive SCC mix.

FIGURE 5.7 Slump for 20 mm and 10 mm MSA for Mix A10 to A12 respectively

Paste volume for all mixes are kept constant at 360.8 litre/m^3, but packing density is varied by varying fine and coarse aggregate proportions and varying size of aggregate. Based on the packing density of blended aggregates and total volume of blended aggregate, free paste volume remained after filling voids of blended aggregates is calculated and presented in TABLE 5.8. It is observed that, for the same paste volume of 360.8 litre/m^3, all mixes show different slump flow value and as free paste volume increases the slump flow is also increases. The relation between slump flow and free paste volume is depicted in FIGURE 5.8.

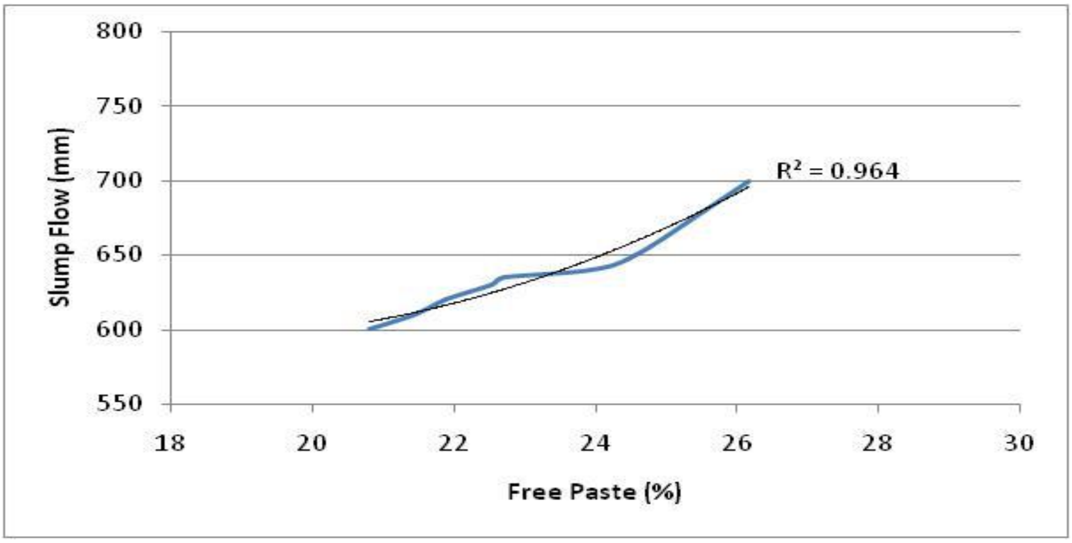


FIGURE 5.8 Slump Flow vs. Free Paste

TABLE 5.8 Effect of Free Paste Volume on Slump Flow for same paste composition

Mix Designation	Combination			Packing Density	Volume of Aggregate (%)	Volume of Voids in Aggregate (%)	Paste Volume (%)	Free paste volume for flow (%)	Slump Flow (mm)
	FA	10 mm	20 mm						
Mix A1	65:00:35			0.845	63.916	9.907	36.08	26.178	700
Mix A2	60:00:40			0.835	63.916	10.547	36.08	25.532	680
Mix A3	55:00:45			0.832	63.916	10.738	36.08	25.341	650
Mix A4	52:00:48			0.810	63.916	12.144	36.08	23.940	640
Mix A5	65:35:00			0.791	63.916	13.377	36.08	22.707	635
Mix A6	60:40:00			0.788	63.916	13.549	36.08	22.535	630
Mix A7	55:45:00			0.778	63.916	14.190	36.08	21.894	620
Mix A8	52:48:00			0.771	63.916	14.637	36.08	21.447	610
Mix A9	48:52:00			0.761	63.916	15.276	36.08	20.808	600
Mix A10	60:10:30			0.819	63.916	11.545	36.08	24.539	700
Mix A11	55:11:34			0.811	63.916	12.080	36.08	24.004	640
Mix A12	52:12:36			0.799	63.916	12.860	36.08	23.224	620

Packing density theory is generally useful when aggregate content is more in concrete mix and cementitious material is less. Generally, for concrete compressive strength from 20 N/mm^2 to 30 N/mm^2, paste volume required is 300 litres/m^3 to 360 litres/m^3. So, the aggregate volume will be 700 litres/m^3 to 640 litres/m^3. In this situation, the optimal packing density of aggregate leads to good fresh properties with less cementitious material. From the above result, it can be seen that packing density has a predominant effect on fresh properties while the strength was not much affected and also if the size of aggregate is decreased mix becomes more cohesive.

5.2.3 Design mixes to find effect of Sand fines

In this study, fine aggregate particles smaller than 150 microns are considered as sand fines. Some researchers [49-50] had studied the effect of different types of sand on properties of SCC. It was found that more fines in the sand are good for fresh properties but it reduces the hardened properties. From result of MIX A1 to A4, the mix having FA:CA ratio 52:48 has little higher compressive strength than other mixes even though possess same paste volume and composition. This may be due to less sand fines in it or may be due to little lower packing density. So, aim of casting these mixes is to determine effect of sand fines on cohesiveness and strength of SCC mix. Therefore sand having more fine content is taken to cast the design mixesAs shown in Table 5.9 fines content in the sand used in this study is about 6.9 % of the weight of fine aggregate

Table 5.9 Sieve analysis of fine aggregate used to find effect of sand fines

Sr. No.	Seive Size	Retained Particles			Passing Particles (%)
		Weight (gm)	Weight retained (%)	Cumulative weight retained (%)	
1	10.0mm	0	0	0.00	100
2	4.75 mm	21	2.1	2.10	97.9
3	2.36 mm	73	7.3	9.40	90.6
4	1.18 mm	168	16.8	26.20	73.80
5	600 micron	82	8.2	34.40	65.6
6	300 micron	351	35.1	69.50	30.5
7	150 micron	236	23.6	93.10	6.9
8	75 µ	69.0	6.9	100.00	0
9	Pan	0	0	100.00	
FINENESS MODULUS				**2.35**	

In SCC mix having FA:CA ratio of 52:48, sand fines content was 3.59% of total aggregate i.e. 61.95 kg per cubic meter of concrete. In 60:40 and 55:45 combinations, sand fines are 70.88 kg/m^3 and 65.32 kg/m^3 respectively. Now to check the effect of sand fines, sand fines in the aggregate combination of 60%:40 % and 55%:45% (FA to 20 mm CA) reduced from 61.95 kg/m^3 to 0 kg/m^3. As SCC made with 10 mm MSA has less packing density and shows poor fresh properties comparing to SCC mix with 20 mm MSA, to find the effect of sand fines, only SCC mix with 20 mm MSA are considered here. TABLE 5.10

shows the mix proportions of Mix A13 to A18 casted to study effect of sand fines. The mixes are prepared with the same amount of constituent material, as taken in Mix A1 to A12; the only change is in fine aggregate content. Total fine aggregate content is divided into two parts, particles coarser than 150 micron and particles finer than 150 microns (sand fines). The sand fines are reduced in steps from 61.95 kg/m^3 to 0 kg/m^3, but total amount of fine aggregate is maintained in mix.

FIGURE 5.9 Sand Fines smaller than 150 micron

TABLE 5.10 Design Mix to check Effect of Sand Fines

Mix Designation	Combination of Aggregate			20 mm (kg)	10 mm (kg)	Sand (>150 micron) (kg)	Sand (<150 micron) (kg)	Cement (kg)	Water (kg)	SP (kg)
	FA	10 mm	20 mm							
Mix A13	60:00:40			684.83	0.00	965.30	61.95	400.00	200.00	3.200
Mix A14	60:00:40			684.83	0.00	997.25	30	400.00	200.00	3.200
Mix A15	60:00:40			684.83	0.00	1027.25	0	400.00	200.00	3.200
Mix A16	55:00:45			774.53	0.00	884.70	61.95	400.00	200.00	3.200
Mix A17	55:00:45			774.53	0.00	916.65	30	400.00	200.00	3.200
Mix A18	55:00:45			774.53	0.00	946.65	0	400.00	200.00	3.200

5.2.3.1 Result and discussion on effect of sand fines on SCC mixes

TABLE 5.11 shows the fresh and hardened properties of Mix A13 to A18. It was found that if sand fines are decreased the strength of mix is increased but the chance of bleeding increases. In mix A13 to A18 shown in TABLE 5.11, strength was almost becomes equal to that with the maximum strength achieved in Mix A1 to Mix A12, without much compromising to slump flow, but chances of bleeding are increased.

TABLE 5.11 Compressive strength and fresh properties of design mix varying the sand fines

Mix Designation	Combination of Aggregate			Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	Compressive Strength (N/mm^2)		Remarks/ Observation
	FA	10 mm	20 mm				7 Days	28 Days	
Mix A13	60:00:40			680	1.59	7.77	21.3	39.36	
Mix A14	60:00:40			700	1.72	6.5	23.29	39.19	
Mix A15	60:00:40			675	1.36	4.8	23.99	41.49	
Mix A16	55:00:45			675	1.57	8.4	17.6	39.84	Bleeding
Mix A17	55:00:45			700	1.51	7.5	19.14	40.02	Bleeding
Mix A18	55:00:45			700	1.34	6.99	23.7	41.81	Bleeding

Fines in fine aggregates taken to prepare SCC mixes are 6.9%. of the fine aggregate volume. But when fine aggregates are blended with coarse aggregate, the fines in total aggregate for FA: CA blending 65:45, 60:40, 55:45 and 52:48 is 4.485%, 4.14%, 3.795% and 3.59% respectively. The strength results from Mix A1 to A4 and Mix A13 to A18 reveals that due to this variation of sand fines compressive strength is decreased by about 5.2%. Also, it can be seen that sand fines mainly affect the cohesiveness of the SCC mix. In present study SCC mix with 65% and 60% fine aggregate content does not show any segregation and bleeding. While as shown in FIGURE 5.10 SCC mix with FA:CA ration 55:45 shows significant bleeding. In the mix having less sand fines cohesiveness of mix can be improved by increasing paste volume, which makes the mix uneconomical. Therefore, it is important that for medium resistance concrete with less paste volume enough amount of sand fines are necessary for making SCC mix cohesive. Here, it can be noted that it is more effective to find sand fines in total aggregate rather than only in fine aggregate. From results it is clear that the minimum volume of sand fines in total aggregate about 4% is necessary in SCC mix to make it cohesive and also due to this compressive strength is not much affected.

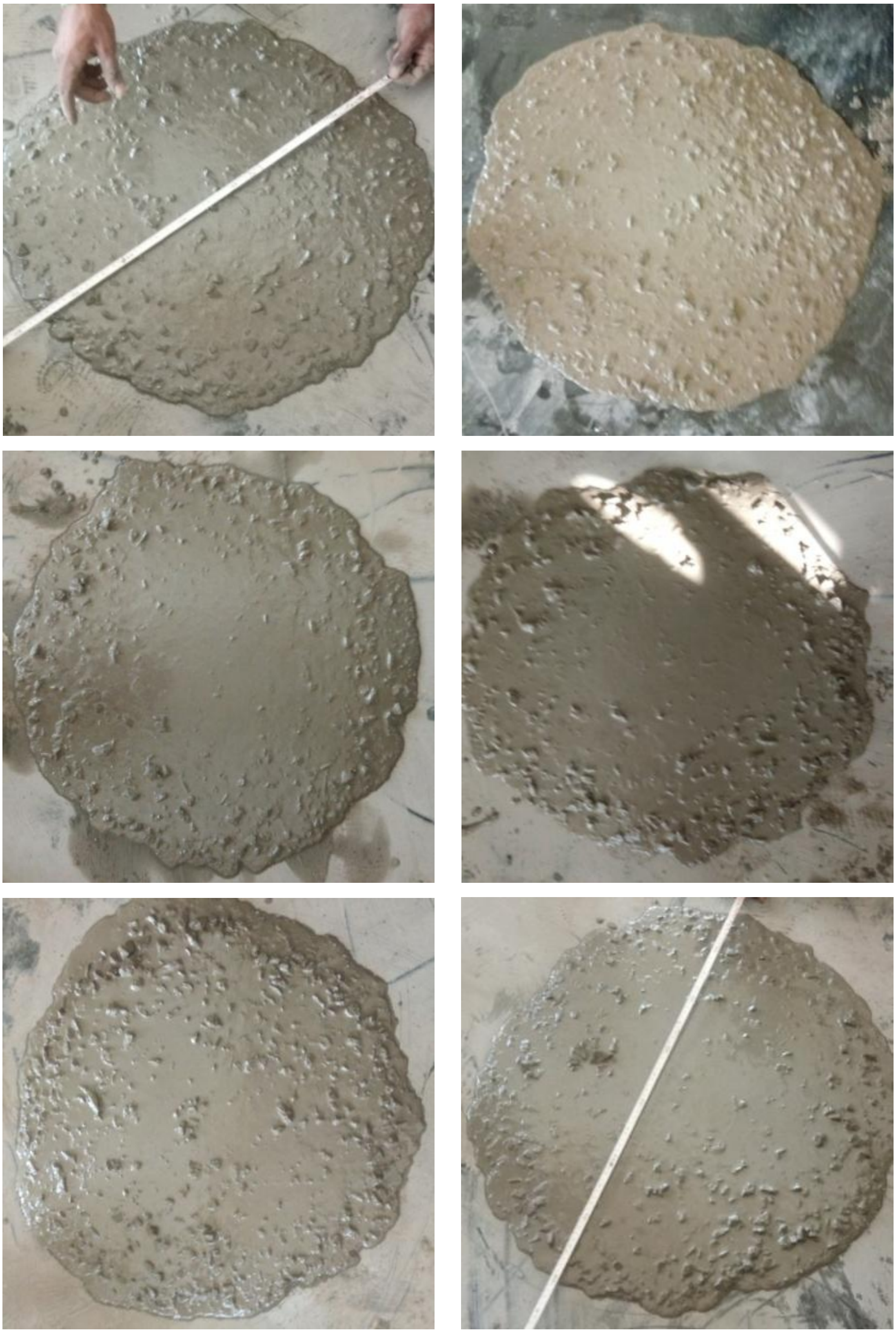


FIGURE 5.10 Slump flow of 20mm MSA mix for mix A13 to A18respectively

5.2.4 Design mixes for effect of paste Composition having same aggregate volume

Nanthgopalan et.al.[26] has revealed that paste volume had a predominant effect on the fresh concrete properties in comparison with water or powder content individually (for a given combination of aggregates). So, the intent of casting these mixes is to find that only free paste volume remained after filling aggregate voids are responsible for fresh properties achieved or paste composition is also equally important. In these design mixes, total paste volume was kept same for all mixes, but paste composition is changed. Paste volume for Mix A1 to Mix A18 was 360.8 litre per m^3 of concrete, same paste volume is kept in these mixes but paste composition is changed. For example in Mix A19, cement volume is 146.55 litre, water volume is 191.12 litre and admixture volume is 3.09 litre, so total paste volume considering 2% air content is 360.8 litre. Similarly in Mix 20, cement volume is 155.17 litre, water volume is 182.40 litre and admixture volume is 3.27 litre, so total paste volume is 360.8 litre. Means, if cement volume increased, to keep paste volume same water volume is decreased. Dosage of admixture is the same 0.8% of cement weight for all mixes. TABLE 5.12 shows the mix proportions of Mix A19 to A24.

