PACKING CONCEPT IN MODERN CONCRETE

FINAL YEAR PROJECT UG-2012

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Abstract

Concrete is the second largest material used after water in the world. The use of concrete in construction industry has increased immensely since its advent. The cost of concrete is primarily controlled by the amount of cement it contains. In order to reduce the paste content without jeopardizing the strength factor of concrete, packing theory is introduced. The packing concept in concrete is defined as the packing or arrangement of solid particles of the mix; mainly aggregate and binder in such a manner that minimizes the voids present in the mix. As small size aggregates fill the voids between large size aggregates and binder fills the voids between fine aggregate, the overall void ratio of the mix decreases.

In the first domain of the project, to achieve the maximum packing, two ranges of material were taken; fine aggregate (0 - 2.36 mm) and coarse aggregate (2.36 - 6 mm). The properties of aggregate both coarse and fine were determined. The particle distribution curves of fine and coarse aggregates were developed and compared with the particle distribution envelope provided by the ASTM standards. The curves were then modelled according to Modified Andreasen & Andersen Model. The purpose was to optimize the particle distribution that would result in maximum packing of aggregate. Prisms (40 x 40 x 160 mm) were then casted having three water-cement ratios of 0.30, 0.35 and 0.40 for both SCM and SCC systems. The strength test results show that, for an optimum value of distribution modulus and lower water-cement ratio, highest strength is achieved.

In the second domain of the project, two ranges of material were taken; fine aggregate (0 - 2.36 mm) and coarse aggregate (13.2 mm down). The specific gravity, rodded and un-rodded bulk densities and void ratios were determined for different combinations of coarse and fine aggregates. The maximum packing was achieved for the mix having equal parts of fine and coarse aggregate. The concrete cubes of 4 inches were then casted for different sand to coarse ratios i.e. 60:40, 50:50 and 40:60 keeping a constant water-cement ratio of 0.42 for the self-consolidating concrete (SCC) systems. The strength test results show that the packing mix that has the minimum amount of voids contains equal parts of coarse and fine aggregate and results in higher strength and durability than a normal concrete.

The research work concludes that higher the packing density of SCC systems, lower is the cement paste demand in the mix. This reduction in the requirement of cement paste leads to higher strength, durability and sustainability.

Contents

List of Figures

List of Tables

List of notations

α	Packing density of the mix
$CPFT$	Cumulative percentage finer than
d	Particle size
d_{max}	Maximum particle size in the mix
d_{min}	Minimum particle size in the mix
d_r	Larger to smaller diametric ratio b/w consecutive sizes of aggregates
ε	Porosity of the mix
L, W, H	Length, width and height of the aggregate particle
M_c	Mass of mix in the container
M_p	Mass of particles filled in the container
OPC	Ordinary Portland cement
PSD	Particle size distribution
q	Distribution modulus for Andreasen & Modified Andreasen model
r_1	Relative volume of large size particles in the mix
r_2	Relative volume of small size particles in the mix
SCC	Self-Consolidating/Compacting Concrete
SCM	Self-Consolidating Mortar
SP	Superplasticizer
V_v	Volume of voids
V_s	Volume of solids in a mix
V_t	Total or bulk volume of the mix
ρ_p	Density of solid particles
ρ_{Bulk}	Bulk density
$\rho_{particle}$	Particle density
u_w	Water/solid ratio
XRF	X-ray Fluorescence
VEA	Viscosity Enhancing Agent
SSD	Saturated-surface dry
WD	Water Demand
ASTM	American Society for Testing and Materials

Chapter 1

Introduction

1.1 General

Concrete is the second largest material used after water. The use of concrete in construction industry has increased immensely since its advent. Concrete is made up of three basic components, namely; Paste, Mortar and concrete. The quality for which concrete is so widely used is the strength and durability it provides to structures. Concrete gains its strength from the paste that surrounds the aggregate. The paste is mixture of powder and water. Powder can be any cementitious material mainly cement itself. The cost of cement is very high and major part of construction cost is due to the quantity of cement used. In order to minimize the use of paste (binder), packing concept is introduced in concrete mix.

The packing concept in concrete is defined as the packing or arrangement of solid particles of the mix mainly aggregate and binder in such a manner that minimizes the voids present in the mix. As aggregate of small size fill the voids between aggregate of large size and binder fills the voids between fine aggregate [1], the overall void ratio of the mix decreases. The water that would have otherwise filled these voids is now available to provide lubrication and workability to the mix. The amount of paste is therefore reduced as the voids are filled by fine aggregate and only less amount of binder is now required. This decrease in binder results in decrease in shrinkage and creep and increase in durability and strength.

The maximum particle size density of aggregate in the concrete mix can be attained by using several packing models. These models are designed to obtain minimum voids in a concrete mix. The pioneer of the field of particle packing in concrete mixes was Furnas [11] who in 1930 proposed a model for binary mixes to predict the optimum particle density. Later, he extended the model to incorporate granular mixes of various sizes. The Furnas model is as follows:

$$CPFT = \frac{{d_r}^{\log d} - {d_r}^{\log dmin}}{{d_r}^{\log dmax} - {d_r}^{\log dmin}} \tag{1.1}$$

Here, CPFT is the cumulative percentage finer than the sieve opening d, d_r is the ratio between consecutive sizes of aggregate particles (larger size to smaller size) and d_{min} and d_{max} are minimum and maximum size of aggregate in the mix respectively.

In the beginning of 20th century, Füller and Thompson [12] proposed particle size distribution model for the design of concrete mixes. The Füller curve is relatively simple and only takes the maximum aggregate size in to account in the calculations for giving the PSD curve. The Füller model is given below:

$$CPFT = (d/d_{max})^q \tag{1.2}$$

Here 'CPFT' is the cumulative percentage of the material finer than the sieve opening d, 'd_{max}' is maximum sized particle in the mix and q is the distribution modulus of value 0.5.

After Füller and Thompson, the efforts were made by Andreasen and Andersen to improve the grading curve by proposing the use of exponent 'q' in the range of 0.33 to 0.50 instead of one fixed value as done previously [12]. The model is as follows:

$$CPFT = (d/d_{max})^q \tag{1.3}$$

Here 'q' is the distribution modulus for the Andreasen & Andersen curve. The value of distribution modulus is the function of shape, texture, angularity, roundness, density and the porosity of the particles for which the ideal PSD curve is being established.

Towards the end of last century, Dinger and Funk [12] observed that the naturally occurring materials have some minimum size limit below which particle size does not exist. To overcome this limitation of Andreasen & Andersen model, they incorporated the diameter of minimum sized particle in the mix to give the model a practical approach [12]. Modified Andreasen & Andersen model is given as follows:

$$CPFT = \frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q} \times 100 \tag{1.4}$$

Here, CPFT is the cumulative percentage finer than the sieve opening d, 'q' is the distribution modulus and d_{min} and d_{max} are minimum and maximum size of aggregate in the mix respectively.

The particle size distribution (PSD) curves given by above discussed models differ from each other due to the varying assumptions in deriving these models. Following Figure 1 gives the comparison of the PSD curves produced from the models described above.

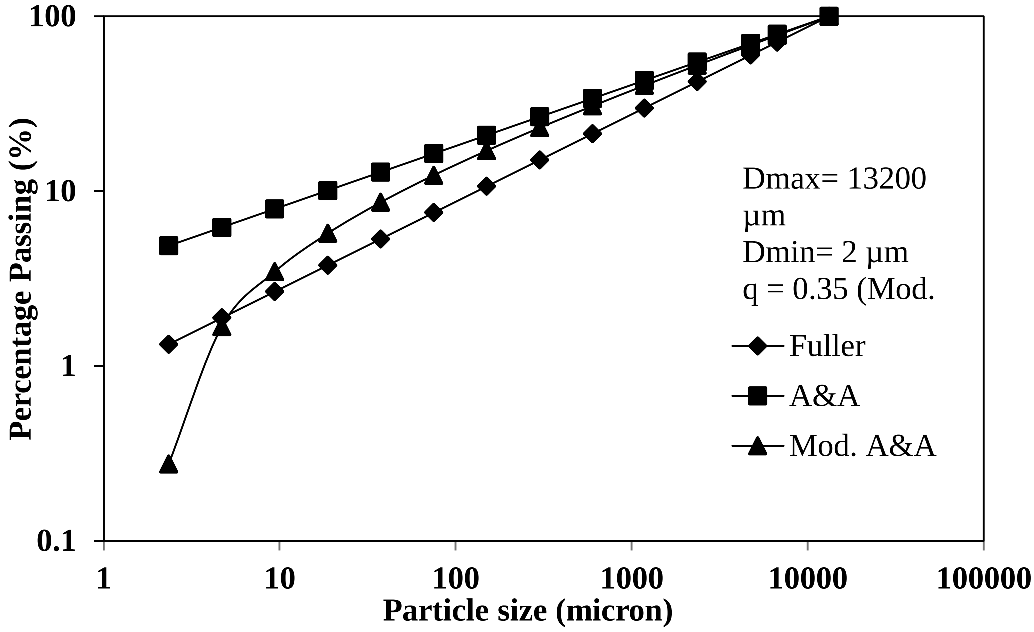

Figure 1: Percentage passing for different models

The present research hence utilizes the Modified Andreasen & Andersen model to find the efficient grading curve for the self-consolidating cementitious systems capable of providing better packing and good workability at low paste content.