TABLE 5.12 Design mix to check effect of paste composition on SCC mixes having same aggregate volume

Mix Designation	Combination of Aggregate			20 mm (kg)	10 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (kg)
	FA	10 mm	20 mm						
Mix A19	60:00:40			684.83	0.00	1027.25	425.00	191.12	3.400
Mix A20	60:00:40			684.83	0.00	1027.25	450.00	182.40	3.600
Mix A21	55:00:45			774.53	0.00	946.65	425.00	191.12	3.400
Mix A22	55:00:45			774.53	0.00	946.65	450.00	182.40	3.600
Mix A23	48:00:52			901.72	0.00	832.36	425.00	191.12	3.400
Mix A24	48:00:52			901.72	0.00	832.36	450.00	182.40	3.600

5.2.4.1 Result and discussion on effect of paste composition on SCC mixes having same aggregate volume

TABLE 5.13 Compressive strength and fresh properties of design mix A19 to A24

Mix Designation	Paste Volume (litre/m^3)	W/C ratio	Packing Density	Free Paste volume (litre/m^3)	Slump Flow (mm)	T500 (Sec)	V Funnel (Sec)	Compressive Strength		Remarks/Observation
								7 Days	28 Days	
Mix A19	360.8	0.45	0.835	255.3	630	4.45	17	28	44.46	
Mix A20	360.8	0.41	0.835	255.3	635	5.43	8	29.32	44.82	
Mix A21	360.8	0.45	0.832	253.4	640	2.64	8	23.42	46.45	Bleeding
Mix A22	360.8	0.41	0.832	253.4	620	8	21	28.69	48.68	
Mix A23	360.8	0.45	0.821	246.3	620	5	12	22.57	46.13	Bleeding
Mix A24	360.8	0.41	0.821	246.3	630	4.44	26.85	27.07	46.54	

FIGURE 5.11 Slump flow of 20mm MSA mix for Mix A19 to A24respectively

TABLE 5.13 represents the fresh and hardened properties of MIX A19 to Mix A24. It can be observed based on the result that for same paste volume of 360.8 litre, as shown in TABLE 5.8, comparing to MIX A2 and Mix A3, that has 400 kg cement with 0.5 w/c ratio and FA:CA ratio 60:40 and 55:45 respectively, these mixes in spite of having more cementitious material shows lower slump flow. So, it is evident that paste composition has predominant effect on fresh properties of SCC mix. It can be seen that, though the FA:CA ration, packing density, aggregate volume and paste volume of mix A2 and A19 is equal, due to paste composition Mix A19 is showing less slump flow then mix A2. Here, comparing to Mix A2, in mix A19 cement volume is increased by 8.62 liter/m^3 and water volume is decreased by 8.88 liter/m^3 to maintain paste volume of 360.8 liter/m3 same for both mixes. Cement volume and water volume is changed in equal amount but still the slump flow is reduced in mix A19 comparing to mix A2 by 7.35%. Even after increase of cement volume slump flow is decreased due to decrease in water volume. So, it can be concluded that in paste composition particularly water volume affects more on fresh properties comparing to cement volume. Therefore, it is clear that to make medium resistance concrete economical, paste volume and paste composition both needs to be optimized. Also, FIGURE 5.11 show the slump flow of Mix A19 to A24. It is found that slump flow does not solely depend on paste volume; it also depends on paste composition.

5.3 Design Mixes for Paste Phase

All the mixes in paste phase are designed using 20 mm MSA, as 20 mm MSA aggregate gives more packing density and thereby better fresh properties comparing to the 10 mm MSA for the same amount of cementitious material. As, optimum packing density is achieved for FA: CA ratio of 65:35 and 60:40, SCC mixes are prepared using 65% and 60% of fine aggregate in total aggregate. W/C ratio is varied from high to low until a fresh property of SCC is achieved satisfactorily. As, objective of the research is to produce economical SCC mix using cement content equivalent to conventional concrete, cement content to make SCC mixes are taken as 400 kg, 380 kg, 360 kg and 340 kg per cubic meter of concrete mix. For all cement content, w/c ratio and fine aggregate percentage in the total aggregate are varied. The fresh properties are measured using slump flow, T500, V-Funnel, L-Box and Sieve segregation test and for hardened properties cube compressive strength test is performed. In the result tables, compressive strength is converted in the grade of concrete, in accordance with IS: 456-2000. As per Indian standard, IS: 456-2000

[36], concrete having characteristic strength after 28 days of curing period is 20 N/mm^2 is termed as M20 grade of concrete. For design mixes prepared in the laboratory, target compressive strength is considered, so for M20 grade of concrete, target compressive strength considered for mix design is 26.6 Mpa. Similarly, target compressive strength for M25, M30, M35 and M40 grade is 31.6 Mpa, 38.25 Mpa, 43.25 Mpa and 48.25 Mpa respectively. Also, As per IS:456-2000, the water to cementitious material ration cannot be kept more than 0.55 for concrete to be used for Reinforced cement concrete (RCC) work in mild exposure and 0.50 for RCC work in moderate exposure condition. Similarly, as per ACI-301 [37] maximum w/p ratio allowed for durability requirement is 0.50. So, the study is limited up to w/c ratio 0.50 for all the mixes. The experimental program prepared for the paste phase is as below.

TABLE 5.14 Test Matrix of Paste Phase

Mix Designation	Mechanical Properties		Fresh Properties			
	Cube Compressive		Slump Flow and T-500	V-Funnel	L-Box	Sieve Segregation
	7 Days	28 Days				
Design Mixes using 400 kg cement ,w/c Ratio 0.5,0.475,0.45,0.40, FA:CA ratio 65:35,60:40						
Mix P1 to P8	24	24	8	8	8	8
Design Mixes using 380 kg cement ,w/c Ratio 0.5,0.475,0.45,0.42, FA:CA ratio 65:35,60:40						
Mix P9 to P15	21	21	7	7	7	7
Design Mixes using 360 kg cement ,w/c Ratio 0.5,0.475,0.45, FA:CA ratio 65:35,60:40						
Mix P16 to P19	12	12	4	4	4	4
Design Mixes using 340 kg cement ,w/c Ratio 0.5,0.475 FA:CA ratio 65:35,60:40						
Mix P20 to P23	12	12	4	4	4	4
Total Sample	138		24	24	24	24

5.3.1 Mix with 400 kg Cement

In Self compacting concrete mix designed using 400 kg Cement, Water-Cement ratio was varied as 0.5, 0.475, 0.45 and 0.40. It was found that it is not possible to produce SCC using a W/C ratio less than 0.40 using 400 kg cement. As shown in TABLE 5.15, for each water-cement ratio two variations of FA: CA ratio, 65:35 and 60:40 were taken. PCE based admixture is also varied. It is found that the dosage of PCE based admixture required for given W/C ratio found using Marsh cone test is not perfectly suitable to produce cohesive SCC mix; dosage should be modified depending on the volume of fine and coarse aggregate. As shown in TABLE 5.16**,** Slump flow was ranging from 700 mm to 630 mm and 28 days compressive strength was ranging from 38 N/mm^2 to 50 N/mm^2. FIGURE

5.12 and FIGURE 5.13 shows the Slump flow for mixes having 65% FA and 60% FA respectively for different W/C ratio.

TABLE 5.15 Design mix varying paste composition and volume for 400 kg Cement

Mix Designation	Combination of Aggregate		W/C Ratio	20 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (%cement weight)	Aggregate Volume (%)	Paste Volume (%)
	FA	20 mm								
Mix P1	60:40		0.500	685.81	1028.71	400	200.00	0.40	64.12	35.88
Mix P2	65:35		0.500	597.94	1110.47	400	200.00	0.45	64.01	35.99
Mix P3	60:40		0.475	685.81	1028.71	400	190.00	0.40	65.10	34.90
Mix P4	65:35		0.475	605.23	1124.01	400	190.00	0.45	64.90	35.10
Mix P5	60:40		0.450	707.04	1060.56	400	180.00	0.50	65.99	34.01
Mix P6	65:35		0.450	614.39	1141.01	400	180.00	0.55	65.88	34.12
Mix P7	60:40		0.400	728.28	1092.41	400	160.00	0.55	67.97	32.03
Mix P8	65:35		0.400	634.06	1177.54	400	160.00	0.60	67.99	32.01

TABLE 5.16 Test result for SCC mix with 400 kg Cement

Mix	w/c	PD	Paste for Flow	Strength (N/mm^2)		Slump Flow (mm)	T500 (sec)	V-Funnel (Sec)	L-Box	Sieve Segregation Portion (%)	Grade
				7 days	28 Days						
Mix P1	0.500	0.835	25.43	22.84	40.19	690	2.7	4.98	1	6.66	M30
Mix P2	0.500	0.845	25.94	26.26	40.95	700	2.13	4.92	1	5.76	M30
Mix P3	0.475	0.835	24.19	25.93	42.41	670	3	5.66	0.95	6.22	M30
Mix P4	0.475	0.845	25.04	26.31	43.96	660	3	6.1	0.96	5.21	M35
Mix P5	0.45	0.835	23.12	27.95	48.53	650	4	7.98	0.9	5.13	M40
Mix P6	0.45	0.845	23.91	27.91	47.67	650	3.5	7.25	0.89	4.85	M35
Mix P7	0.400	0.835	20.81	32.57	49.85	625	3.7	10.57	0.87	3.68	M40
Mix P8	0.400	0.845	21.47	33.86	50.76	630	4	9.82	0.85	3.43	M40

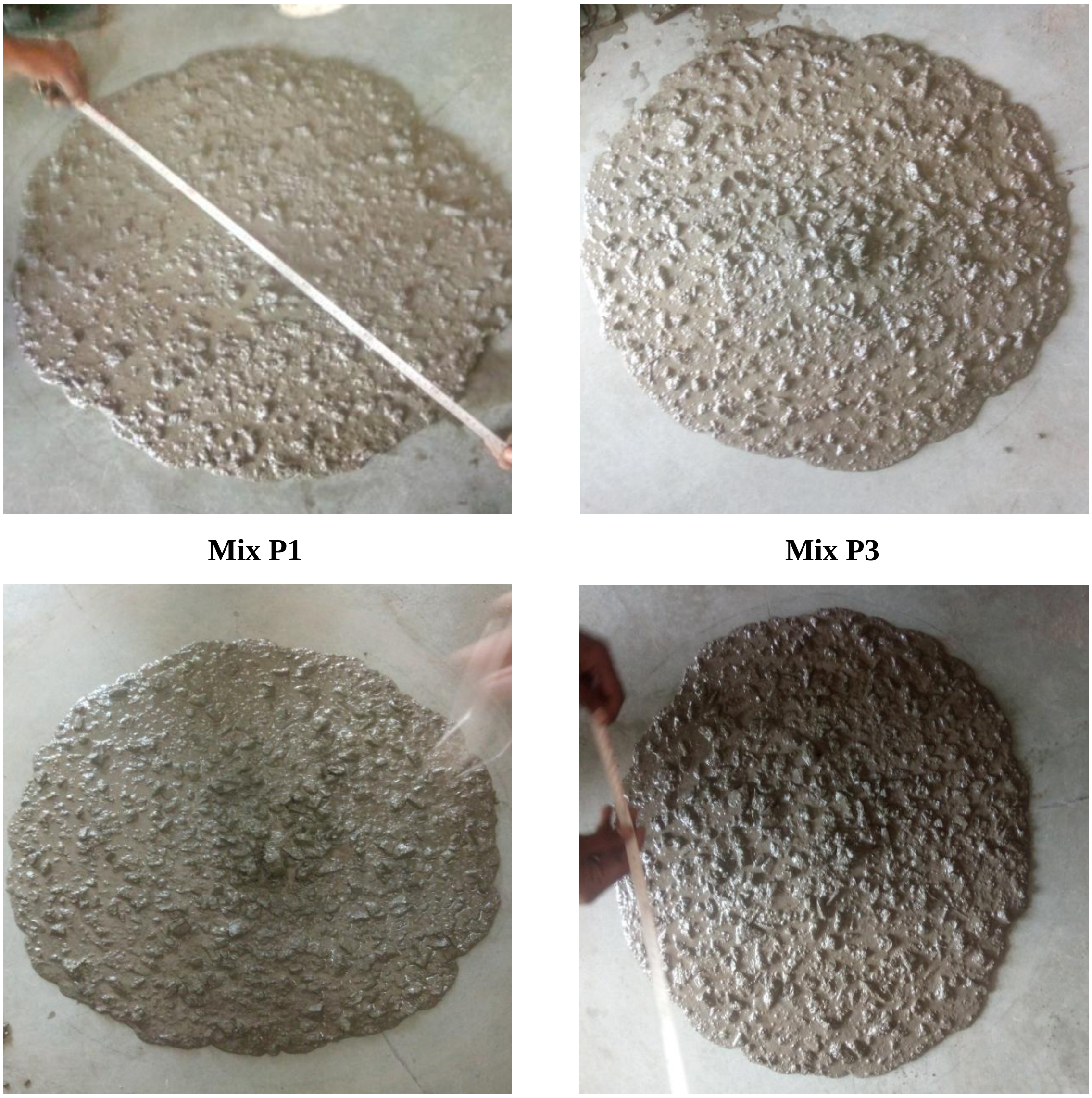
Mix P2

Mix P4

Mix P6

Mix P8

FIGURE 5.12 Slump flow using 400 kg Cement in decreasing order of W/C Ratio for FA 65%



Mix P1 **Mix P3**

Mix P5 **Mix P7**

FIGURE 5.13 Slump flow using 400 kg Cement in decreasing order of W/C Ratio for FA 60%

5.3.2 Mix with 380 kg Cement

In Self compacting concrete mix designed using 380 kg Cement, Water-Cement ratio was varied as 0.5, 0.475, 0.45 and 0.42. It was found that it is not possible to produce SCC using a W/C ratio less than 0.42 for 380 kg cement. As shown in TABLE 5.17, for each water-cement ratio, two variations of FA: CA ratio, 65:35 and 60:40 were taken. As shown in TABLE 5.18**,** Slump flow was ranging from 680 mm to 550 mm and 28 days compressive strength was ranging from 34 N/mm^2 to 45 N/mm^2. FIGURE 5.14 and FIGURE 5.15 shows the Slump flow for mixes having 65% FA and 60% FA respectively for different W/C ratio.

TABLE 5.17 Design mix varying paste composition and volume for 380 kg Cement

Mix Designation	Combination of Aggregate		W/C Ratio	20 mm (kg)	Sand (kg)	Cement (kg)	Water (kg)	SP (%cement weight)	Aggregate Volume (%)	Paste Volume (%)
	FA	20 mm								
Mix P9	60:40		0.5	704.39	1056.58	380	190.00	0.45	65.84	34.26
Mix P10	65:35		0.5	612.94	1138.31	380	190.00	0.50	65.72	34.28
Mix P11	60:40		0.476	703.83	1055.75	380	180.74	0.40	65.69	34.31
Mix P12	65:35		0.468	620.67	1152.68	380	177.68	0.68	65.68	34.32
Mix P13	60:40		0.450	724.01	1086.01	380	171.00	0.55	67.57	32.43
Mix P14	65:35		0.45	629.37	1168.83	380	171.00	0.70	67.49	32.51
Mix P15	60:40		0.420	744.18	1116.27	380	159.51	1.00	69.45	30.55

Mix P10

Mix P12

Mix P14

FIGURE 5.14 Slump flow using 380 kg Cement in decreasing order of W/C Ratio for FA 65%

Mix P9

Mix P11

Mix P13

Mix P15

FIGURE 5.15 Slump flow using 380 kg Cement in decreasing order of W/C Ratio for FA 60%

TABLE 5.18 Test result for SCC mix with 380 kg Cement

Mix	w/c	PD	Paste for Flow	Strength (N/mm^2)		Slump Flow (mm)	T500 (sec)	V-Funnel (Sec)	L-Box	Sieve Segregation Portion (%)	Grade
				7 days	28 Days						
Mix P9	0.500	0.835	23.40	25.75	39.35	665	3.34	6.22	0.93	4.99	M30
Mix P10	0.500	0.845	24.21	25.07	40.9	680	3.21	6.17	0.94	4.91	M30
Mix P11	0.476	0.835	23.735	27.66	41.55	650	6	5.45	0.90	5.17	M30
Mix P12	0.468	0.845	24.11	27.49	42.7	660	3.15	5.32	0.92	5.05	M30
Mix P13	0.450	0.835	21.27	28.06	42.46	625	6	8.68	0.88	4.45	M30
Mix P14	0.45	0.845	22.05	27.23	45.06	635	5	7.47	0.86	4.39	M35
Mix P15	0.420	0.835	19.08	34.93	51.32	550	11	11.07	0.83	2.96	M40

5.3.3 Mix with 360 kg Cement

In SCC mix designed using 360 kg Cement, Water-Cement ratio was varied from 0.5, 0.475 to 0.45. It was found that it is not possible to produce SCC using a W/C ratio less than 0.45 for 360 kg cement. As shown in TABLE 5.19**,** for each water-cement ratio two variations of FA: CA ratio, 65:35 and 60:40 were taken. As shown in TABLE 5.20, Slump flow was ranging from 650 mm to 550 mm and 28 days compressive strength was ranging from 30 N/mm^2 to 43 N/mm^2. FIGURE 5.16 and FIGURE 5.17 shows the Slump flow for mixes having 65% FA and 60% FA respectively for different W/C ratio.

TABLE 5.19 Design mix varying paste composition and volume for 360 kg Cement

Mix Designation	Combination of Aggregate		W/C Ratio	20 mm	Sand	Cement	water	SP (%cement weight)	Aggregate Volume (%)	Paste Volume (%)
	FA	20 mm								
Mix P16	60:40		0.5	721.95	1082.92	360	180.00	0.50	67.38	32.62
Mix P17	65:35		0.5	628.32	1166.89	360	180.00	0.65	67.37	32.63
Mix P18	60:40		0.475	731.10	1096.65	360	171	0.77	68.23	31.77
Mix P19	65:35		0.475	644.96	1197.78	360	171	0.85	68.21	31.79

TABLE 5.20 Test result for SCC mix with 360 kg Cement

Mix	w/c	PD	Paste for Flow	Strength		Slump Flow	T500	V-Funnel (Sec)	L-Box	Sieve Segregation Portion (%)	Grade
				7 days	28 Days						
Mix P16	0.500	0.835	21.50	19.44	38.06	600	4.55	10.15	0.88	4.79	M25
Mix P17	0.500	0.845	22.24	22.58	35.29	650	2.85	9.88	0.9	4.7	M25
Mix P18	0.475	0.835	19.47	25.85	39.53	550	11	19.65	0.87	3.09	M30
Mix P19	0.475	0.845	21.12	28.56	40.82	570	10	13.28	0.88	3.86	M30

Mix-P17

Mix P19

FIGURE 5.16 Slump flow using 360 kg Cement in decreasing order of W/C Ratio for FA 65%

Mix P16

Mix P18

FIGURE 5.17 Slump flow using 360 kg Cement in decreasing order of W/C Ratio for FA 60%

5.3.4 Mix with 340 kg Cement

In SCC mix designed using 340 kg Cement. As shown in TABLE 5.21, Water-Cement ratio was varied from 0.5 and 0.475. But satisfactory results were not found. As shown in TABLE 5.22, for one mix slump flow of 550 mm was obtained. And 28 days compressive strength of 33 N/mm^2 was obtained. FIGURE 5.18 and FIGURE 5.19 shows the Slump flow for mixes having 65% FA and 60% FA respectively for different W/C ratio.

TABLE 5.21 Design mix varying paste composition and volume for 340 kg Cement

Mix Designation	Combination of Aggregate		W/C Ratio	20 mm	Sand	Cement	water	SP (%cement weight)	Aggregate Volume (%)	Paste Volume (%)
	FA	20 mm								
Mix P20	60:40		0.500	740.27	1110.41	340	170.00	0.67	69.09	30.91
Mix P21	65:35		0.500	644.05	1196.09	340	170.00	0.70	69.06	30.94
Mix P22	60:40		0.475	748.06	1122.09	340	161.5	1	69.82	30.18
Mix P23	65:35		0.475	650.82	1208.67	340	161.5	1.10	69.79	30.21

TABLE 5.22 Test result for SCC mix with 340 kg Cement

Mix	w/c	PD	Paste for Flow	Strength		Slump Flow	T500	V-Funnel (Sec)	L-Box	Sieve Segregation Portion (%)	Grade
				7 days	28 Days						
Mix P20	0.500	0.835	19.51	23.76	32.95	500	14	21	0.8	3.72	M25
Mix P21	0.500	0.845	20.24	22.5	33.54	560	12.5	15.35	0.82	3.65	M25
Mix P22	0.475	0.835	17.61	26.12	39.25	450	11.7	Block	Block	2.87	M30
Mix P23	0.475	0.845	18.47	17.8	34.08	500	13.35	Block	Block	2.76	M25

Mix P21

Mix P23

FIGURE 5.18 Slump flow using 340 kg Cement in decreasing order of W/C Ratio for FA 65%

Mix P20

Mix P22

FIGURE 5.19 Slump flow using 340 kg Cement in decreasing order of W/C Ratio for FA 60%

5.3.5 Discussion on result of Design Mixes of Paste Phase

The SCC mixes in this study are prepared using locally available material. Also, as SCC mixes are targeted to be used for reinforced cement concrete (RCC) in the current study maximum water-cement ratio (w/c) ratio taken is 0.50. Based on the result, it is clear that SCC can be produced by cement content as low as 340 kg using locally available material using the proposed particle packing approach. Further, in this phase paste composition is varied by varying cementitious material, w/c ration and super plasticizer dosage. FIGURE 5.20 and FIGURE 5.21 shows the paste volume taken for different design mixes. As Water is reduced for the same cement content, paste volume reduces. Paste volume is varied from 360 liters to 309 liters for 400 kg cement and 340 kg cement respectively. The paste volume considered in SCC mix is nearly the same for conventional concrete and still, required rheological properties are achieved without compromising to strength due to packing approach.

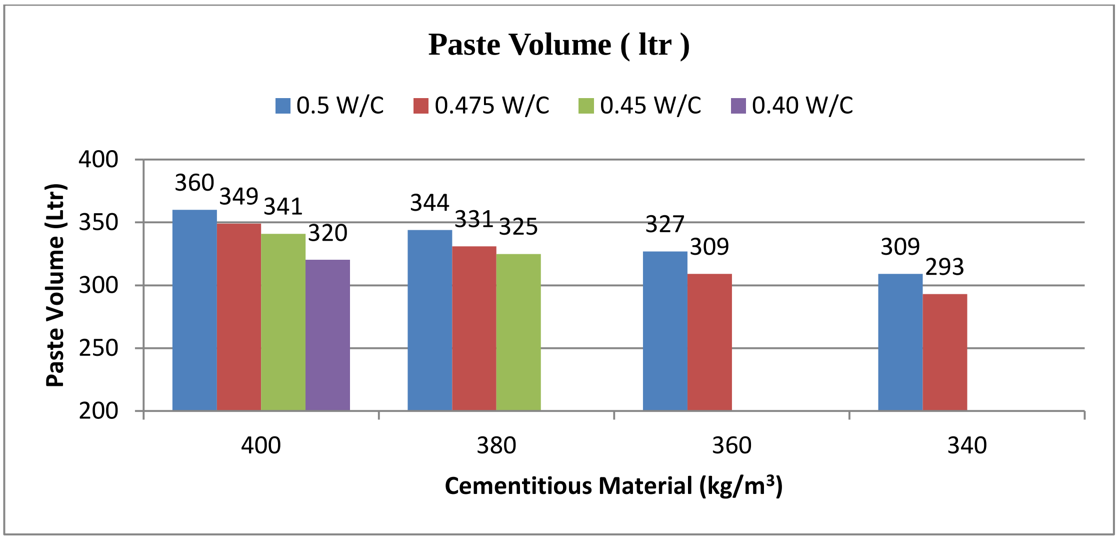


FIGURE 5.20 Paste Volume taken in Design mix for different W/C Ratio for FA 65%

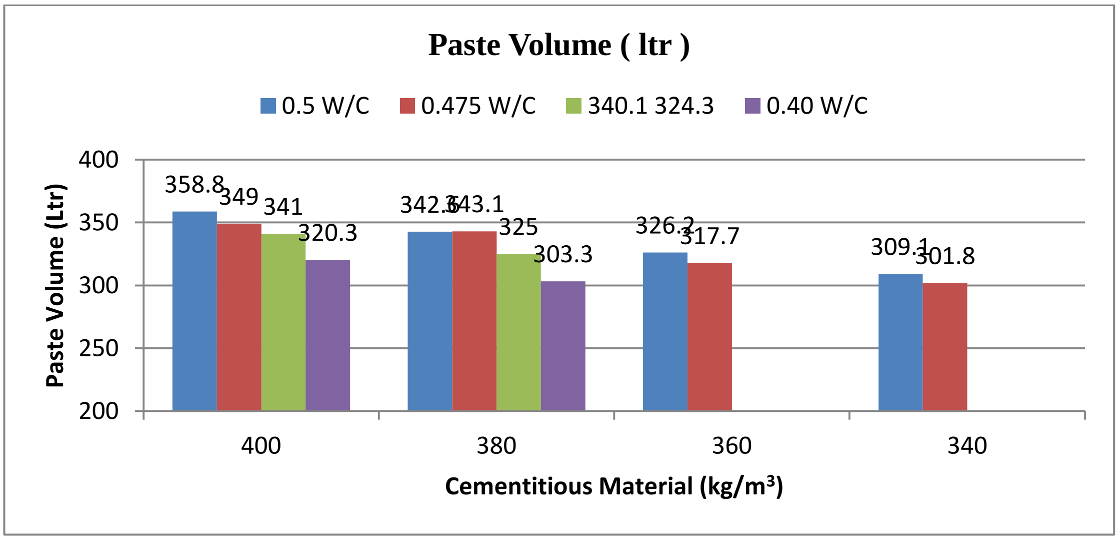


FIGURE 5.21 Paste Volume taken in Design mix for different W/C Ratio for FA 60%

As the objective of the study is to reduce the binder content for designing economical SCC mix, the different response of the SCC mix is measured against the amount of the cementitious material. Compressive strength, Slump flow, T500 time, V-funnel time, L-box (H2/H1) value and sieve segregation portion (%) is measured for different cementitious material and w/c ratio, and the results are presented in TABLE 5.16, TABLE 5.18, TABLE 5.20 and TABLE 5.22. Also, FIGURE 5.12 to FIGURE 5.19 are represented to visualize the quality of SCC mix produced in terms of segregation and bleeding. It can be visualize that all mixes area without bleeding, but due to less cementitious material and w/c ratio, SCC mixes P18, P20, P22 and P23 shows accumulation of aggregate in centre, apart from these mixes all mixes satisfy the required rheological properties.

The results of compressive strength are depicted in FIGURE 5.22 and FIGURE 5.23, the range of compressive strength is varied from 32.95 MPa to 51.32 Mpa for different cementitious material and w/c ratio. So, as targeted, from M20 to M40 grade of concrete is produced using the design mixes. One can choose cementitious material and w/c ratio, as per the requirement of fresh properties. Packing density has positive effect on compressive strength. SCC mixes with FA:CA ratio 65:35 shows little more compressive strength comparing to FA:CA ratio 60:40.

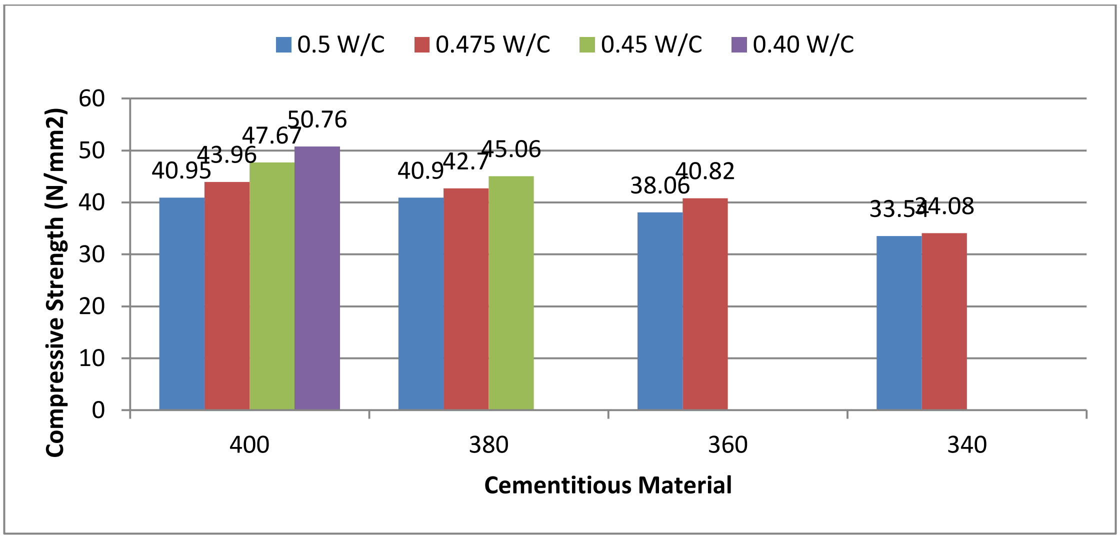


FIGURE 5.22 Compressive strength of Design mix with different W/C Ratio for FA 65%

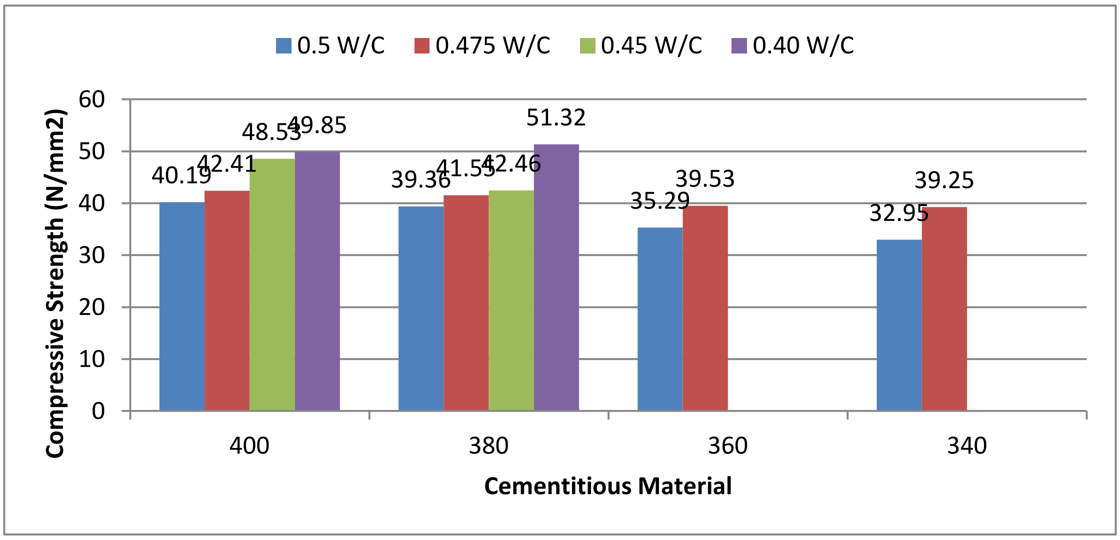


FIGURE 5.23 Compressive strength of Design mix with different W/C Ratio for FA 60%

It is observed that as the amount of cementitious material and w/c ratio is reduced, Slump flow reduces. As presented in FIGURE 5.24, Slump flow mainly depends on free paste flow available after filling the voids of blended coarse and fine aggregate. As the fine aggregate amount is decreased, the dosage of super plasticizer is also reduced. Fine aggregate is necessary for the cohesiveness of the SCC mix. SP dosage can be decided not only based on Marsh cone test but also fine aggregate volume. For different cementitious material and w/c ratio, slump flow value ranges from 550 mm to 700 mm.