1.2 Research Objective

The purpose of this project is to establish the optimum grading curve that will give the maximum particle density using the aggregates of Pakistan. Secondly, to study the effect caused by effective water cement ratio on the mechanical properties of the mix.

1.3 Scope of Research

The presented research aimed at studying the concept of particle packing and its effects on the fresh and hardened properties of self-compacting concrete systems. The scope of the research was extended to include concrete component and modelling the aggregates according to Modified Andreasen & Andersen model to obtain maximum particle density. The concrete cubes were casted considering the effect of density on the void ratio of the mix.

Chapter 2

Literature Review

2.1 Definition of Packing Density:

The packing density of a particle system is defined as the volume occupied by the solid aggregate per unit volume of the mix [1]. The packing density provides the information that how efficiently the particles are filled in a certain volume. The packing degree of a mix is generally denoted by ‘α’ and is given as follows.

$$\alpha = V_s/V_t = V_s/(V_s + V_v) \; = \; \rho_{bulk}/\rho_{particles} \qquad [1]\ (2.1)$$

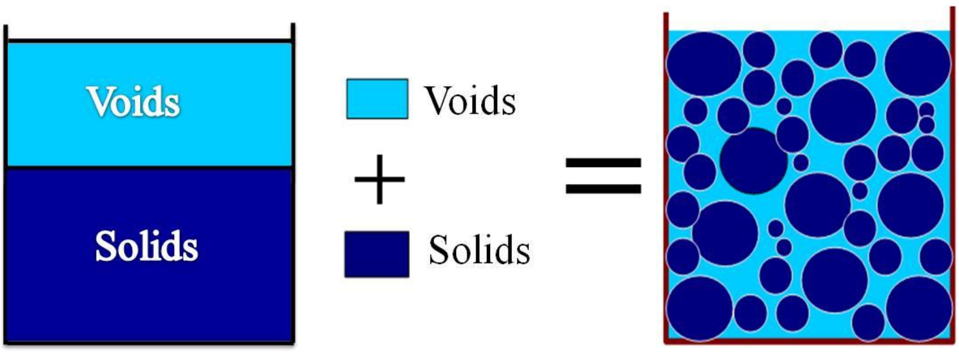

Figure 2 : Schematic of Packing Density of Particles [1]

Here

α = Packing density of a particle system.

V_s = Volume of solids

V_t = Total volume = Solid volume + Volume of voids

ρ_{bulk}= Bulk density

$\rho_{particles}$= Particle density

Packing density can also be expressed in terms of porosity:

$$\alpha = 1 - \varepsilon \qquad (2.2)$$

Here

ε = porosity of a mix

The packing degree 'α' of a mix can be calculated by using the following equation:

$$\alpha = {}^{M_p}\!/_{\rho_p} \times V \qquad (2.3)$$

Here,

M_p= Mass of particles filled in a container

ρ_p = Density of solid particles

V = Volume of the container

The volume and the densities of the each material in a mix are the two key factors effecting the degree of packing, if it has the materials of different sizes and properties. The following modified equation is also taking into account the materials having different sizes [2].

$$\alpha = \frac{M_p/V}{\rho_w u_w + \rho_\alpha R_\alpha + \rho_\beta R_\beta + \cdots + \rho_n R_n} \qquad (2.4)$$

Here 'ρ_w' is the density of water, 'ρ_α' and 'ρ_β' are the densities of the materials 'α' and 'β' respectively, 'u_w' is the water/solid ratio, and 'R_α, R_β' are the volumetric ratios of 'α' and 'β' respectively.

The degree of packing is dependent upon the shapes of particles and the particle size distribution (PSD). Moreover, it is also pertained to the total volume occupied by the solid particles in a mix. Therefore, degree of packing is affected by any external action or energy like compaction or vibration.

2.2 Concept:

It was proposed in the early 1960s by Powers that concrete mix is generally a mixture of two components i.e. cement paste and aggregate particles. According to him, the cement paste which is in excess and freely available is only enhancing the lubrication of the concrete mix while the paste present within the voids of the aggregate has no contribution in the lubrication of the mix [3]. The strength of the concrete produced is ameliorated by the improved packing density. Higher the degree of packing, lower the water demand (WD), thus, allowing the use of lower w/c ratio for achieving higher strength. As the packing of the concrete system increases, with the addition of finer particles, the void ratio of the system decreases, the increase in strength is proportional to packing of the system. This is because, the addition of finer particles in the concrete matrix, produces very insignificant individual Inter particular forces between particles but the effect of these forces are very significant in the system. Higher degree of packing decreases the water demand of the system and increases the effective water available for hydration, this allows the use of lower water cement ratio in packed systems. Packed systems have greater strength than an unpacked system, this is because the effect of Inter particle forces are more significant than the effective water available for hydration. Also Strength can further be increased by reducing the w/c ratio. This is because there are two forces acting in the microstructure of concrete namely physical packing effect and the effective w/c ratio. Due to the Moreover, permeability and bleeding in the fresh cement paste will also be reduced by better packing of the bulk of cementitious materials.

2.3 Theory of Packing:

To mix the available aggregates in such a way that the optimal packing degree is achieved while having the satisfactory workability, is one of the objectives of optimization of concrete mixtures. The improved concrete mixtures will have higher degree of packing, demanding less cement paste. Therefore, they will have less durability problems like drying shrinkage, porosity and heat generation caused by the cement paste [4].

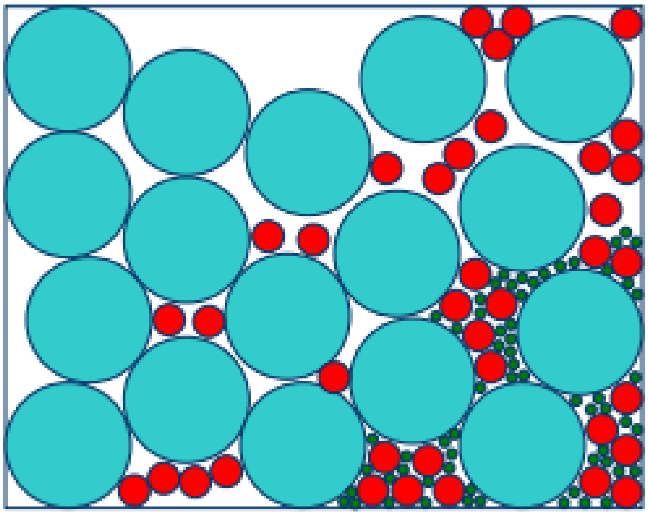

Figure 3: Packing Concept

2.4 Factors Affecting Particle Packing/ Degree of Packing

The packing density of particles in a concrete mix is very important as lower packing density will lead to higher void content and therefore increase the paste demand with a decrease in durability. The packing density or degree of packing is dependent on the aggregate characteristics, compaction methods and the dimensions of the container. It can be seen from the figure below, that the packing density of a mix can be increased by adding finer particles in the void/aggregate matrix but there are size and characteristics limitations for aggregate materials which affects their packing in the mix. Some factors which affect degree of packing such as particles density, particle porosity, shape of aggregate, particle stability, surface texture, particle size and particle size distribution in the mix are discussed below.

2.4.1 Particle Density

Degree of packing is generally independent of the density of aggregate particles as packing density is the ratio of the volume of solids to their bulk volume. Particles having similar size, shape and surface texture show same degree of packing in spite of varying particle density. However particle density plays a major role when two or more materials with different particle densities are packed together. Segregation potential of a mix can be increased substantially with larger variations in particle densities. Higher segregation potential of the mix causes the larger particles to settle at the bottom of the container, decreasing the packing degree of the mix [5].

2.4.2 Particle Porosity

Porosity of the particles also affects the packing density of the mix. Particles with closed pores cause a reduction in specific gravity of the mix, whereas particles with open pores also reduce the degree of packing of the mix. This is due to the fact that water penetrates in the open pores and aggregates shows higher absorption leading to higher water demands.