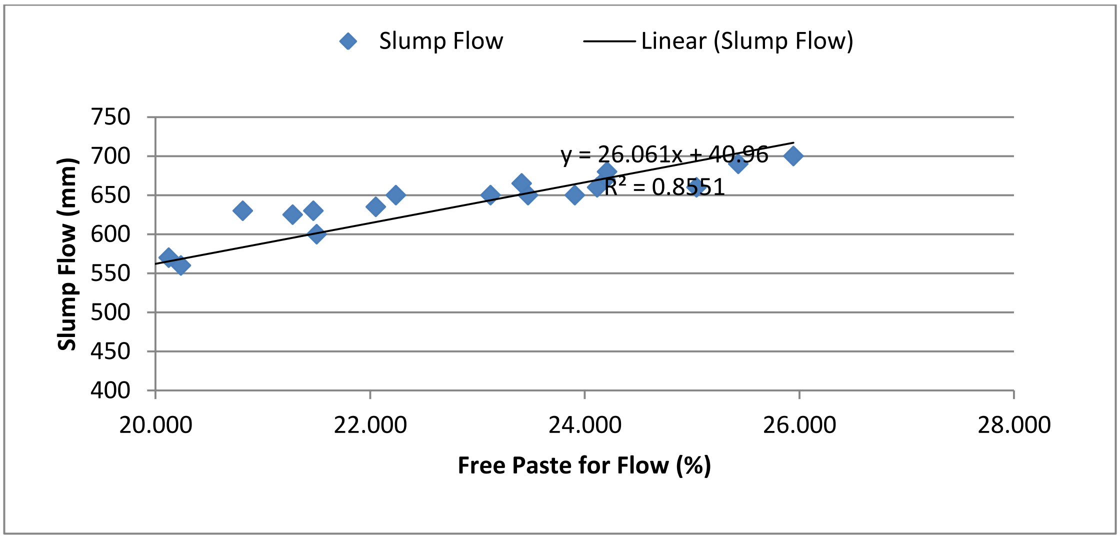


FIGURE 5.24 Slump Flow for Design mix with different W/C Ratio and paste volume

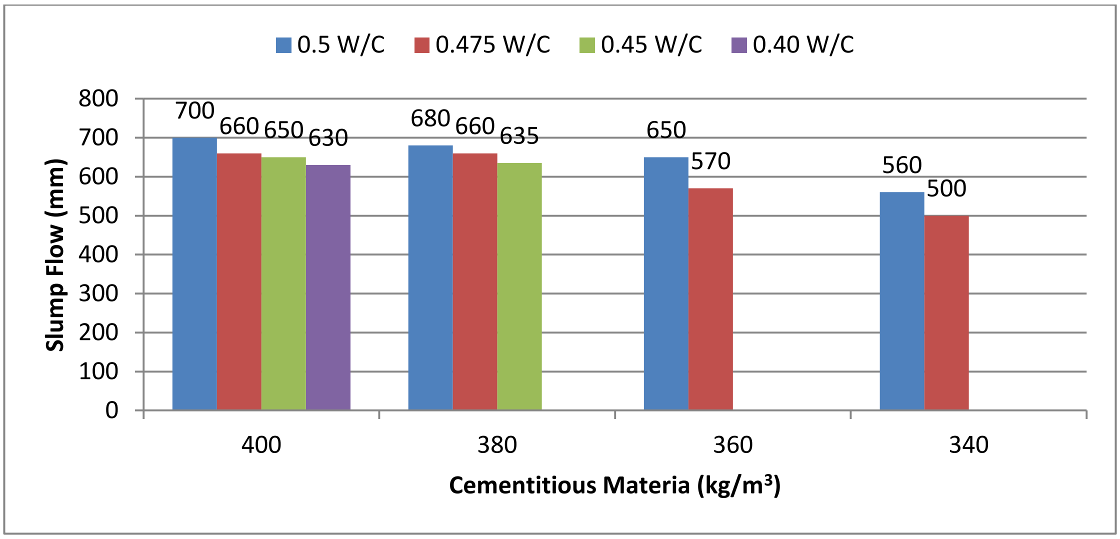


FIGURE 5.25 Slump Flow for Design mix with different W/C Ratio for FA 65%

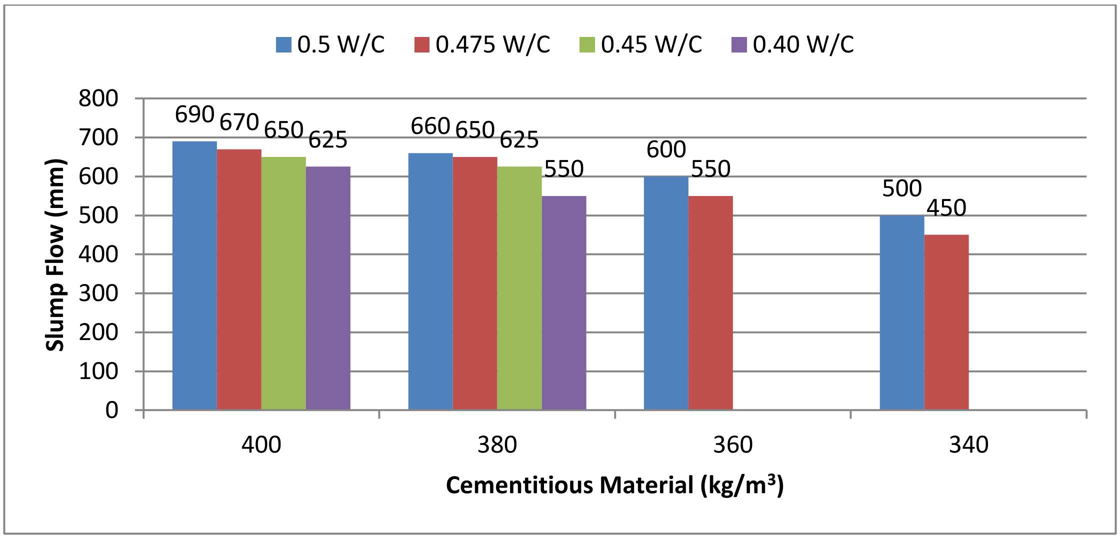


FIGURE 5.26 Slump Flow for Design mix with different W/C Ratio for FA 60%

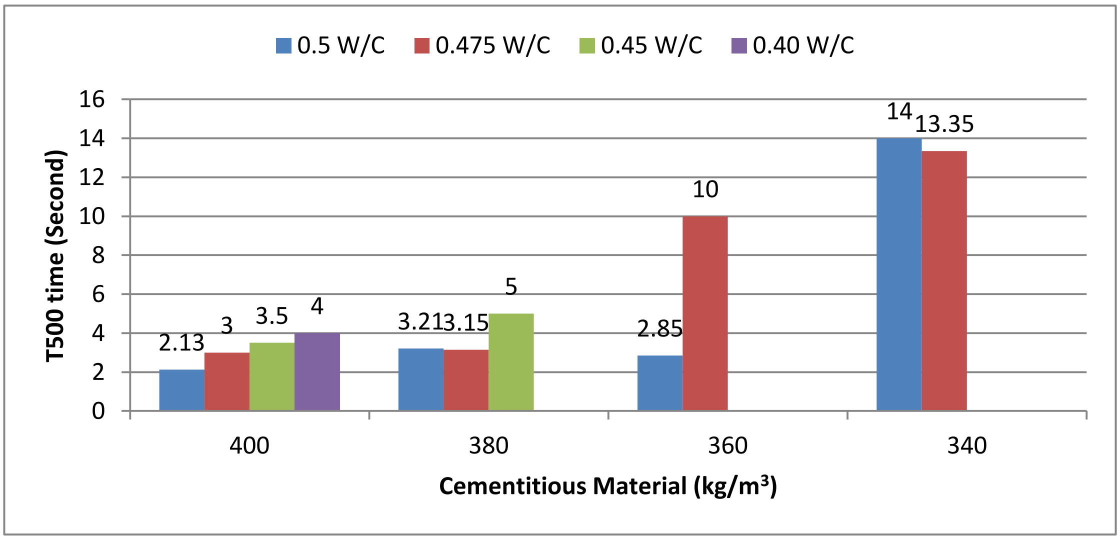


FIGURE 5.27 T_{500} time for Design mix with different W/C Ratio for FA 65%

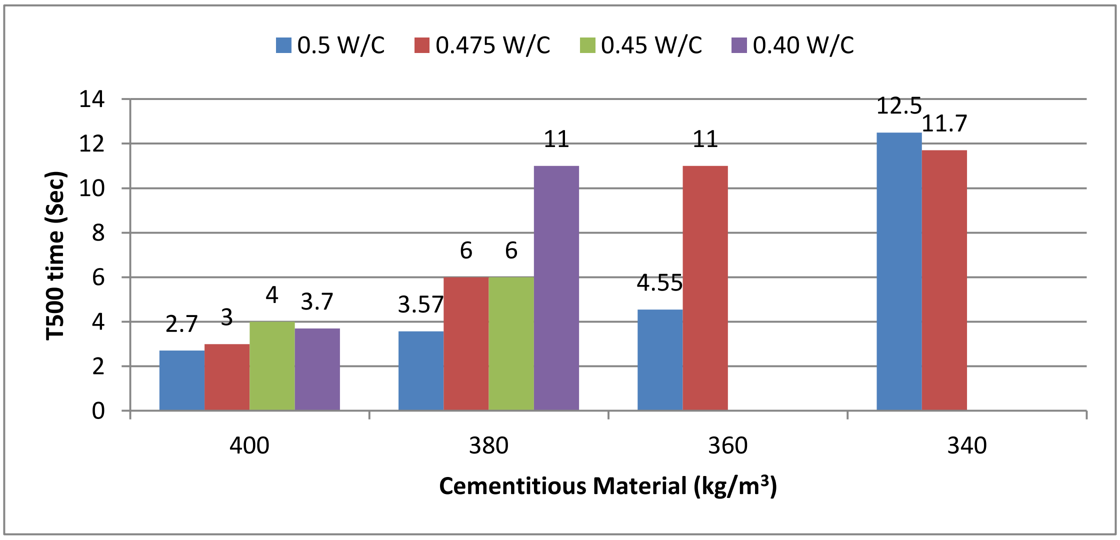


FIGURE 5.28 T_{500} time for Design mix with different W/C Ratio for FA 60%

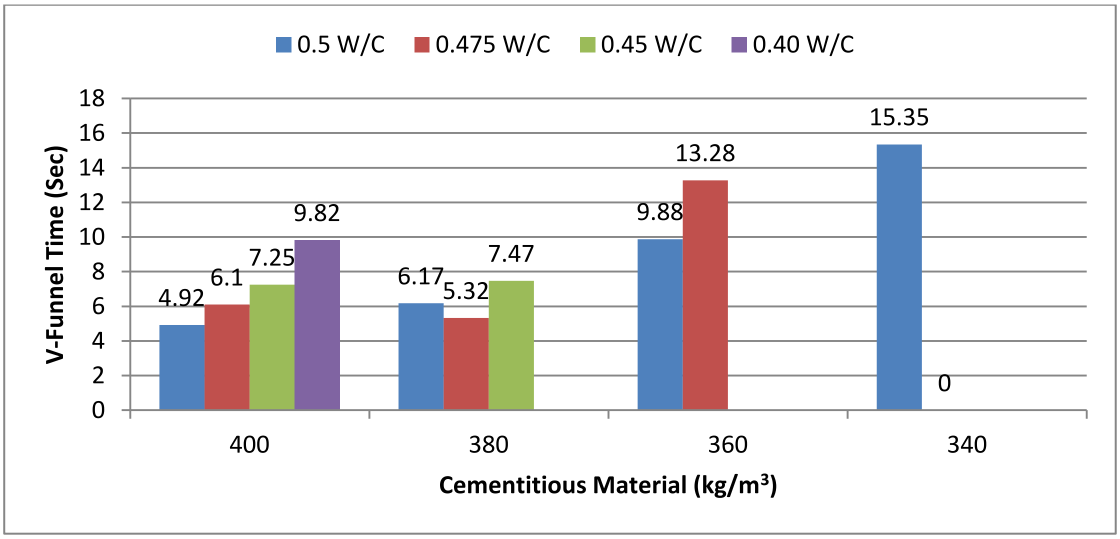


FIGURE 5.29 V-Funnel time for Design mix with different W/C Ratio for FA 65%

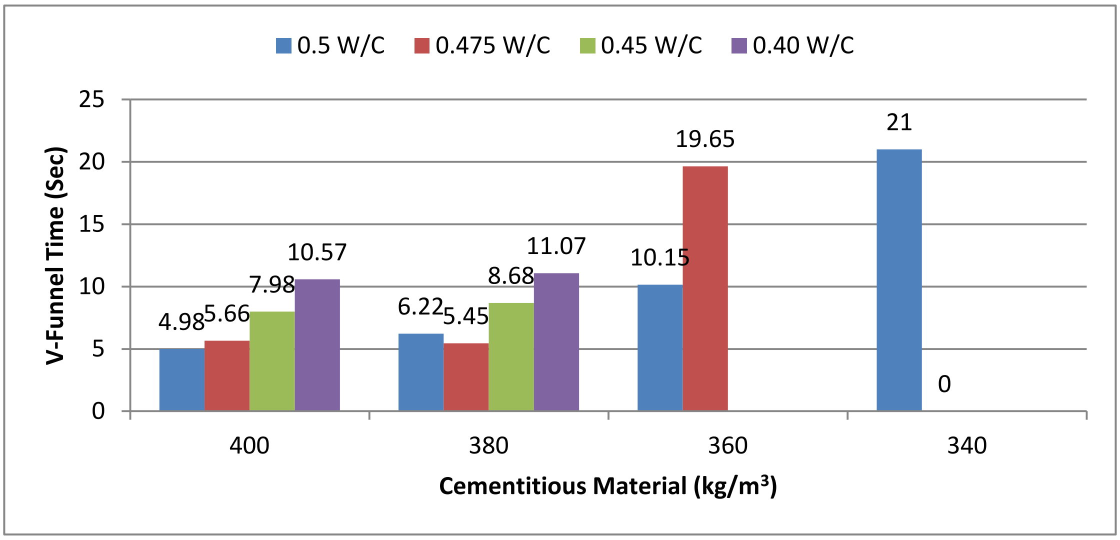


FIGURE 5.30 V-Funnel time for Design mix with different W/C Ratio for FA 60%

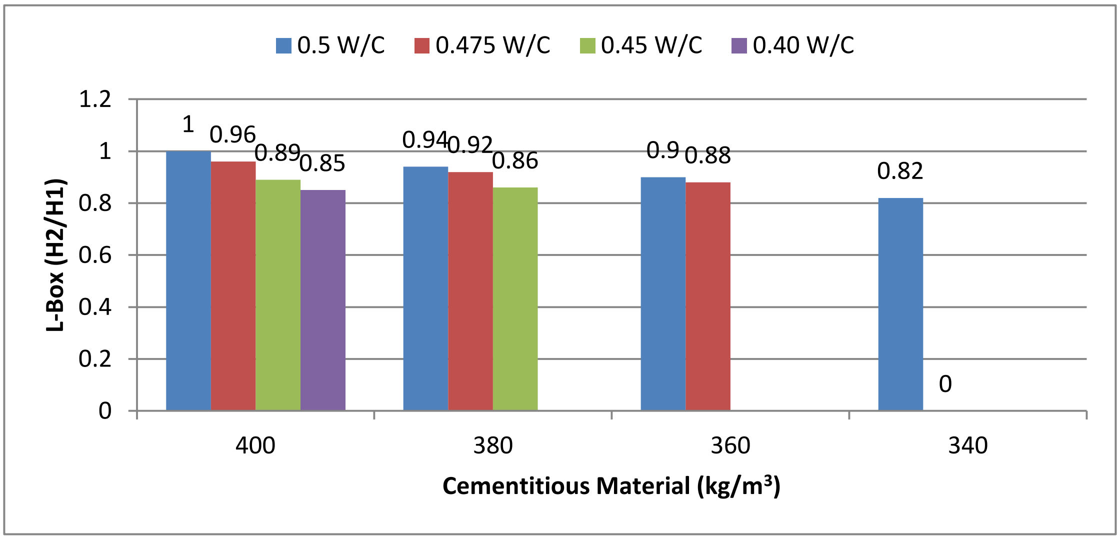


FIGURE 5.31 L-Box (H2/H1) for Design mix with different W/C Ratio for FA 65%

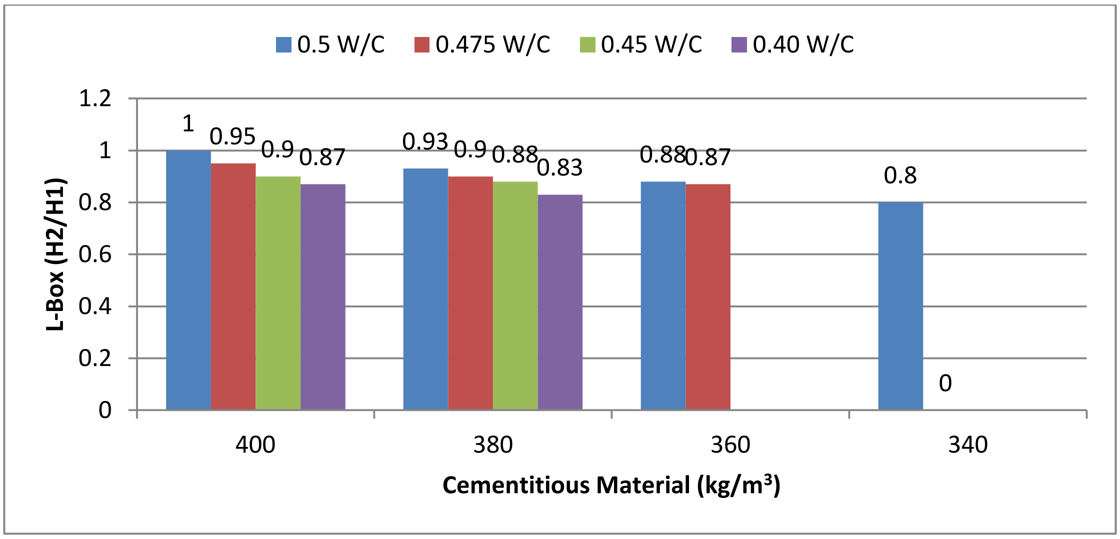


FIGURE 5.32 L-Box (H2/H1) for Design mix with different W/C Ratio for FA 60%

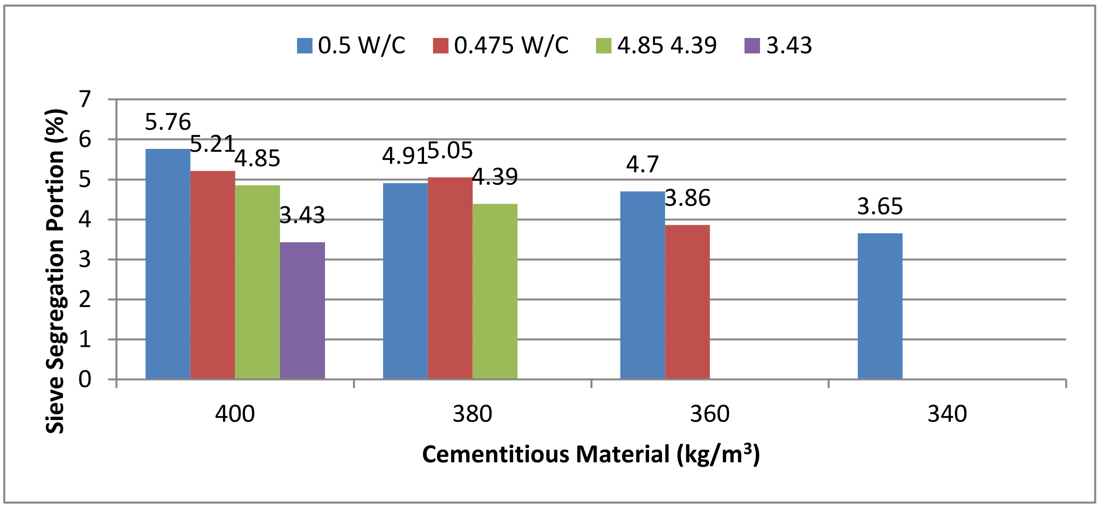


FIGURE 5.33 Sieve Segregation Portion (%/) for design mix with different W/C Ratio for FA 65%

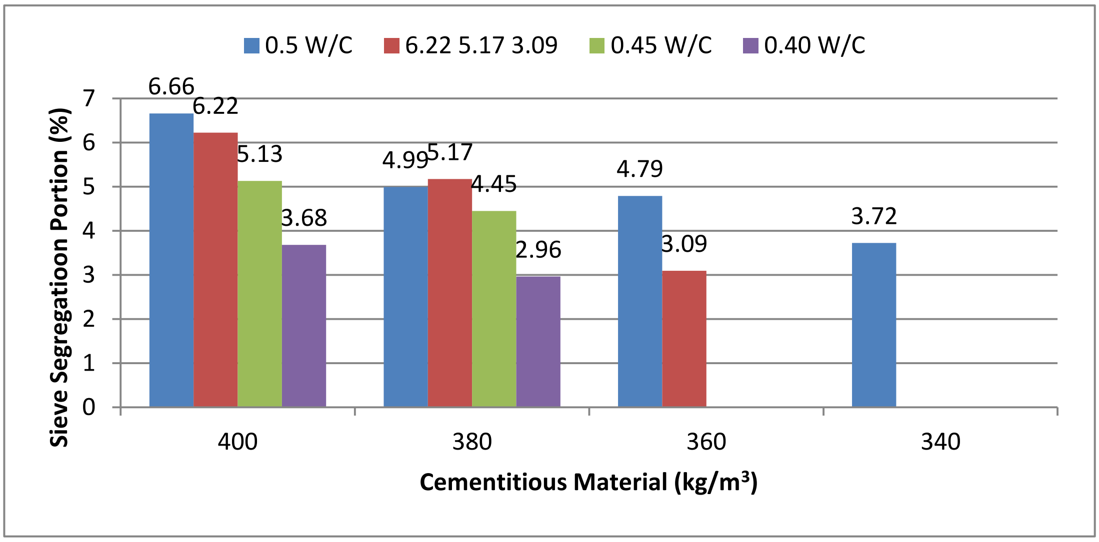


FIGURE 5.34 Sieve Segregation Portion (%/) for design mix with different W/C Ratio for FA 60%

The following conclusion can be made by analyzing the trend shown in FIGURE 5.22 to FIGURE 5.34. In following table trend of different properties of SCC mix measured are presented in the form of + (plus) and - (minus) sign. Plus sign indicates positive correlation i.e. if parameter value increases, the test result value increases and vice versa. E.g. if cementitious material increases, the value of compressive strength increases, so it is denoted by a plus sign.

Parameter	Compressive Strength (MPa)	Slump Flow (mm)	T500 (Sec)	V-funnel (Sec)	L-box	Sieve segregation portion (%)
Cementitious material	+	+	-	-	+	+
w/c	-	+	-	-	+	+

Based on the mix proportion and result presented in TABLE 5.15 to TABLE 5.22 and by analyzing the trend shown in FIGURE 5.22 to FIGURE 5.34 , a guideline for mix proportining of SCC mix is prepared and presented in TABLE 5.23. But, these guidelines are applicable only when packing density is found for fully compacted aggregate (optimal packing) using mechanical vibration.

TABLE 5.23 Guideline for SCC mix proportion based on target strength and slump flow using 20 mm MSA

Target strength	Target Slump Flow	Cementitious material	W/C Ratio	Paste Volume (%)	Free Paste for flow (%)	Packing Density	Fine Aggregate in Total Aggregate
M40	600-650	400 kg	0.40-0.42	32-34	21-23	0.840-0.850	0.60-0.65
M35	660-700	400 kg	0.45-0.47	34-35	23.-24	0.840-0.850	0.60-0.65
	600-650	380 kg	0.42-0.45	30-31	20-21	0.840-0.850	0.60-0.65
M30	700-750	400 kg	0.5	35-36	25-26	0.840-0.850	0.60-0.65
	660-700	380 kg	0.47	33-34	23-24	0.840-0.850	0.60-0.65
	550-650	360 kg	0.45-0.47	31-32	19-20	0.840-0.850	0.60-0.65
M20-M25	660-750	380 kg	0.5	34-35	23-24	0.840-0.850	0.60-0.65
	600-650	360 kg	0.5	32-33	21-22	0.840-0.850	0.60-0.65
	550-600	340 kg	0.5	30-31	18-20	0.840-0.850	0.60-0.65

5.3.6 Relation of Slump Flow with other Fresh Properties of SCC

It is observed that for validation of fresh properties of SCC mix design, slump flow gives the overall idea. At the construction site, many a time only a slump flow test is performed to verify or for speedy determination of the fresh properties. Based on slump flow result of SCC mix having different w/c ratio, paste volume, fine aggregate content, its relation with the other fresh properties like T_{500} time, V-Funnel time, L-Box result and sieve segregation test result are compared and presented in FIGURE 5.35, FIGURE 5.36, FIGURE 5.37 and FIGURE 5.38 respectively. It is clear that from the trends that all the fresh properties are interrelated, therefore for speedy determination of fresh property of SCC mix slump flow can be performed. But, from experiments, it was found that when the mix is not properly cohesive i.e if segregation and bleeding occur in the SCC mix due to improper proportion of the constituent materials, the fresh properties are not interrelated. It happened that, slump flow and T500 time can be measured, but in V-funnel due to bleeding slurry comes out and aggregates got blocked and the same thing happened with L-box, so for all properties to be interrelated, it is necessary to have a good cohesive mix.