2.4.3 Particle Size and Particle Size Distribution

Packing density is a function of particle sizes in the mix and uniform sized particles generally show the same level of packing. Loosed packed particles have gravitational and inter-particular forces acting on the particles. The gravitational forces are directly related to the size of particles and it starts dominating the inter-particular forces when particle size is approximately 100μm. Below 100μm, the dominant force is the inter-particular force between the particles [5].

It is evident that packing density increases with the introduction of small size materials in the voids of the mix. If smaller sized particles can fit into the voids then this will enhance the packing, but if the particles have larger size than the cavity, then the larger particles will be pushed away to accommodate the small particles thus disturbing the packing density. This fact is elaborated in Figure 4.

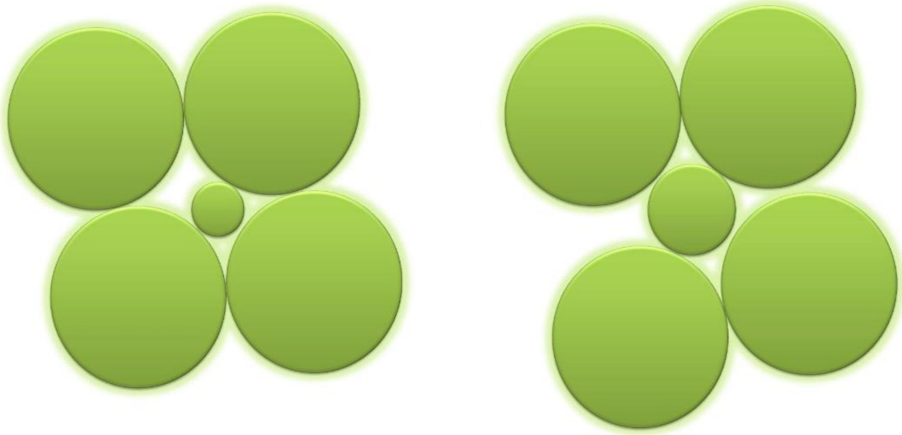

Figure 4 : Effect of Relative Particle Size on Packing Density of System

2.4.4 Particle Shape

The shape of particles affects the workability of concrete mix, rounded aggregates provides more workable concrete as compared to angular ones. This is because of the fact that shape of particles affects the degree of packing of the mix and as a result the workability behaviour changes. Aggregates are divided into four categories on the basis of their shapes; rounded, angular, irregular and flaky [7]. Shape of an aggregate particle is measured by its sphericity, shape factor, angularity or roundness [6].

The sphericity of an aggregate particle in a mix takes into account the lengths of its three principal axis namely; Length (L), Width (W) and Height (H).The sphericity of an aggregate particle is given by the following equation:

$$Sphericity = \sqrt[3]{W.H/_{L^2}} \qquad (2.5)$$

Here:

L = Length (The longest dimension)

W = Width (The shortest dimension)

H = Height (The intermediate dimension)

Shape of aggregate particle can be described by their shape factor as it is the measure of the relation among the three principal axis dimensions of a particle and is calculated by the following equation:

$$Shape\ factor = {L.W}/{H^2} \tag{2.6}$$

Angularity describes the average sharpness of edges of particles whereas sphericity describes that how much particle shape is near to a perfect sphere. Based on angularity particles are divided into following categories.

Angular : Particle having sharp edges

Sub angular : Particles having little bit wear on edges but surfaces are untouched

Sub rounded : Particles having considerable wear on edges as well as on faces

Rounded : Particle edges almost vanished but having signs of edges

Well rounded : Particles are exactly smooth surface

While working on the classification of aggregate particles on the basis of their sphericity and angularity, charts were prepared for the visual assessment of the aggregate sphericity and angularity [8]. A typical chart is shown in Figure 5.

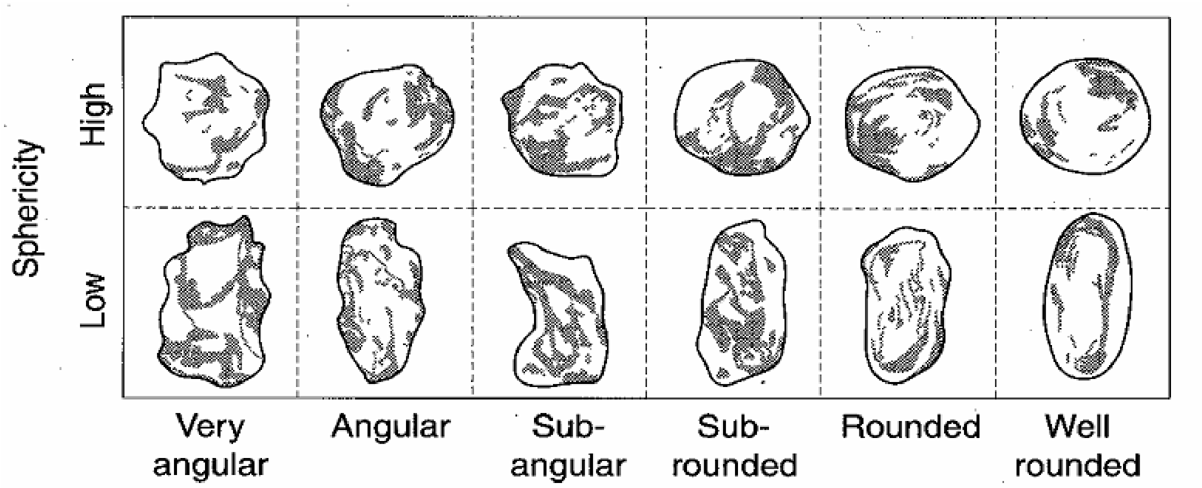

Figure 5: Aggregate Sphericity [8]

2.4.5 Particles Stability

The effects of particles shape and size on the packing density is already discussed. It is also important that the particles remain stable, and do not change their shape against internal and external forces, which can affect packing. The soft and elastic particles will have more degree of packing as compared to the hard and stable particles. The materials used for the production of self-compacting cementitious systems are generally stable against elastic and thermal stresses and preserve their shape in ordinary conditions.

2.5 Particle Size Distribution

PSD of a powder or granular material is a list of values or a mathematical function that indicates what sizes of particles are present in what proportions in the sample particle group to be measured. There are many methods by which the PSD of a material can be determined such as Sieve analysis, Air elutriation analysis, Photo-analysis etc. but sieve analysis method was employed.

2.6 Optimization/gradation of Particles

Optimization is the set of procedures used to make a system as effective as possible. Aggregate mix design is an essential part of concrete mix design and optimization. There are two ways to determine the composition of an aggregate mix: by means of an ideal grading curve and by means of theoretical and practical determination of aggregate packing value. Ideal aggregate grading can be provided if sand and coarse aggregate are divided into fractions and combined in corresponding share. But this way is difficult and too expansive [9].

The overall standpoint in mix design follows the well-known fundamentals of mix economics: maximize the cheapest components while minimizing the more costly ones-all while providing the best concrete performance possible. From the availability point of view, in a geographic region lacking a certain sized aggregate, one mix may be optimized if it produces good concrete while omitting that particular size [4].

2.7 Particle Density Models

There are two basic type of particle packing models:

- Discrete packing models
- Continuous packing models

Discrete models are the systems of two or more discrete particle sizes whereas continuous models are the system of all particle sizes [10]. Manufactured aggregate can be classified as discrete particles and natural aggregate are classified as continuous particles. Figure 6 shows the type of particle packing model and its further classifications.