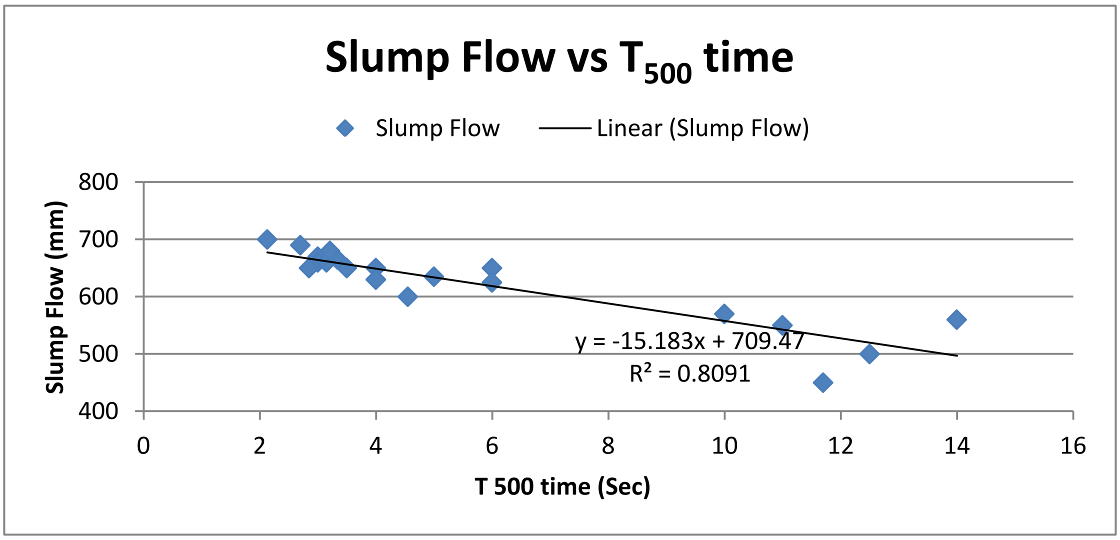


FIGURE 5.35 Correlation between slump flow and T_{500} time

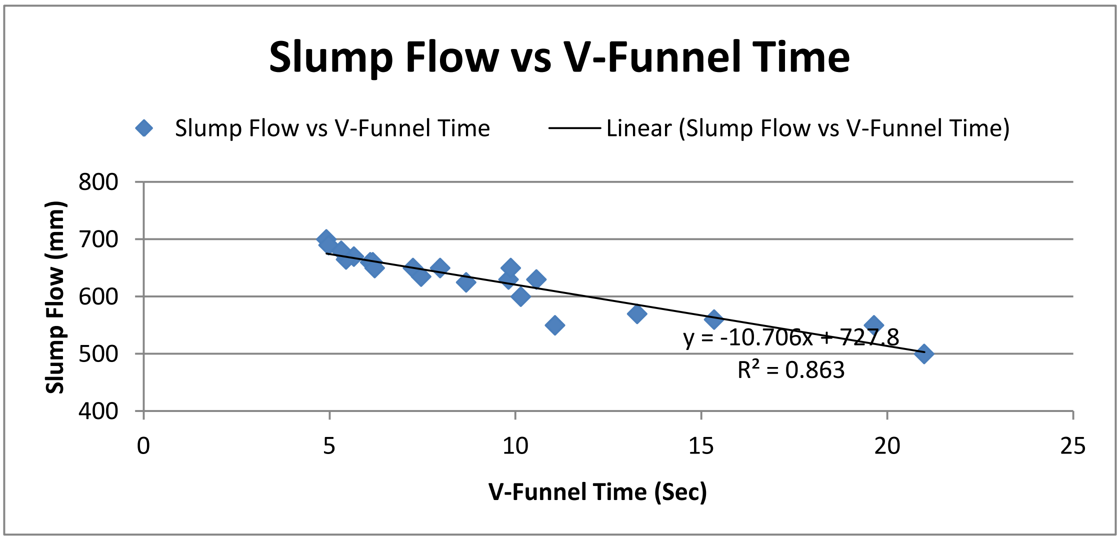


FIGURE 5.36 Correlation between slump flow and V-funnel time

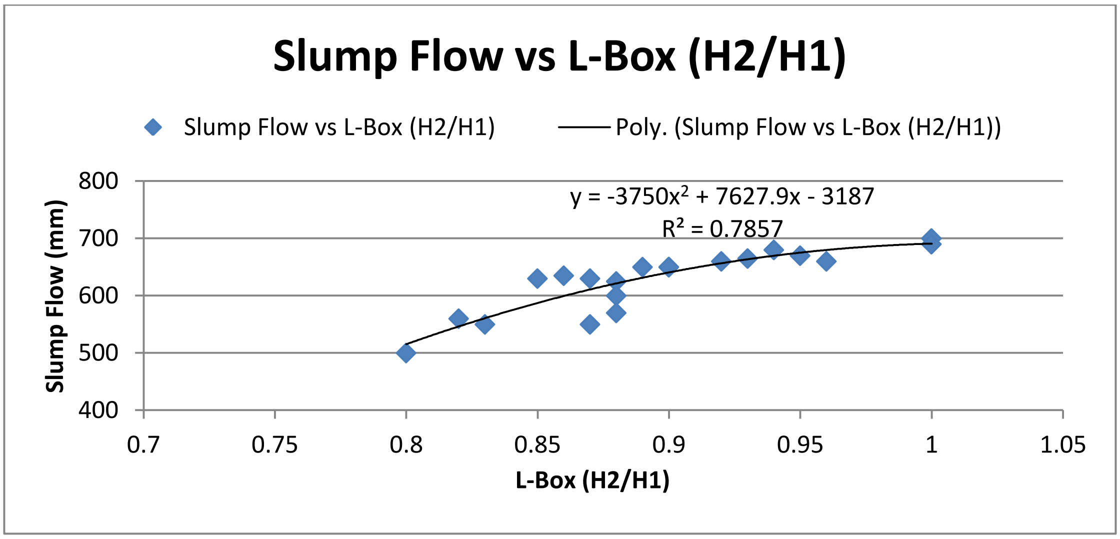


FIGURE 5.37 Correlation between slump flow and L-box value

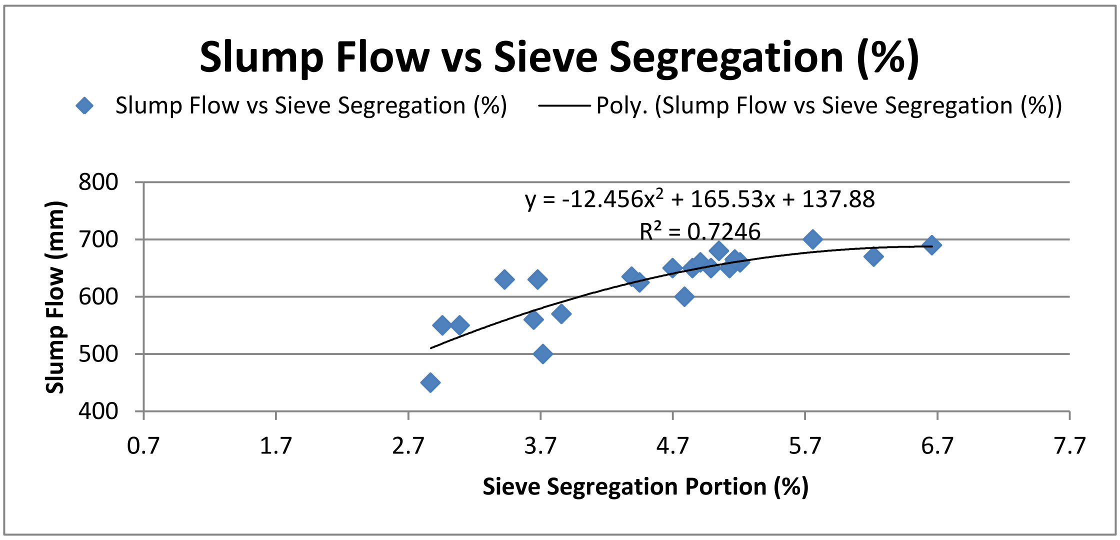


FIGURE 5.38 Correlation between slump flow and Sieve segregation portion

5.4 Multiple Linear Regression Analysis

If a number of variables affecting the response are more, it is not possible to find the effect of all parameters simultaneously on response using Microsoft Excel. There are some powerful tools available for statistical analysis to find the effect of multiple variables on response. The regression model is developed using Minitab software. Minitab is very efficient software used for statistical analysis of research data. In multiple linear regression analysis, a relationship is developed between variables. Here, different variables considered are packing density (PD), Fine aggregate volume (F_V), Paste Volume (P_V), Water to Cementitious material ratio (W/C), Cement Volume (C_V), Water Volume (W_V) and Free Paste Volume (FP). The experimental data and results obtained and presented in aggregate and paste phase are taken for regression analysis. The correlation and effect of these variables on response variable compressive strength (CS), slump flow (SF) and Superplasticizer dosage (SP) were found using regression analysis.

When regression analysis is performed, the goodness of the model must be verified. The values to be observed in regression models are P-value, R square, R square adjusted, Variance inflation Factor (VIF), Standard error and residual plots. If the confidence interval is 95%, then the P-value should be less than 0.05. The variables which have P-Value less than 0.05 are significantly affecting the response. R square value shall be looked at along with residual plots, VIF and P-value. In a residual plot of residuals versus fitted value plot, there should not be any pattern observed. The standard error represents the average distance that the observed values fall from the regression line. Smaller values are better because it indicates that the observations are closer to the fitted line. The VIF estimates how much the variance of a regression coefficient is inflated due to multi collinearity in the model. Lower VIF value is good. Sometimes in the regression model, R square value is very high up to 0.99 but at the same time VIF is also very high more than 10 than the model is not considered good. Minitab software removes the variable, for which the P-value is more than 0.05. After removing the less significant variable having P value more than 0.05, for remaining variables, again R square value is calculated, which is considered as R square adjusted value. Lesser the difference between, R square and R adjusted square value, the model is considered good.

5.4.1 Regression Model for Compressive Strength

Following is the output of Minitab software, showing regression model of Compressive strength (CS) as a response variable. The model suggests that Water volume, Water cement ratio and fine aggregate volume has P value less than 0.05, so they have a significant effect on compressive strength. Other variables which are highly correlated and not significant for predicting compressive strength are automatically omitted by the software. The standard error and VIF are also low. R square value is good. The residual versus fitted value plot does not have any pattern. So, the regression model is quite good for predicting compressive strength.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	477.176	159.059	83.37	0.000
Wv	1	94.467	94.467	49.51	0.000
W/C	1	439.730	439.730	230.48	0.000
Fv	1	9.123	9.123	4.78	0.040
Error	21	40.066	1.908		
Total	24	517.242			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.38127	92.25%	91.15%	87.99%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	91.16	8.10	11.26	0.000	
Wv	0.2359	0.0335	7.04	0.000	2.82
W/C	-214.7	14.1	-15.18	0.000	1.95
Fv	0.0231	0.0106	2.19	0.040	1.65

Regression Equation

CS = 91.16 + 0.2359 Wv - 214.7 W/C + 0.0231 Fv

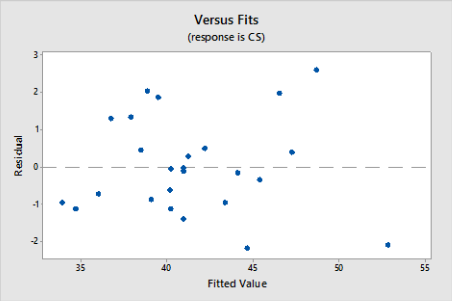


FIGURE 5.39 Residual versus fitted value plot for regression model of Compressive strength (CS)

5.4.2 Regression Model for admixture Dosage

All the criteria of the good regression model are satisfied by the model. It is found that the variables which significantly affect the admixture dosage (SP) are packing density, Paste volume and fine aggregate volume. The residual versus fitted value plot does not have any pattern. So, the regression model is quite good for predicting compressive strength.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regressiaon	3	0.70181	0.233936	28.63	0.000
PD	1	0.42423	0.424230	51.92	0.000
Pv	1	0.31361	0.313611	38.38	0.000
Fv	1	0.07190	0.071905	8.80	0.007
Error	21	0.17158	0.008171		
Total	24	0.87339			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0903917	80.35%	77.55%	73.05%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	9.569	0.976	9.80	0.000	
PD	-9.68	1.34	-7.21	0.000	3.61
Pv	-0.00681	0.00110	-6.20	0.000	1.62
Fv	0.00323	0.00109	2.97	0.007	4.07

Regression Equation

SP = 9.569 - 9.68 PD - 0.00681 Pv + 0.00323 Fv

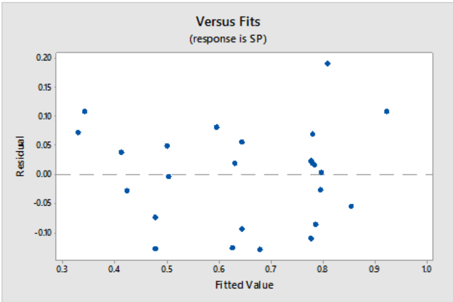


FIGURE 5.40 Residual versus fitted value plot for regression model of admixture Dosage (SP)

5.4.3 Regression Model for Slump Flow

For slump flow (SF) many regression models were tried. In one regression model, R square value obtained was 0.98 with P value less than 0.05. But VIF values were too high. Also, the standard error was high. So, the following model was finalized as a good regression model for slump flow. It is very clear that the significant factor for slump flow is the free paste volume remained after filling of voids between aggregates.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	45428	45427.7	179.45	0.000
FP	1	45428	45427.7	179.45	0.000
Error	23	5822	253.1		
Total	24	51250			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
15.9105	88.64%	88.15%	86.40%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	166.5	34.2	4.86	0.000	
FP	2.072	0.155	13.40	0.000	1.00

Regression Equation

SF = 166.5 + 2.072 FP

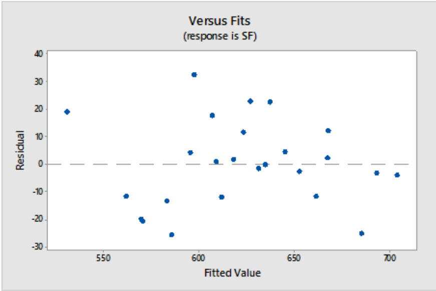


FIGURE 5.41 Residual versus fitted value plot for regression model of Slump Flow (SF)

5.5 Proposed Method for mix design

This new approach aims to develop a mix design method for medium resistance SCC mix proportioning through optimization of voids and paste content. The proposed method aims to develop self-compacting concrete with minimum trials and economy, as currently, self-compacting concrete is not prevalent due to its cost and cumbersome and arbitrary mix design methods.

Based on the result achieved and considering other parameters like packing density, paste volume etc, a guideline for SCC mix proportion is provided in TABLE 5.23.

As discussed earlier, as slump flow value can be correlated with other SCC test like V-funnel, L-box, sieve segregation etc., the present mix design is based on target slump flow and target compressive strength. Also, the present mix design method is developed for concrete compressive strength from 20 MPa to 35 MPa and w/c ratio limit of 0.5, and based on the experimental results presented in this study.

5.5.1 Flow chart showing procedure of mix design of SCC

As discussed earlier, the proposed mix design method is based on the particle packing approach. The mix design is divided into two phase aggregate phase and paste phase. In FIGURE 5.42, proposed mix design procedure is explained through flow chart.

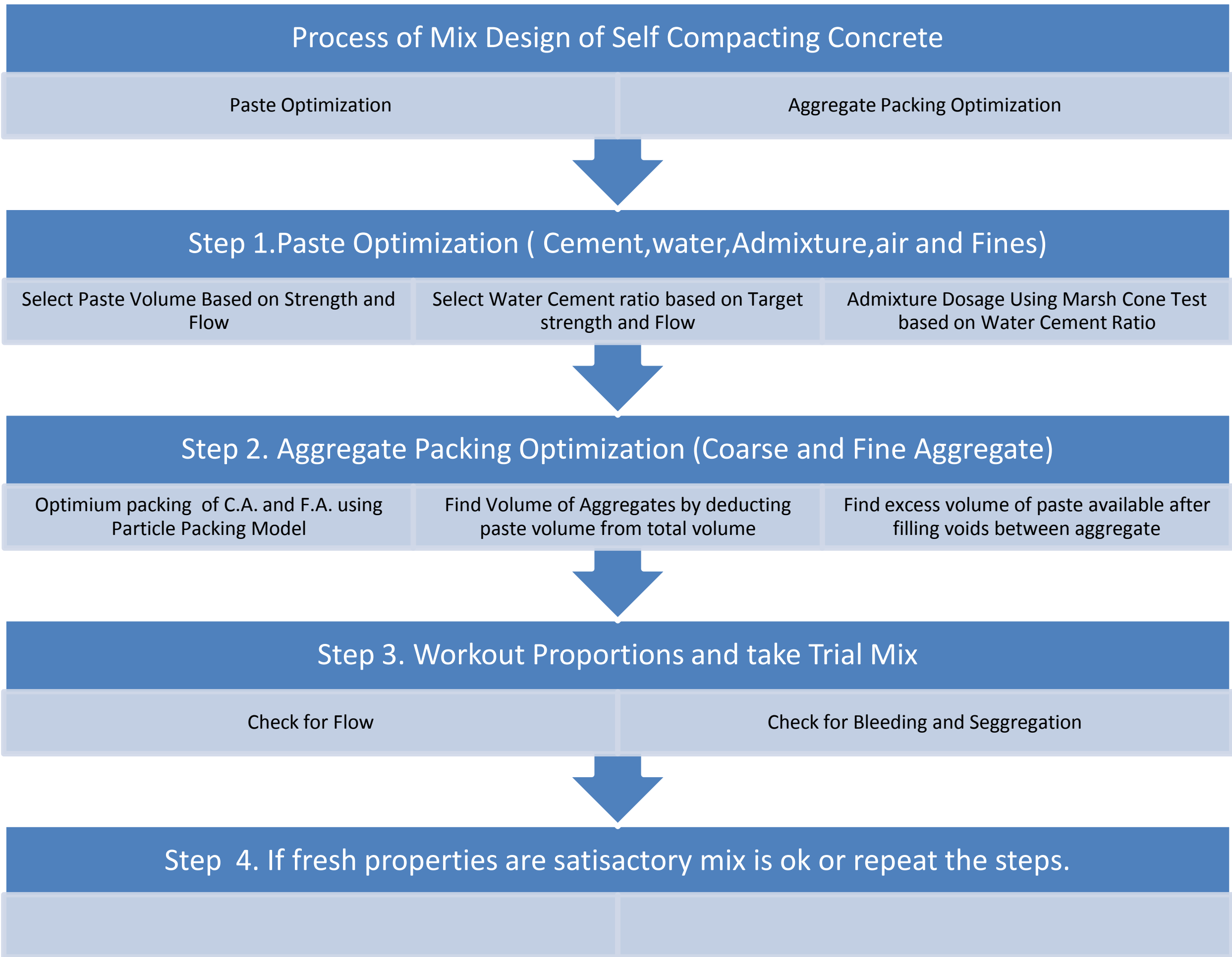


FIGURE 5.42 Flowchart for proposed mix design

5.5.2 Stepwise Procedure of mix design

Step-1 Find out material properties like specific gravity, gradation, water absorption and bulk density.