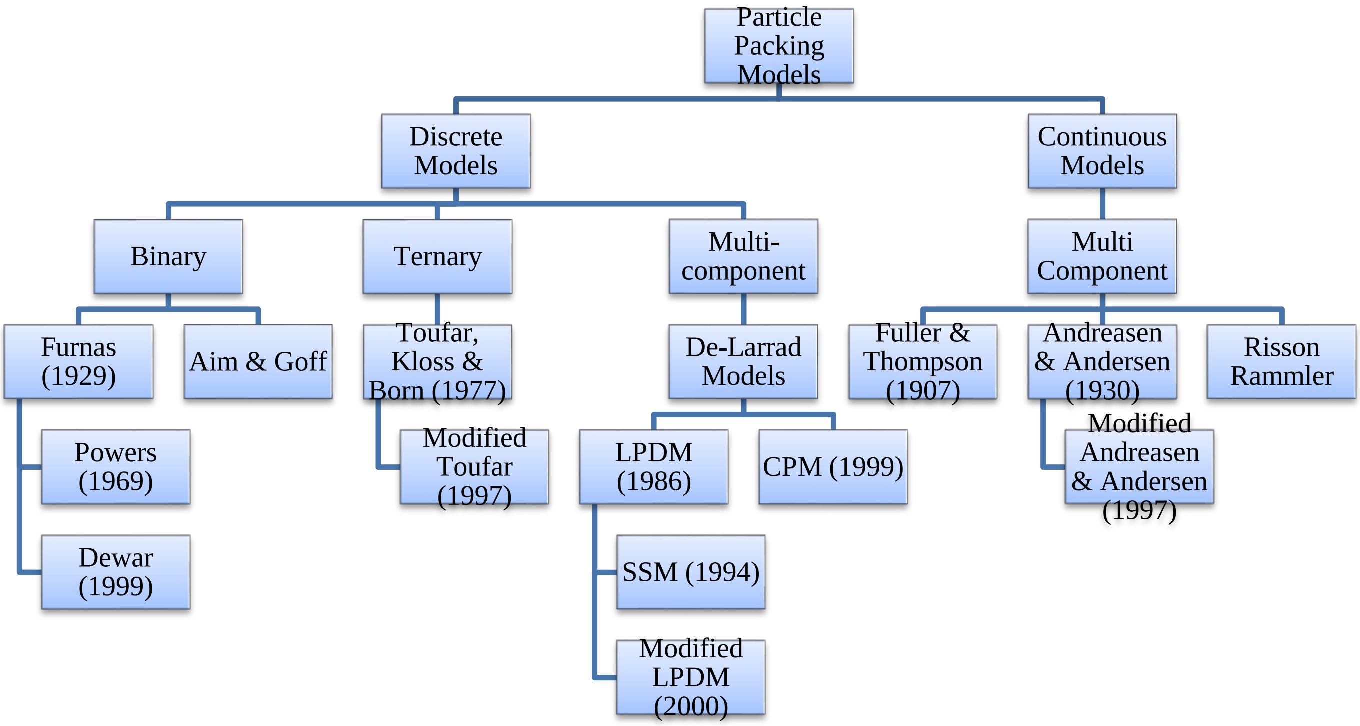

Figure 6: Packing Distribution Model ((Adopted from 'Aggregates in Concrete' By M.g. Alexander, 2005)

2.7.1 Discrete Packing Model

2.7.1.1 Furnas Model

Furnus started the basic research in the field of particles packing in concrete mixes. His theory was set up for sphere shaped particles and was based on the assumption that the small particles fill out the cavities between the big particles without disturbing the packing of the big particles. In 1930, he proposed a model for predicting the packing density of the binary mixes, further he extended the model to incorporate the subsequent sizes and produced an ideal PSD curve aimed at providing the maximum packing of the granular mixes. The Furnas model is as follows:

$$CPFT = \frac{{d_r}^{\log d} - {d_r}^{\log dmin}}{{d_r}^{\log dmax} - {d_r}^{\log dmin}} \qquad [11](2.7)$$

Here,

CPFT = Cumulative percentage finer than the specific diameter of aggregate d

d_r = Ratio between consecutive sizes of aggregate particles (larger size to smaller size)

d_{min} = Minimum size of aggregates in the mix

d_{max} = Maximum size of aggregate in the mix

The Furnas PSD curve is based on the assumption that the diametric ratio 'dr' is about √2 for the complete PSD curve whereas particles may or may not be having the stated diametric ratio. Depending upon the volume fraction of fine and coarse aggregate, two cases may be considered:

- Fine Grain Dominant: The volume fraction of small particle is large (y1>>y2).
- Coarse Grain Dominant: The volume fraction of coarse particle is large (y2>>y1).

When the diameter of the binary mix is approximately equal, i.e. the size of fines approaches the size of the coarse particles, the interaction effect occurs. The effect is classified as wall effect and loosening effect.

- Loosening effect: when a fine particle is in the matrix of coarse particle and the small particle is too large to fit into the interstices of the coarse aggregate, it disturbs the packing density of coarse particles.

– Wall effect: when an isolated coarse particle is in the matrix of fine aggregates it disturbs the packing density of fine aggregate. There increased voids around the fine particles causing wall effect [14].

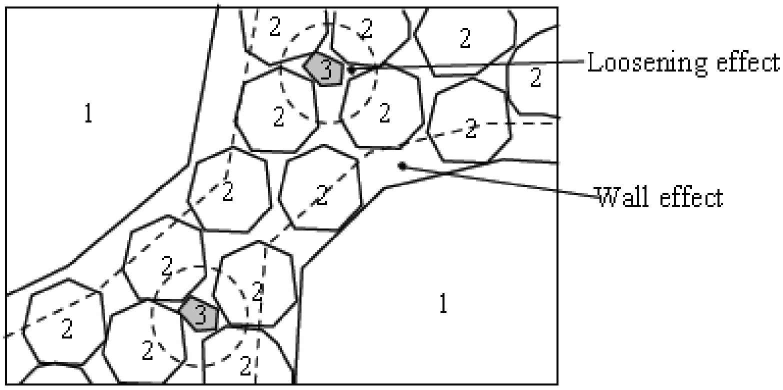

Figure 7 : Wall effect and loosening effect in a binary mixture [10]

Furnas studied bimodal systems at first instance. By studying binary mixtures of particles, it was concluded that the greater the difference in size between the two components, the greater the decrease in void volume [11].

2.7.2 Continuous Model

2.7.2.1 Füller & Thompson Model

In 1907 Füller and Thomson proposed the gradation curves for maximum density, which is well known as "Füller's ideal curve". The characteristic equation of this model is:

$$CPFT = (\frac{d}{d_{max}})^q \qquad [12](2.8)$$

Here,

CPFT = Cumulative (volume) percent finer than

d = Sieve opening

d_{max} = Maximum size of particle

q = 0.5

In this model, the particle distribution curve is the function of maximum particle size in the mix. Füller & Thompson approach is based on the concept that smaller and smaller particles fill the voids created by large particles in the mix.

For normal concrete, most design codes require continuous grading to achieve tight packing. The Füller curve ranges from 250µm to a maximum particle size and are S-shaped in a single-logarithmic graph. This curve is best suited for materials with particle size greater than 500 µm. For modern concretes, such as High Strength Concrete (HSC) and SCC this Füller curve is less suited. When applying this curve to materials with fine constituents, the mix obtained has poor paste properties and is less workable. Standards therefore require a minimum content of fine materials (< 250µm) in normal concrete. As the content and PSD of fine materials (powder) cannot be determined properly with the Füller curve, it is less suited for SCC as a large part of the solids consist of powder [12].

In order to achieve the maximum strength and workability parameters, Füller and Thompson concluded in their research that for aggregates to give the greatest density, they should be graded in sizes and combined with water. They developed a gradation curve that represented the greatest density of aggregates, but concluded that this gradation might not produce the greatest density when combined with cement and water because of the way cement particles fit in the pores [13].

2.7.2.2 Andreasen & Andersen

Andreasen et al studied the particle size distribution for packing density with a continuous approach and proposed the "Andreasen equation" for ideal packing.

$$CPFT = \left(\frac{d}{d_{max}}\right)^q \qquad [12] \quad (2.9)$$

Here,

CPFT = Cumulative (volume) percent finer than

d = Sieve opening

d_{max} = Maximum size of particle

q = distribution modulus (0.21 to 0.37)

In the model it was assumed that the smallest particles would be infinitesimally small. A variable “q", known as the distribution modulus, was introduced which can be varied from 0.21 to 0.37 as per the workability requirements. The value of distribution modulus depends on the following parameters, namely; shape, texture, angularity, roundness, density and the porosity of the particles. Andreasen and Andersen found that optimum packing is obtained when q ≈ 0.37 [12].

The value of distribution modulus increases with the increase in the amount of coarse material and it decreases with the increase in the amount of fine particle. The exponent value, q, gives the indication of the finer fraction that could be accommodated in the mixture. In general, the more powders (< 250μm) in a mix, smaller the ‘q’ that best characterizes the PSD of the mix. The exponent q provides a reasonable base for selecting an appropriate quantity of water which in turn determines the volume of fines in the mix. Also, q provides a reasonable approximation for appropriate amount of rheological agents such as SP.

If the model proposed by Füller & Thompson is compared with A &A model, it can be concluded that the case presented by Füller & Thompson’s packing theory is a special case within the more general packing theory given by Andreasen and Andersen. The grading by Füller is obtained when ‘q’ is equal to 0.5. The variable ‘q’ renders the Andreasen & Andersen model suitable for particle sizes smaller than 500µm. In general, the more powders (< 250 µm) in a mix, smaller the ‘q’ that best characterizes the PSD of the mix [12]. A continuous grading of all solids (aggregate and powders) will result in a better workability and stability of the concrete mix [13].

2.7.2.3 Dinger & Funk (Modified Andreasen) Model

Dinger and Funk recognized Dinger and Funk, towards the end of last century, observed that Andreasen & Andersen model requires particles of finer and finer sizes and make it impracticable to follow that model because the finest particles in real materials are finite in size. Therefore, they modified the Andreasen equation considering the minimum particle size in the distribution.

The modified Andreasen & Andersen model is characterized from the following equation:

$$CPFT = \left(\frac{d-d_{min}}{d_{max}-d_{min}}\right)^q x\ 100 \qquad [12](2.9)$$

CPFT = Cumulative (volume) percent finer than

d = Sieve opening

d_{max} = Maximum size of particle

d_{min} = Minimum size of particle

q = distribution modulus

The Modified Andreasen Model produces a very smooth curve capable of producing mixes with optimized packing density. The modified "Andreasen & Andersen" PSDs are convex for $q < 1$ and concave for $q > 1$. The same holds for the original Andreasen & Andersen PSD, which features the limitation 'q' > 0. Note that for q => ∞ and for q => -∞, tends to a monosized distribution with particle size d_{min} and d_{max} respectively [13].

While modelling gradation curves using Andreasen & Andersen and Funk & Dinger characteristics equation, it was realized that all models once plotted for value of distribution modulus in the range of 0.2 to 0.5 converge and even the divergence is observed at particle size of 1 micron. This is very interesting and it can be realized that future concept of particle packing considering all phases of cementitious systems contributing in packing density and taken into account Nano-particles, similar plots of grading curves using Andreasen & Andersen and Funk & Dinger Model will be obtained. Gradation curve plot of Andreasen & Andersen Model remains unchanged and display a fixed behaviour once plotted on graph. However gradation curve of Funk & Dinger varies considerably once plotted for particles larger than 1 micron as shown in Figure 8.

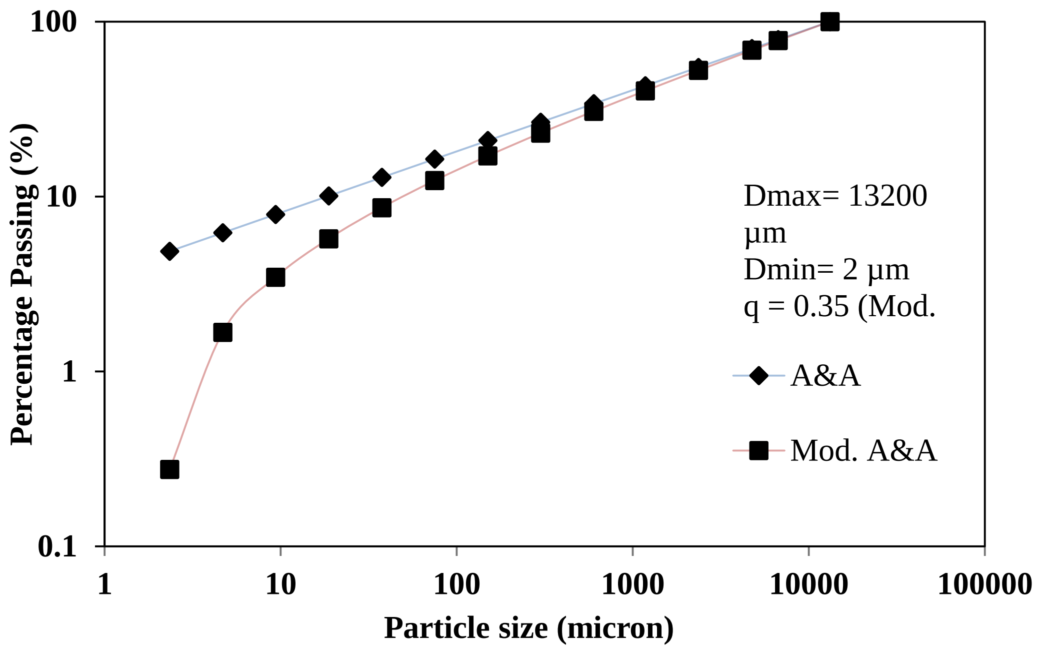

Figure 8: Comparison of A&A model and Mod. A&A model

A brief summary of the continuous packing models is shown below.

Researcher	**Characteristics Equation**	**Best value of Distribution Modulus (q)**
Füller & Thompson	$CPFT = \left(\frac{d}{d_{max}}\right)^q$	q = 0.5
Andreasen & Andersen	$CPFT = \left(\frac{d}{d_{max}}\right)^q$	q = 0.37 less fines q = 0.25 more fines
Funk & Dinger	$CPFT = \frac{(d^q - d_{min}^q)}{(d_{max}^q - d_{min}^q)}$	q = 0.3

Table 1 : Continuous Particle Packing Models [12]

Chapter 3

Methodology

3.1 Materials

3.1.1 Cement

In our research work, Ordinary Portland Cement (OPC) manufactured by Bestway Cement Ltd was uutilized. According to the manufacturer OPC was of grade 53 and contains 95% clinker and 5% gypsum. The particle size analysis of cement was performed by Horiba LA-920 laser granulometer.

The chemical composition of cement oxides was determined using "X-ray fluorescence" (XRF) technique. The results of oxide analysis are presented below:

Table 2: Chemical composition of OPC

Properties/ Oxides	Fauji Cement (mass %)
CaO	65.00
SiO_2	19.19
TiO_2	0.29
Al_2O_3	4.97
Fe_2O_3	3.27
MnO	0.04
MgO	2.23
Na_2O	0.58
K_2O	0.51
P_2O_5	0.08
Loss on Ignition (%)	**3.84**
Specific Gravity	**3.18**

3.1.2 Fine Aggregate

The fine aggregate utilized for this research project was taken from sand deposits of Lawrencepur. It is medium sized sand with a fineness modulus of 2.06. Sieve analysis of the sand was done and its gradation was checked with respect to ASTM C-33 and it was found that between 1-300 μm, the grading curve of sand is within the ASTM limits and afterwards, it becomes finer as compared to the ASTM limits. The PSD and ASTM limits are shown in Figure 9.

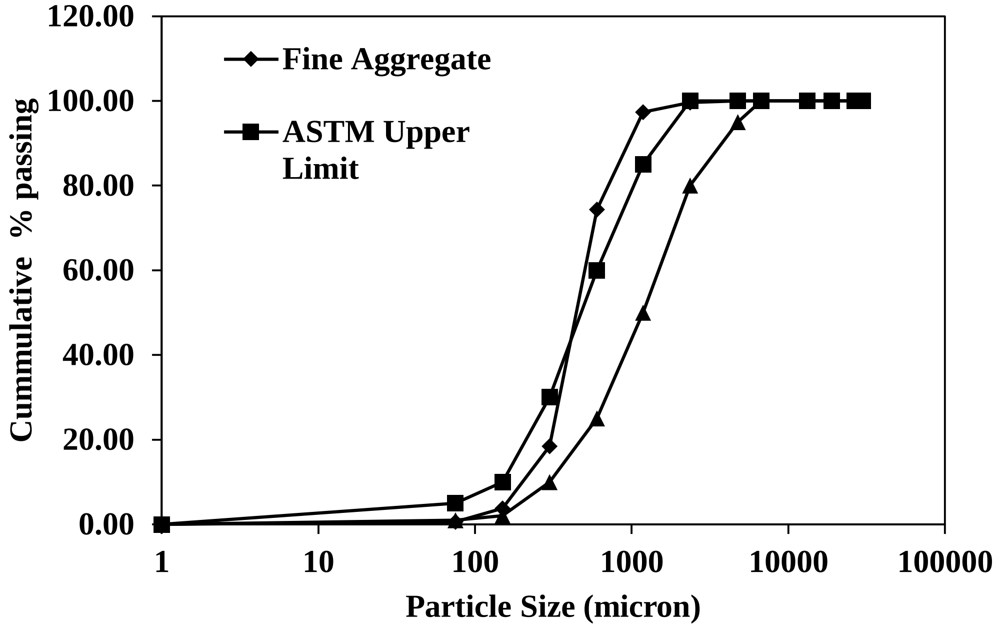

Figure 9: Gradation curve of fine aggregate

3.1.3 Coarse Aggregate

The coarse aggregate used in this research project was acquired from Margalla Hills. Its Bulk Specific Gravity is 2.43 and a Rodded Bulk Density of 1509 kg/m^3. Sieve analysis of the aggregate was done and its gradation was checked with respect to ASTM C-33. It was found that between 4.75-6.75 mm, the grading curve of coarse aggregate is within the ASTM limits. The PSD and ASTM limits are shown in Figure 10.