Step-2 Using the proposed particle packing model, determine the aggregate combination which gives the maximum packing density. Here aggregate includes both fine and coarse aggregate as well as any filler material used. The gradation of blended fine and coarse aggregate should follow the gradation given in below table, which is prepared using particle packing model. Also, work out voids in the aggregate based on the packing density. **(Aggregate Phase)**

Suggested Combined gradation for SCC			
Sieve	**Percentage passing**	**Range of sieve**	**Percentage 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

Step-3 Verify the packing density experimentally for a given combination of aggregate.**(Aggregate Phase)**

Step-4 Based on the target cube compressive strength and slump flow, assume weight of cementitious material and water to cementitious material ratio as per the guidelines given in TABLE 5.23. Find out weight and volume of the cement, water and admixture. Also, determine the paste volume, which includes the volume of cementitious material, water, admixture and assumed air content. Based on the packing density, determine free paste volume available after filling the voids of aggregates. Free paste volume and paste composition determine the target slump flow. **(Paste Phase)**

Using marsh cone test find out the optimum dosage of PCE based admixture for cement used and for given water-cement ratio. The dosage of superplasticizer needs to be adjusted based on the fine and coarse aggregate amount.

Find free paste using the following formula.

$$SF = 166.5 + 2.072\ FP$$

Where, SF is the targeted slump flow and FP is the free paste available.

Mix Design Guideline for SCC mix proportion based on target strength and slump flow using 20 mm MSA

Target strength	Target Slump Flow	Cementitious material	W/C Ratio	Paste Volume (%)	Free Paste for flow (%)	Packing Density	Fine Aggregate in Total Aggregate
M40	600-650	400 kg	0.40-0.42	32-34	21-23	0.840-0.850	0.60-0.65
M35	660-700	400 kg	0.45-0.47	34-35	23.-24	0.840-0.850	0.60-0.65
	600-650	380 kg	0.42-0.45	30-31	20-21	0.840-0.850	0.60-0.65
M30	700-750	400 kg	0.5	35-36	25-26	0.840-0.850	0.60-0.65
	660-700	380 kg	0.47	33-34	23-24	0.840-0.850	0.60-0.65
	550-650	360 kg	0.45-0.47	31-32	19-20	0.840-0.850	0.60-0.65
M20-M25	660-750	380 kg	0.5	34-35	23-24	0.840-0.850	0.60-0.65
	600-650	360 kg	0.5	32-33	21-22	0.840-0.850	0.60-0.65
	550-600	340 kg	0.5	30-31	18-20	0.840-0.850	0.60-0.65

Step-5 Find Volume of aggregate and weight of aggregate.

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

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= Total Volume of blended aggregate

W= Total weight of blended aggregate

G= Specific gravity of material

P= Percentage proportion of aggregate in total aggregate

Step-6 Verify the regression equation of compressive strength and superplasticizer dosage

CS = 91.16 + 0.2359 Wv - 214.7 W/C + 0.0231 Fv

SP = 9.569 - 9.68 PD - 0.00681 Pv + 0.00323 Fv

To prepare the final concrete mix, first coarse and fine aggregate where mixed in the dry state thoroughly, then cementitious material is added and again mixing is done in dry state till homogeneous dry mix is produced. In second step, first 75% water is added in the dry mix and mixing is done, and then in remaining 25% water PCE based admixture is added.

5.5.3 Sample calculation of Mix design for Self compacting concrete

Let the Target cube compressive strength is 25 N/mm^2 and targeted slump flow is 660-700 mm for normally reinforced concrete structure.

Step-1 Find out material properties like specific gravity, gradation, water absorption and bulk density and packing density.

Material	Specific Gravity	Water Absorption
Cement	2.9	-----
Coarse Aggregate (20 mm)	2.86	1.11
Coarse Aggregate (10 mm)	2.86	1.41
Fine Aggregate	2.57	1.89
PCE based Super Plasticizer Master Glenium Sky 8549	1.1	-----

Material	Bulk Density (kg/m3)	Voids (%)	Packing Density=(100-Voids)/100
Coarse Aggregate (20 mm)	1637.39	42.75	0.573
Coarse Aggregate (10 mm)	1718.54	39.91	0.601
Fine Aggregate	1885.62	26.63	0.734

Step-2 Using the proposed particle packing model, determine the aggregate combination which gives the maximum packing density.

	Fine Aggregate (Sand)	**Coarse Aggregate (10 mm)**	**Coarse Aggregate (20 mm)**	**Combined gradation of 65% 20 mm CA blended with 35% FA**		
Packing Density	0.734	0.601	0.573	0.845		
Sieve Size (mm)	% Passing	% Passing	% Passing	% Passing	Range of Sieve	%passing between two consecutive sieve
20	100	100	92.5	97.38	20-10	30.10
10	100	90.5	14	69.90	10-4.75	8.67
4.75	94.2	6.5	0	61.23	4.75-2.36	6.27
2.36	84.55	1	0	54.96	2.36-1.18	11.54
1.18	66.8	0	0	43.42	1.18-0.6	6.34
0.6	57.05	0	0	37.08	0.6-0.3	20.18
0.3	26	0	0	16.90	0.3-0.15	13.29
0.15	5.55	0	0	3.61	0.15-0.075	3.09
0.075	0.8	0	0	0.52		

So, maximum packing density of 0.845 is achieved when 65% 20 mm CA blended with 35% FA. Also, combined gradation follows the guideline prepared using particle packing model.

Step-3 Verify the packing density experimentally for a given combination of aggregate. (Aggregate Phase)

Step-4 Based on the target cube compressive strength and slump flow, assume weight of cementitious material and water to cementitious material ratio as per the guidelines given in TABLE 5.23. Find out the weight of the cement, water and admixture. (Paste Phase)

From, guideline given in Table, for slump flow 660-700 and M25 grade of concrete 380 kg cementitious material with w/c ratio 0.5 can be taken for trial. Also, paste volume shall be around 34-35%.

Find free paste using the following formula.

$$SF = 166.5 + 2.072\ FP$$

Let for slump flow 670 mm, Free paste volume required is = 243liter

Now, Paste volume for current mix is calculated as below.

Cement volume = 380/2.9= 131.03 liter

Water Volume = 190 liter(For w/c =0.5)

Assume 2% air volume for 20 mm MSA. = 20 liter

Superplasticizer dosage = 0.7% of weight of cement (Marsh cone test)

= 2.66 kg = 2.66/1.1= 2.42 liter

Therefore, total paste volume = 343.45 liter

So, Total aggregate volume = 1000 – 343.45 = 656.55 liter

Now, for 0.845 packing density, volume of voids in 656.55 liter aggregate

= 0.155 * 656.55 = 101.76 liter

Therefore, free paste available = 343.45 – 101.76 = 241.69 liter

Step-5 Find Volume of aggregate and weight of aggregate.

Volume of aggregate = 656.55 liter.

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

$$W = \frac{656.55}{\frac{0.65}{2.57}+\frac{0}{2.86}+\frac{0.35}{2.86}+\frac{0}{2.72}} = 1750.8 \text{ kg}$$

W_{FA}=0.65X1750.8=1137.55 kg and

W_{20mm}=0.35X1750.8=612.78 kg

So, final proportions are

Material	**Weight (kg)**	**Volume (litre)**
Cement	380	131.03
Water	190	190
20 mm CA	612.78	214.26
Fine Aggregate	1137.55	442.63
Superplasticizer	2.66	2.42
Air Content	0	20
Total	**2322.99 Kg**	**1000 litre**

Step-6 Verify the regression equation

CS = 91.16 + 0.2359 Wv - 214.7 W/C + 0.0231 Fv

= 91.16+0.2359*190-214.7*0.5+0.0231*442.63

= 38.85 N/mm2 > 31.25 N/mm2 Hence OK

SP = 9.569 - 9.68 PD - 0.00681 Pv + 0.00323 Fv

= 9.569 -9.68 * 0.845 -0.00681 * 343.45 + 0.00323 * 442.63

= 0.48 % < 0.70 %

So, initially superplasticizer should be added 0.48% of cement weight and if mix is not workable enough, it can be increased up to 0.70%.

5.6 Major Conclusions from Chapter

- It is possible to produce SCC mix using locally available material just like conventional concrete without any specialized material except superplasticize using particle packing approach.
- Particle packing approach saves binders for manufacturing SCC particularly for medium resistance concrete where to achieve target slump flow more paste is required using conventional approach.
- Increase in packing density results in more free paste and therefore SCC mixes shows better fresh properties. Also, as packing density increases the proneness to segregation is decreases.
- For medium resistance concrete having less paste volume (equivalent to conventional concrete) required more sand fines, to make SCC mixes cohesive and to reduce segregation.
- It is more suitable to find fines in total aggregate rather in fine aggregate particularly for SCC mix having medium resistance, because fine aggregate proportion in total aggregate is different so fines will be varied in total aggregate with the change in amount of fine aggregate. Based on study it is recommended to have at least 4% fines in total aggregate for good cohesive SCC mix without segregation.
- Based on the mix design guideline and using particle packing model a simplified mix design approach for medium resistance concrete is successfully articulated, the approach very robust as well as economical.
- Regression model prepared using experimental data is successfully validated by performing mix design of SCC.

CHAPTER 6

Conclusion

6.1 Conclusion

6.1.1 Conclusions on Particle Packing Model

- The proposed model is very efficient in calculating packing density. It also clearly and fundamentally explains the particle packing phenomenon. The proposed model does not involve any complex mathematical calculation and is simple and easy to use for practical implementation. The tests used in the proposed method are conventional, simple, and cheap, and could be performed in any laboratory.
- Packing density for gradation of other models is found using proposed model and shown in Table.4.13. The comparison of proposed model with other models and also with experimental results proves the efficiency of the model in predicting packing density for multi-component angular aggregate.
- The error in predicting packing density goes on decreasing as packing density approaches to optimum level, and for optimum packing density the difference between experimental and analytical packing density is less than 1%.
- The particle packing model is checked for two different size of coarse aggregate, having different gradation and volume of particles. The result of estimated packing density closely matches with the experimental packing density with less than 5% error. Therefore, proposed model can be used for any size of aggregate universally.
- The gradation range of blended coarse and fine aggregate for optimum packing density found using proposed particle packing model is compared with continuous and discrete models. The particle size distribution obtained through present particle packing model closely matches with compression packing model for particle size 0.6-20 mm and with modified A&A model having distribution modulus 0.29 for particle size smaller than 0.6 mm. The Optimum PSD using present model contains more fine particles same as CPM model, which is more suitable in producing SCC.

- By adjusting the volume and size of particles, it is possible to get optimum packing density using this model. To achieve optimum packing density ternary and binary packed particles should be maximized, and unpacked particles should be minimized.

6.1.2 Conclusions based on experimental work

- Maximum slump flow for 10 mm MSA was 635 mm using 400 kg cementitious material, while 650 mm slump flow was observed using only 360 kg cementitious material for 20 mm MSA, due to higher packing density. So, about 15-20% binders can be saved using the particle packing approach.
- In the present study, for same aggregate volume, paste volume and paste composition but different packing density, the increment of 12.86% was observed in slump flow, while increment of 2.64% was observed in compressive strength due to increase in packing density. So, it can be concluded that packing density has a predominant effect on fresh properties while the strength was not much affected and also if the size of aggregate is decreased mix becomes more cohesive.
- It is observed that, dosage of Super plasticizer cannot be decided only on the basis of Marsh cone test, it also depends volume of fine aggregate. As the fine aggregate amount is decreased, the dosage of super plasticizer is also reduced. SP dosage decided by Marsh cone test should be modified based on fine aggregate volume.
- It is important that for medium resistance concrete with less paste volume enough amount of sand fines are necessary for making SCC mix cohesive. It is more effective to find sand fines in total aggregate volume rather than in fine aggregate volume. From results it is clear that the minimum volume of sand fines in total aggregate about 4% is necessary in SCC mix to make it cohesive and also due to this compressive strength is not much affected.
- In paste composition, water volume affects more on fresh properties comparing to cement volume. So, for economical SCC mix for medium resistance concrete, water volume should be kept as maximum as possible so that it does not cause bleeding and segregation, at the same time it should be within the limits of structural concrete.
- To produce economical SCC mix having less cementitious material EFNARC guidelines must be compromised. In the current study for 20 MSA water/powder ration by volume is used up to 1.45 and for 10 MSA up to 1.23. EFNARC guideline suggests 0.85-1.1. Similarly, sand to the total aggregate ratio by weight is suggested as 0.48-

0.55, but in the present study, it is successfully taken up to 0.48-0.65 for 20 MSA and 0.52-0.65 for 10 MSA.

- A guideline for mix proportining of SCC mix is prepared and presented in Table 5.23. But, this guidelines are applicable for optimum packing density of aggregate (fully compacted) found using mechanical vibration.
- All the fresh properties of SCC are interrelated, therefore for speedy determination of fresh property of SCC mix only slump flow can be performed at site, provided that SCC mix is cohesive without segregation and bleeding.
- New mix design procedure proposed using particle packing model, based on the target slump flow and compressive strength is simple and effective to produce good SCC mix with less binders.
- To estimate compressive strength (CS), Superplasticize dosage (SP) and slump flow (SF) following equations are derived performing multiple regression analysis in Minitab.

  $CS = 91.16 + 0.2359\ Wv - 214.7\ W/C + 0.0231\ Fv$

  $SP = 9.569 - 9.68\ PD - 0.00681\ Pv + 0.00323\ Fv$

  $SF = 166.5 + 2.072\ FP$
- The paste volume considered in SCC mix is nearly the same for conventional concrete and still, required rheological properties are achieved without compromising to strength due to packing approach.
- In countries like India, If SCC replaces conventional concrete, durability issues produced due to lack of compaction can be eliminated and thereby maintenance cost of concrete structures can be reduced and age of structures can be increased.

6.2 Achievements with respect to objectives

All the objectives of the research are achieved. The developed particle packing model is effective and simple in predicting compacted packing density of blended coarse and fine aggregate. The basic theory and parameters which affect particle packing are identified and presented successfully. Also using this model, mix design procedure for self-compacting concrete is given. The mix design procedure is very simple and it is possible to produce economical SCC using cementitious material nearly equal to conventional concrete with least trials. This encourages the users to use SCC in general construction in place of conventional concrete and thereby the quality of concrete and age of concrete can be increased. Gradation of blended coarse and fine aggregate is suggested which can be helpful to produce SCC in minimum trials. The suggestion is given to modify EFNARC guidelines to produce economical SCC. Also using regression analysis, variables significantly affecting compressive strength, slump flow and admixture dosage are identified and the relation between them is established to predict the response

6.3 Future Scope

The SCC mix can be further developed by even more less binders by introducing an air-entraining agent to improve fresh properties and using silica fume to improve hardened properties with less binders.

The work done in this research can be further investigated for higher strength of concrete. Also, utilization of waste materials having the capacity to improve fresh and hardened properties of concrete can be investigated. Also, long term durability test and microstructure analysis can be performed.

Further, the particle packing concept is more useful when the amount of aggregate volume is more in the SCC mix. It can be investigated that up to what amount of aggregate volume, packing concept is useful for different grade of concrete.

The effect of specific gravity of the coarse aggregate on fresh properties of SCC mix can be studied.

Optimum requirement of water for fixed cementitious material so that no segregation is observed in SCC mix can be found.