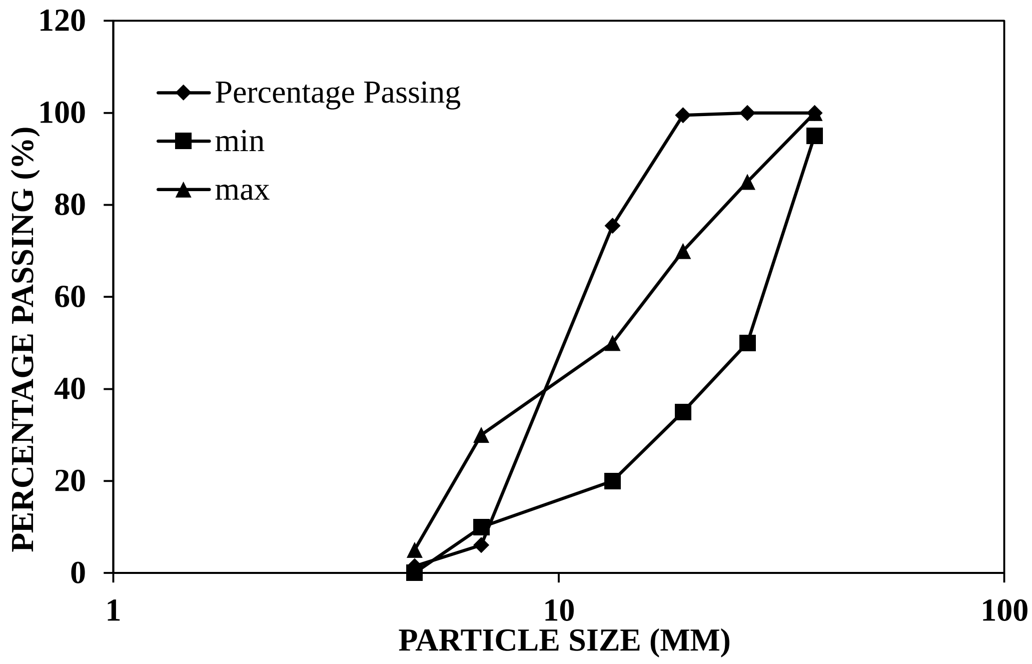

Figure 10: Gradation curve of coarse aggregate

3.1.4 Superplasticizers

High Range Water Reducer Admixtures (HRWRA) are superplasticizers (SP) used to enhance workability of cementitious systems at low w/c ratio and are considered essential component for production of SCCS. When water is added in the concrete mix the cement particles form agglomerates due to presence of surface charge on the cement particles. This is because of the presences of different phases of cement in the mix carrying opposite charges. There are four main phases of cement namely C2S, C3S, C3A and C4AF. In a fresh cement paste without SP, silicate phase of OPC (C2S and C3S) possess a negative zeta potential whereas aluminate phase (C3A and C4AF) possess a positive zeta potential [15]. Due to difference in their electrical charges they collide and form flocs of grains. The water entrap in capillary pores of the flocs lowering the effective water content thus making the mix less workable.

When SP is added into the mix, it is grafted on the aluminate phases of the OPC. Due to the grafting of SP on cement grains, the flock breakup leaving the entrapped water of the capillary pores hence resulting in highly plastic and workable mix.

Advances in the molecular technology brought the second and third generation super plasticizers known as high range and ultra-high range water reducers. These plasticizers are polycarboxylic ether based. polycarboxylate molecules are classified as being comb polymer

[14]. SP's are also responsible for lowering the porosity of cementitious systems in hardened state [15].

In our project, Sika 'ViscoCrete -20 HE' and 'Melflux 2651 F' were utilized.

3.1.4.1 Melflux 2651 F

Melflux 2651 F is a free-flowing spray dried powder of a modified polycarboxylic ether. It is a high performance superplasticizer for cement based construction materials.

It was used in SCM and SCC systems for the casting of prisms (4x4x16 cm^3).

Its technical specifications are mentioned below.

Table 3: Properties of Melflux 2651 F

Physical Shape	Powder
Appearance	Characteristic, yellowish to brownish
Drying loss	Max. 2.0 %
Bulk Density	300 - 600 kg/m^3
Dosage recommendation (% of cement)	0.05 – 1.0 %
pH value at 20 ^oC, 20% solution	6.5 – 8.5

3.1.4.2 Sika ViscoCrete -20 HE

Sika ViscoCrete -20 HE is a third generation superplasticizer for concrete and mortar. It is suitable for tropical and hot climatic conditions.

It was used in SCC systems for the casting of Cubes (10x10x10 cm^3).

Its technical specifications are mentioned below.

Table 4: Properties of Sika ViscoCrete -20 HE

Form	Liquid
Appearance	Light brownish, clear to slightly cloudy
Chemical Base	Aqueous solution of modified polycarboxylates
Density (at 25 ^{o}C)	Approximately 1.08 kg/litre
pH value	4.3
Chloride content	Nil
Effect of setting	Non-retarding
Effect of overdosing	Bleeding may occur

3.1.5 Viscosity Modifying Agents (VMA)

By changing concrete flow properties using SP, problems in concrete production may result. Viscosity modifying agents (VMA) can be used to enhance the resistance to segregation and bleeding. Viscosity Modifying Agents (VMAs) are admixtures that increase the viscosity of mixing-water and enhance the ability of cement paste to retain its constituents in suspension. As far as flow is concerned, the use of a VMA along with adequate superplasticizers (SPs) content ensures high deformability along with stability.

For this research work, BASF 'RheoMATRIX 110' was utilized.

3.1.5.1 RheoMATRIX 110

RheoMATRIX 110 is an aqueous solution of a high-molecular weight synthetic copolymer. It imparts a level of viscosity within a mix which enables the right balance between fluidity and resistance to segregation. The balance is lacking when the fluidity of the concrete is obtained by adding water.

It was used in SCC systems for the casting of concrete cubes (10x10x10 cm^3). Its technical specifications are mentioned below.

Table 5: Properties of RheoMATRIX 110

Physical Form	Liquid
Appearance	Light brown to dark brown
pH value at 25 ^{o}C	9.5
Recommended Dosage (% of weight of fines)	0.1 – 0.5%

3.2 Experimental Procedures

3.2.1 Grading of sand

In order to optimize the packing density of fine aggregate, Modified Andreasen model is utilized. By varying distribution modulus, we prepared various sand mixes by following Modified Andreasen model. Moreover, by varying distribution curves, the cumulative particle size distribution curves were drawn according to the model and are presented in table.

The maximum and minimum sizes of the sand particles were limited to 2360μm and 75μm respectively. The sand was sieved and stored in five compartments with respect to their sizes as shown below:

Table 6: Grading of Sand

Notation	Upper Size Limit		Lower Size Limit	
	Passing Sieve #	**Opening (μm)**	**Retained Sieve #**	**Opening (μm)**
S_1	#8	2360	#16	1180
S_2	#16	1180	#30	600
S_3	#30	600	#50	300
S_4	#50	300	#100	150
S_5	#100	150	#200	74

3.2.2 Grading of coarse aggregate

In order to optimize the packing density of coarse aggregate, Modified Andreasen model is utilized. By varying distribution modulus, we prepared various coarse aggregate mixes by following Modified Andreasen model. Moreover, by varying distribution curves, the cumulative particle size distribution curves were drawn according to the model and are presented in table.

The maximum and minimum sizes of the sand particles were limited to 6350μm and 75μm respectively. The sand was sieved and stored in five compartments with respect to their sizes as shown below:

Table 7: Grading of Coarse Aggregate

Notation	Upper Size Limit		Lower Size Limit	
	Passing Sieve #	**Opening (µm)**	**Retained Sieve #**	**Opening (µm)**
CA1	¼"	6350	#4	4750
CA2	#4	4750	#8	2360
S_1	#8	2360	#16	1180
S_2	#16	1180	#30	600
S_3	#30	600	#50	300
S_4	#50	300	#100	150
S_5	#100	150	#200	74

3.2.3 Packing Density

Packing density test was performed on the fine and coarse particle. Firstly, packing density for each individual class of fine and coarse aggregate was measured and then the mixes obtained from Modified Andreasen & Andersen model were tested for the packing density. There are two methods to measure the packing density:

1. Rodded (compacted) Packing Density.
2. Un-rodded (un-compacted) Packing Density.

3.2.3.1 Un-rodded Packing Density

To perform packing density test, a 5 dm^3 cylinder was used [ASTM C29]. The material was filled in the cylinder in three layers without any tamping or vibration. The weight of the cylinder was measured before and after it was filled with the material. The material on the top of the cylinder was struck off to obtain a level surface. In order to calculate the density, the mass of the material and cylinder minus mass of cylinder is divided by the volume of the cylinder. Each material was tested three times and an average value was taken as the packing density.

3.2.3.2 Rodded Packing Density

In rodded packing density test, a tamping rod was used to compact the material. The material was filled in three layers and after each layer the material was tamp 25 times using the tamping rod. The tamping rod should be allowed to fall freely from the height not more than 6 inches. The above mentioned procedure is repeated to calculate density.

3.2.4 Composition of Mortar

On the basis of Modified Andreasen & Andersen model, sand mixes were composed and their packing densities were measured using packing density methods.

The formulation used for the composition of mortar was **1: 1.33** i.e. for 1 part of binder (cement), 1.33 part of fine aggregate will be used. For the fixed value of q = 0.35, trial mortars were composed using Hobart Mixer in order to determine the demand of super plasticizer for three different water-cement ratio. The amount of cement taken for each trial was 400 g and amount of fine particles was 532 g. The amount of water was changed in accordance with the water-cement ratio under consideration. The super plasticiser content that satisfied the flow test were selected for three different mixes having different water-cement ratio.

3.2.5 Composition of Concrete

On the basis of Modified Andreasen & Andersen model, mixes containing both coarse and fine particles were composed and their packing densities were measured using packing density methods.

The formulation used for the composition of SCC systems was **1: 1.33** i.e. for 1 part of binder (cement), 1.33 part of aggregate (coarse and fine) will be used. For the fixed value of q = 0.35, trial mortars were composed using Hobart Mixer in order to determine the demand of super plasticizer for three different water-cement ratio. The amount of cement taken for each trial was 400 g and amount of fine particles was 532 g. The amount of water was changed in accordance with the water-cement ratio under consideration. The super plasticiser content that satisfied the flow test were selected for three different mixes having different water-cement ratio.

From the relation between the sand/coarse mixes and the void ratio, it was concluded that the mix having 50% sand and 50% coarse has the least void ratio and maximum packing density. To verify the results obtained from rodded and un-rodded bulk density tests, three formulation of concrete were made and for each formulation the water-cement ratio was kept constant i.e. 0.42. The SP and VEA demand for each formulations were obtained by performing flow test using Hagerman cone flow apparatus and the contents which satisfied the flow conditions were selected. The table below shows the formulations with SP and VEA content:

Table 8: Formulations with SP and VEA content

C:A	S:C	Formulations C:S:C	w/c	SP %	VEA %	Spread (cm)
1:3	60:40	1:1.8:1.2	0.42	1.15	0	70
1:3	50:50	1:1.5:1.5	0.42	1	0.3	70
1:3	40:60	1:1.2:1.8	0.42	1.4	0.6	69

3.2.6 Mixing Regime

The purpose of mixing was to achieve a target flow spread of 30±2 cm for self-consolidating mortars. Mixing regime consists of 30 seconds of dry mixing of materials at slow speed in a 5.0 L Hobart mixer with 80% of the total water and super plasticizer, followed by 60 seconds of mixing at fast speed. The mixer is then stopped and the interior wall of mixer is cleaned and remaining water is added. Three minutes of additional mixing at fast rate was done making the total mixing time of 4 minutes and 30 seconds.

3.2.7 Flow test

3.2.7.1 Hagerman Cone Flow test

The flow test for SCM and SCC systems were performed using Hagerman Cone flow apparatus [ASTM C1437]. Different formulations of mortar and concrete were composed using Hobart Mixer and for every formulation, number of trials were run in order to determine the amount of super plasticiser required to achieve D30. The flow test consists of the round mirror plate, on which circles are marked showing spread of 25 cm and 30 cm. The Hagerman cone in placed on the centre of the plate once the plate is levelled. The mixer prepared in the Hobart mixer is immediately placed in the cone after mixing and the Hagerman cone is lifted and the flow is observed. The time that the mix takes to reach D25 and D30 was also noted.

3.2.7.2 Abraham Cone Test

The flow test of fresh concrete was performed using Abraham cone or slump cone [ASTM C1611]. The cone is placed on a level hard surface. The concrete fresh from the mixer in poured in the cone and the excess concrete in struck off flush to the top of the mould. The cone is then lifted vertically upwards without disturbing the concrete inside the cone. The time that concretes take to reach the spread of 50 cm and 70 cm in noted. The SP demand of the formulation is determined when the flow reached the spread of 70 ± 1 cm.

3.2.7.3 V-Funnel Test

Place the V-funnel [BS EN 12350-9] vertically on a stable and flat ground, with the tap opening horizontally positioned. Wet the interior of the funnel with a moist sponge or towel and remove the surplus water, e.g. through the opening. Close the gate and place a bucket under it in order to retain the concrete to be passed. Fill the funnel completely with the representative sample of SCC without applying any compaction or rodding. Open the gate after a waiting period of (10 ± 2) seconds. Start the stopwatch at the same time the gate opens and look inside the funnel and stop the time at the moment when clear space is visible through the opening of the funnel. The stopwatch reading is recorded as the V-funnel flow time. The V-funnel flow time is the period from releasing the gate until first light enters the opening, expressed to the nearest 0.1 second.

3.2.7.4 J-Ring

The purpose of J-ring [ASTM C 1621] test is to investigate both the filling ability and the passing ability of SCC. It can also be used to investigate the resistance of SCC to segregation by comparing tet results from two different portions of sample. The J-ring test measures three parameters: total flow spread and total flow time and/or T50 cm. The J-ring indicates the restricted deformability of SCC due to blocking effect of reinforcement bars and the flow time T50 cm indicates the rate of deformation within a defined flow distance. The blocking step quantifies the effect of blocking. The main factors influencing the passing ability are:

- The ratio of clear spacing between re-bars to maximum aggregate size,
- The coarse aggregate content,
- The flowability,
- Segregation resistance.

After the mixing is completed, let the sample to stand still for about 1 minute. Wet the inner surface of the cone and the test surface of the base plate using the moist sponge or towel and place the cone in the centre on the 200 mm circle of the base plate. Place the J ring on the base plate after that fill the cone with the sample from the bucket without any external compaction, after a short rest (no more than 30 seconds for cleaning and checking the moist state of the test surface), lift the cone perpendicular to the base plate in a single movement, in such a manner that the concrete is allowed to flow out freely without obstruction from the cone, and start the stopwatch the moment the cone loses contact with the base plate. Stop the stopwatch when the front of the concrete first touches the circle of diameter 500 mm. The stopwatch reading is recorded as the T50 cm value. The test is completed when the concrete flow has ceased. Also note the total spread and time taken.

3.2.7.5 L-Box

The basic aim of L-box test [BS EN 12350-10] method is to investigate the passing ability of SCC through reinforcement. It measures the reached height of fresh concrete after passing through the specified gaps of steel bars and flowing within a defined distance. With this reached height, the passing or blocking behaviour of SCC can be determined. Two types of gates can be used, one with 3 bars or other with 2 smooth bars. The gaps are 41 and 59 mm, respectively. Fill the vertical part of the L-box, with the extra adapter mounted, with 12.7 litres of representative fresh SCC. Let the concrete rest in the vertical part for one minute (± 10 seconds). During this time the concrete constituents will adjust themselves in suspension. Lift the sliding gate and let the concrete flow out in the vertical part into the horizontal part of the L-box, and when the concrete has stopped moving, measure the average distance, noted as Δh between the top edge of the box and the concrete that reached the end of the box (H_2/H_1) and the flow time at three positions 20 cm, 40 cm and 60 cm.

3.2.8 Compression and Flexure Test of Mortar and Concrete

The prisms for hardened state tests were casted using steel moulds of 4 x 4 x 16 cm^3 as per EN 196-1. Strengths of mortar and concrete systems were determined as per EN 196-1:1994 at the age of 1, 7 and 28 days. The flexural strength and compressive strength at any age was an average of three specimens. In total 27 prisms were casted for self-compacting concrete system and 18 prisms were casted for self-compacting mortar system in laboratory at a temperature of 25±2 ^oC and relative humidity of 50±5%. The results of the strength test are given in annexure.

Similarly, the cubes were casted for hardened state tested using steel moulds of 4 in^3 as per ASTM C39/C39M. Strengths of concrete systems were determined as ASTM C39/C39M at the age of 1, 7 and 28 days. In total 30 cubes were casted for self-compacting concrete system in the laboratory at the temperature of 26 ± 2 ^oC.