LIST OF REFERENCES

1. H Okamura,M Ouchi, Self-compacting concrete, Journal of advanced concrete technology, 1(1) (2003) 5-15.
2. Shi C, Wu Z, Lv K, Wu L, A review on mixture design methods for self-compacting concrete, Constr. Build. Mater., 84 (2015) 387-398.
3. W.B. Fuller, S.E. Thompson, The laws of proportioning concrete, Trans. ASCE. 33 (1907) 67–172.
4. A.H.M. Andreasen, J. Andersen, Relation between grain size and interstitial space in products of unconsolidated granules, Kolloid. 50 (1930) 217–228.
5. J.E. Funk, D.R. Dinger, Particle-packing phenomena and their application in materials processing, Mrs Bulletin, 22(12) (1997) 19-23.
6. H.J.H. Brouwers, H.J. Radix, Self-compacting concrete: theoretical and experimental study, Cem. Concr. Res. 35 (11) (2005) 2116–2136.
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. I.Mehdipour, K.H. Khayat., Understanding the role of particle packing characteristics in rheo-physical properties of cementitious suspensions: A literature review, Construction and Building Materials, 161 (2018) 340-353.
9. B.Esmaeilkhanian, K.H.Khayat, O.H.Wallevik, Mix design approach for low-powder self-consolidating concrete: Eco-SCC—content optimization and performance. Materials and Structures 50(2) (2017) 124.
10. 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.
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 optimization with 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. J Dewar,Computer modeling of concrete mixtures, CRC Press, 2002.
16. RK McGeary, Mechanical packing of spherical particles, Journal of the American Ceramic Society. 44(10) (1961) 513-522.
17. JA Elliott, A Kelly, AH Windle, Recursive packing of dense particle mixtures, Journal of Materials Science Letters. 21(16) (2002) 1249-1251.
18. 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.
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. 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.
21. 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.
22. 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.
23. F.Pelisser, A.Vieira, A.M.Bernardin, Efficient self-compacting concrete with low cement consumption, Journal of Cleaner Production, 175 (2018) 324-332.
24. P.Ghoddousi, A.A.S.Javid, J.Sobhani, Effects of particle packing density on the stability and rheology of self-consolidating concrete containing mineral admixtures, Constr. Build. Mater., 53 (2014) 102-109.
25. C.Bibm, E.E.Ermco, The European guidelines for self-compacting concrete:specification, production and use, 2005.
26. P. Nanthgopalan and M. Santhanam, An empirical approach for the optimization of aggregate combinations for self-compacting concrete, Materials and structures 45 (2012) 1167-1179.
27. P. Nanthgopalan and M. Santhanam, Experimental investigations on the influence of paste composition and content on the properties of Self-Compacting Concrete, Construction and building materials 23 (2009) 3443-3449.
28. Nan Su, KC Hsu, HW Chai, A simple mix design method for self-compacting concrete, Cement and concrete research, 31(12) (2001), 1799-1807.

29. MR Jones, L Zheng, MD Newlands, Comparison of particle packing models for proportioning concrete constituents for minimum voids ratio, Materials and structures, 35(5)(2002) 301-309.
30. MN Mangulkar, SS Jamkar, Review of particle packing theories used for concrete mix proportioning, International Journal Of Scientific & Engineering Research,4(5) (2013) 143-148.
31. D'Souza B, Yamamiya H, Applications of smart dynamic concrete InThird International Conference on Sustainable Construction Materials and Technologies, (2013) 18-21.
32. A Bhattacharya, I Ray, J Davalos, Effects of aggregate grading and admixture/filler on self-consolidating concrete, Open Construction and Building Technology Journal. 2 (2008) 89-95.
33. J. Guru Jawahar, C. Sashidhar, IV Ramana Reddy, J. Annie Peter, Effect of coarse aggregate blending on short-term mechanical properties of self compacting concrete, Materials & Design, 43 (2013), 185-194.
34. BIS: 456, Plain and reinforced concrete code for practice, Bureau of Indian Standards.(2000).
35. ACI 301, Specifications for structural concrete, American Concrete Institute. (2010).
36. BIS 9103, Concrete Admixtures: Specification, Bureau of Indian Standard, Delhi. (1999).
37. BIS 1489, Portland pozzolona cement-specifications, Part 1–Fly ash based, Bureau of Indian Standards. (2015).
38. BIS 383, Specification for coarse and fine aggregates from natural sources for concrete. (2016).
39. BIS 2386 (Part I), Methods of test for aggregate for concrete Part I Particle Size and Shape, Bureau of Indian Standards. (2002).
40. 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).
41. ASTM C29. Standard test method for bulk density ('unit weight') and voids in aggregate. American Society for Testing and Materials. 2003.
42. Shrivastava AK, Kumar M. Compatibility issues of cement with water reducing admixture in concrete. Perspectives in Science. 2016 Sep 1;8:290-2.
43. Roussel N, Le Roy R. The Marsh cone: a test or a rheological apparatus?. Cement and Concrete Research. 2005 May 1;35(5):823-30.

44. Neville AM. Properties of concrete. London: Longman; 1995 Jan.
45. Shetty MS. Concrete technology. S. chand & company LTD. 2005 May:420-53.
46. BIS 516, Method of Test for Strength of Concrete, Bureau of Indian Standards. (1999).
47. H. Zhao, S Wei, W. Xiaoming and G Bo, The effect of sand ration on the properties of self-compacting concrete, Magazine of concrete research, 65(5) (2013) 275-282.
48. T Bouziani, Assessment of fresh properties and compressive strength of self-compacting concrete made with different sand types by mixture design modelling approach, Construction and Building Materials 49 (2013) 308-314.
49. Ana S, Jose A, Noe V., Antonio A., Experimental study about the effects of granular skeleton distribution on the mechanical properties of self-compacting concrete (SCC), Constr. Build. Mater., 76 (2015) 40-49.
50. Nikbin I.M., Beygi M.H.A, Kazemi M.T., Vasighi A.J., Rehmani E. and Rabbanifar S., A comprehensive investigation into the effect of aging and coarse aggregate size and volume on mechanical properties of self-compacting concrete, Materials and Design, 59 (2014) 199-210.

LIST OF PUBLICATIONS

[1] Nimodiya, P. N. and Patel, H. S. “Effect of Packing Density on Properties of Self Compacting Concrete”. International Journal of Civil Engineering and Technology (IJCIET)**(Scopus Indexed Journal**), 9(11), 2018, pp. 2126-2131.ISSN: 0976-6308

[2] Nimodiya P.N., Patel H.S.,"Experimental Investigation of Effect of Sand Fines on Properties of Self Compacting Concrete",International Journal of Emerging Technologies and Innovative Research**(UGC Approved Journal)**, Sep 1,5 (9),2018 ,pp980-985. ISSN: 2349-5162

Appendices

APPENDIX A: Spreadsheet calculations of Packing Density for 35% 20 mm Coarse aggregate blended with 65% fine aggregate

1. Calculation of Combined gradation

Sieve Size (mm)	1/7th size of Particle	Available size for packing		Fine Aggregate (Sand)	Coarse Aggregate (10 mm)	Coarse Aggregate (20 mm)	65:00:35		
				PD 0.734	PD 0.601	PD 0.573	Packing Density (PD) 0.847		
		Passing	Retained	Passing (%)	Passing (%)	Passing (%)	Combined Passing (%)	Particle retained between two consecutive sieves (%)	passing between two consecutive sieve (%)
20	2.86	2.36	1.18	100	100	92.5	97.38	20-10	30.10
10	1.43	1.18	0.6	100	90.5	14	69.90	10-4.75	8.67
4.75	0.68	0.60	0.30	94.2	6.5	0	61.23	4.75-2.36	6.27
2.36	0.34	0.30	0.15	84.55	1	0	54.96	2.36-1.18	11.54
1.18	0.17	0.150	0.075	66.8	0	0	43.42	1.18-0.6	6.34
0.6	0.09	0.075	Pan	57.05	0	0	37.08	0.6-0.3	20.18
0.3	0.04			26	0	0	16.90	0.3-0.15	13.29
0.15				5.55	0	0	3.61	0.15-0.075	3.09
0.075				0.8	0	0	0.52		0.52

Voids in 20 mm Coarse Aggregate = 0.427

2. Calculation of Ternary Packing of Aggregates

	Size Range of particle (mm) (1)	Available Particle (%) (2)	Voids (%) (3)	Packed particle (%) (4)	Unpacked Particle (2)-(4) (%) (5)	Volume of Particles (6)
Ternary Packing 1	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	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. Calculation of Binary and Single component Packing of Aggregates

Size Range of particle (%)	Particle left after ternary packing (%)	Voids (%)	Particle range available for void filling (mm)	Available particle for packing (%)	Used Particle for packing (%)	Binary packed particles (%)	Volume of coarser particle (%)	Volume of finer particle (%)	Unpacked (Single Component) Particle (%)
20-10	1.26	0.54	2.36-1.18	0.00	0.00	0.00			1.26
10-4.75	0.00	0.00	1.18-0.6	2.64	0.00	0.00			0.00
4.75-2.36	6.27	2.68	0.6-0.3	20.18	2.68	8.95	**70.1%**	**29.9%**	-2.68
2.36-1.18	0.00	0.00	0.30-0.15	8.37	0.00	0.00			0.00
1.18-0.6	2.64	1.13	0.15-0.075	1.51	1.13	3.76	**70.1%**	**29.9%**	-1.13
0.6-0.3	20.18	----	----	0.00	0.00	0.00			20.18
0.3-0.15	8.37	----	----	0.00	0.00	0.00			8.37
0.15-0.075	1.51	----	----	0.00	0.00	0.00			1.51
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

$$\text{Packing Density} = \frac{59.26 * 0.947 \ + \ 12.71 * 0.859 + 28.03 * 0.625}{59.26 + 12.71 + 28.03} = \mathbf{0.847}$$

APPENDIX B: Spreadsheet calculations of Packing Density for 35% 10 mm Coarse aggregate blended with 65% fine aggregate

1. Calculation of Combined gradation

Sieve Size (mm)	1/7th size of Particle	Available size for packing		Fine Aggregate (Sand)	Coarse Aggregate (10 mm)	Coarse Aggregate (20 mm)	65:35:00		
				PD 0.734	PD 0.601	PD 0.573	Packing Density (PD) 0.784		
		Passing	Retained	Passing (%)	Passing (%)	Passing (%)	Combined Passing (%)	Particle retained between two consecutive sieves (%)	passing between two consecutive sieve (%)
20	2.86	2.36	1.18	100	100	92.5	100	20-10	3.33
10	1.43	1.18	0.6	100	90.5	14	96.67	10-4.75	33.17
4.75	0.68	0.60	0.30	94.2	6.5	0	63.50	4.75-2.36	8.20
2.36	0.34	0.30	0.15	84.55	1	0	55.31	2.36-1.18	11.89
1.18	0.17	0.150	0.075	66.8	0	0	43.42	1.18-0.6	6.34
0.6	0.09	0.075	Pan	57.05	0	0	37.08	0.6-0.3	20.18
0.3	0.04			26	0	0	16.9	0.3-0.15	13.29
0.15				5.55	0	0	3.61	0.15-0.075	3.09
0.075				0.8	0	0	0.52		0.52

Voids in 10 mm Coarse Aggregate = 0.40

2. Calculation of Ternary Packing of Aggregates

	Size Range of particle (mm) (1)	Available Particle (%) (2)	Voids (%) (3)	Packed particle (%) (4)	Unpacked Particle (2)-(4) (%) (5)	Volume of Particles (6)
Ternary Packing 1	10-4.75	33.17	13.27	15.84	17.33	**64.1%**
	1.18-0.6	6.34	2.54	6.34	0.00	**25.6%**
	0.15-0.075	3.09	----	2.54	0.55	**10.3%**
	Total	**42.60**		**24.72**	**17.88**	100%
Ternary Packing 2	20-10	3.325	1.33	3.325	0.00	**64.1%**
	2.36-1.18	11.8875	0.53	1.33	10.56	**25.6%**
	0.30-0.15	13.2925	----	0.53	12.76	**10.3%**
	Total	**28.505**		**5.19**	**23.32**	100%
Total ternary packed particles=				**24.72+5.19= 29.91 %**		

3. Calculation of Binary and Single component Packing of Aggregates

Size Range of particle (%)	Particle left after ternary packing (%)	Voids (%)	Particle range available for void filling (mm)	Available particle for packing (%)	Used Particle for packing (%)	Binary packed particles (%)	Volume of coarser particle (%)	Volume of finer particle (%)	Unpacked (Single Component) Particle (%)
20-10	0.00	0.00	2.36-1.18	10.56	0.00	0.00			0.00
10-4.75	17.33	6.93	1.18-0.6	0.00	6.93	0.00			17.33
4.75-2.36	8.1975	3.28	0.6-0.3	20.18	3.28	11.48	0.714	0.286	-3.28
2.36-1.18	10.56	4.22	0.30-0.15	12.76	4.22	14.78	0.714	0.286	-4.22
1.18-0.6	0.00	0.00	0.15-0.075	0.55	0.00	0.00			0.00
0.6-0.3	20.1825	----	----	0.00	0.00	0.00			20.18
0.3-0.15	12.76	----	----	0	0.00	0.00			12.76
0.15-0.075	0.55	----	----	0	0.00	0.00			0.55
Pan	0.52								0.52
Total	**69.58**					**26.26**			43.84

Total Ternary packed particle.	29.90
Total Binary packed particle	26.26
Total Unpacked particle	43.84
Total	100

Packing Density = $$\frac{29.90 * 0.947 + 26.26 * 0.859 + 43.84 * 0.625}{29.90 + 26.26 + 43.84} = \mathbf{0.784}$$

Appendix C: Comparison of Experimental and Analytical Packing Density (PD)

Blending of aggregate (FA:10mm:20mm)	Experimental PD	Analytical PD	Error (%)	Blending of aggregate (FA:10mm:20mm)	Experimental PD	Analytical PD	Error (%)
100:00:00	0.734	0.772	-5.124	100:00:00	0.734	0.769	-4.768
95:00:05	0.78	0.783	-0.420	95:05:00	0.774	0.780	-0.829
90:00:10	0.79	0.795	-0.625	90:10:00	0.785	0.792	-0.871
85:00:15	0.8	0.807	-0.824	85:15:00	0.792	0.803	-1.421
80:00:20	0.81	0.818	-1.019	80:20:00	0.8	0.807	-0.924
75:00:25	0.812	0.830	-2.207	75:25:00	0.796	0.800	-0.447
70:00:30	0.83	0.842	-1.395	70:30:00	0.791	0.792	-0.091
65:00:35	0.845	0.847	-0.292	65:35:00	0.791	0.784	0.899
60:00:40	0.835	0.834	0.066	60:40:00	0.788	0.776	1.516
55:00:45	0.832	0.821	1.271	55:45:00	0.778	0.768	1.257
50:00:50	0.822	0.808	1.654	50:50:00	0.771	0.760	1.376
45:00:55	0.820	0.798	2.744	45:55:00	0.765	0.753	1.627
40:00:60	0.810	0.778	3.909	40:60:00	0.762	0.745	2.268
35:00:65	0.800	0.759	5.104	35:65:00	0.755	0.737	2.399
30:00:70	0.789	0.740	6.210	30:70:00	0.740	0.729	1.479
25:00:75	0.745	0.721	3.244	25:75:00	0.732	0.721	1.473
20:00:80	0.724	0.702	3.085	20:80:00	0.720	0.713	0.919
15:00:85	0.708	0.683	3.602	15:85:00	0.71	0.706	0.627
10:00:90	0.691	0.663	4.004	10:90:00	0.7	0.691	1.325
05:00:95	0.665	0.644	3.133	05:95:00	0.678	0.673	0.701
00:00:100	0.573	0.625	-9.075	00:100:00	0.601	0.638	-6.102