The prisms and cubes were left open in the air after casting. The specimens were demoulded after twenty four hours after casting and weighed. After weighing the specimens were placed in the cuing tank for immersed water curing. Strength tests were performed at SSD conditions.

3.2.9 Relative Water Absorption of Mortar

Water absorption is an indicator of permeability so water absorption test was carried out for the mortar samples. After 24 hours of casting the samples were demoulded, numbered and weighed. Thereafter these were put in water at room temperature. Before being tested for strength at different ages, these were taken out of water. The surface water was removes by using tissue paper and weighed again in SSD condition. The weight difference gave the water absorption of mortars.

Chapter 4

Experimental Results

4.1 Sieve Analysis of Fine Aggregate

The fine aggregate utilized for this research project was taken from sand deposits of Lawrencepur. It is medium sized sand with fineness modulus of 2.06. Sieve analysis of the sand was done and its gradation was checked with respect to ASTM C-33. The PSD of fine aggregate and ASTM limits are shown in Figure 3.1.

4.2 Sieve Analysis of Coarse Aggregate

The coarse aggregate utilized for this research project was taken from Margala crush deposits. The fineness modulus of coarse aggregate is 7.1. Sieve analysis was done and its gradation was checked with respect to ASTM C-33. The PSD of coarse aggregate and ASTM limits are shown in Figure 3.2.

4.3 Specific Gravity of Coarse Aggregate

Following are the readings from the test:

Table 9: Specific Gravity of Coarse Aggregate

Weight of bucket (kg)	694.1
Weight of bucket + coarse aggregate (kg)	1284.7
Weight of aggregate in water (kg)	590.6
Weight of aggregate in SSD (kg)	998
Bulk Specific Gravity	2.43
Apparent Specific Gravity	2.47
Percentage absorption (%)	0.706

4.4 Specific Gravity of Fine Aggregate

Following are the readings from the test:

Table 10: Specific Gravity of Fine Aggregate

Mass of volumetric flask (W_1) (g)	88.4
Mass of flask + dry soil (W_2) (g)	123.4
Mass of flask + soil + water (W_3) (g)	359.7
Mass of flask + water (W_4) (g)	337.8
Specific Gravity	2.67

4.5 Rodded and Un-rodded Bulk Density of Coarse Aggregate

4.5.1 Rodded Bulk Density

Table 11: Rodded Bulk Density of Coarse Aggregate

Mass of empty cylinder (kg)	4.703
Volume of the cylinder (dm^3)	5
Mass of cylinder + coarse aggregate (kg)	12.248
Mass of coarse aggregate (kg)	7.545
Density (kg/m^3)	1509

4.5.2 Un-rodded Bulk Density

Table 12: Un-Rodded Bulk Density of Coarse Aggregate

Mass of empty cylinder (kg)	4.703
Volume of the cylinder (dm^3)	5
Mass of cylinder + coarse aggregate (kg)	11.651
Mass of coarse aggregate (kg)	6.947
Density (kg/m^3)	1389.4

4.6 Void Ratio of Coarse Aggregate

Percentage void in loose state = 42.8 %

Percentage void in compacted state = 37.88 %

4.7 Combinations of Coarse and Fine Aggregates

Series of mixes were prepared consisting of different coarse aggregate to fine aggregate ratios. These combinations were then subjected to above mentioned tests to optimize the grading curve for achieving the highest packing density. Following are the combinations:

Table 13: Combination

Combinations	% Coarse Aggregate	% Fine Aggregate
1	80	20
2	70	30
3	60	40
4	50	50
5	40	60
6	30	70
7	20	80

4.7.1 Sieve Analysis of the Combinations

The table below shows the percentage passing for each combination of coarse and fine aggregates.

Table 14: Sieve Analysis of Combination

Passing Sieve #	C:S= 80:20	C:S= 70:30	C:S= 60:40	C:S = 50:50	C:S = 40:60	C:S = 30:70	C:S = 20:80
1"	100.00	100.00	100.00	100.00	100	100	100
3/4"	100.00	100.00	100.00	100.00	100	100	100
1/2"	81.92	84.18	86.44	88.70	90.96	93.22	95.48
3/8"	55.44	61.01	66.58	72.15	77.72	83.29	88.86
3/16"	20.96	30.84	40.72	50.60	60.48	70.36	80.24
#8	20	29.95	39.90	49.85	59.8	69.75	79.7
#16	19.48	29.22	38.96	48.70	58.44	68.18	77.92
#30	14.88	22.32	29.76	37.20	44.64	52.08	59.52
#50	3.72	5.58	7.44	9.30	11.16	13.02	14.88

Passing Sieve #	C:S= 80:20	C:S= 70:30	C:S= 60:40	C:S = 50:50	C:S = 40:60	C:S = 30:70	C:S = 20:80
#100	0.80	1.20	1.60	2.00	2.4	2.8	3.2
#200	0.16	0.24	0.32	0.40	0.48	0.56	0.64

The graph was plotted for all the combinations and following trend was achieved:

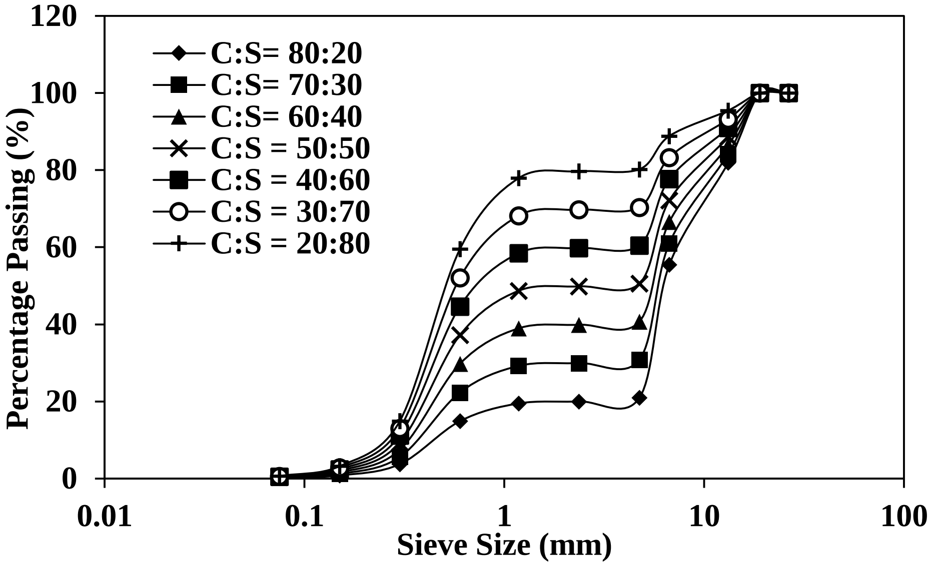

Figure 11: Gradation Curve of Mix Aggregate

4.7.2 Rodded Bulk Density and Void Ratio

Summarized below are the result of bulk density and void ratio test on the above mentioned combinations.

Table 15: Rodded Bulk Density and Void Ratio

Combinations (C:S)	Aggregate + Mass of container	Mass of Aggregate in the container	Density kg/m^3	Density lb/ft^3	Sp. Gravity	Void Ratio
80/20	13.418	8.352	1670.4	104.3	2.47	0.323
70/30	13.96	8.894	1778.8	111.04	2.49	0.285
60/40	14.33	9.264	1852.8	115.66	2.52	0.264
50/50	14.485	9.419	1883.8	117.60	2.54	0.258
40/60	14.2	9.134	1826.8	114.04	2.56	0.286
30/70	13.97	8.904	1780.8	111.17	2.59	0.312

20/80	13.6	8.534	1706.8	106.55	2.62	0.348

4.7.3 Un-Rodded Bulk Density and Void Ratio

Summarized below are the result of bulk density and void ratio test on the above mentioned combinations.

Table 16: Un-Rodded Bulk Density and Void Ratio

Combinations (C:S)	Aggregate + Mass of container	Mass of Aggregate in the container	Density kg/m^3	Density lb/ft^3	Specific Gravity	Void Ratio
80/20	13.059	7.993	1598.6	99.79	2.47	0.352
70/30	13.624	8.558	1711.6	106.85	2.49	0.312
60/40	14.044	8.978	1795.6	112.09	2.52	0.287
50/50	14.088	9.022	1804.4	112.64	2.54	0.289
40/60	13.8	8.734	1746.8	109.04	2.56	0.317
30/70	13.48	8.414	1682.8	105.05	2.59	0.349
20/80	13.175	8.109	1621.8	101.24	2.62	0.380

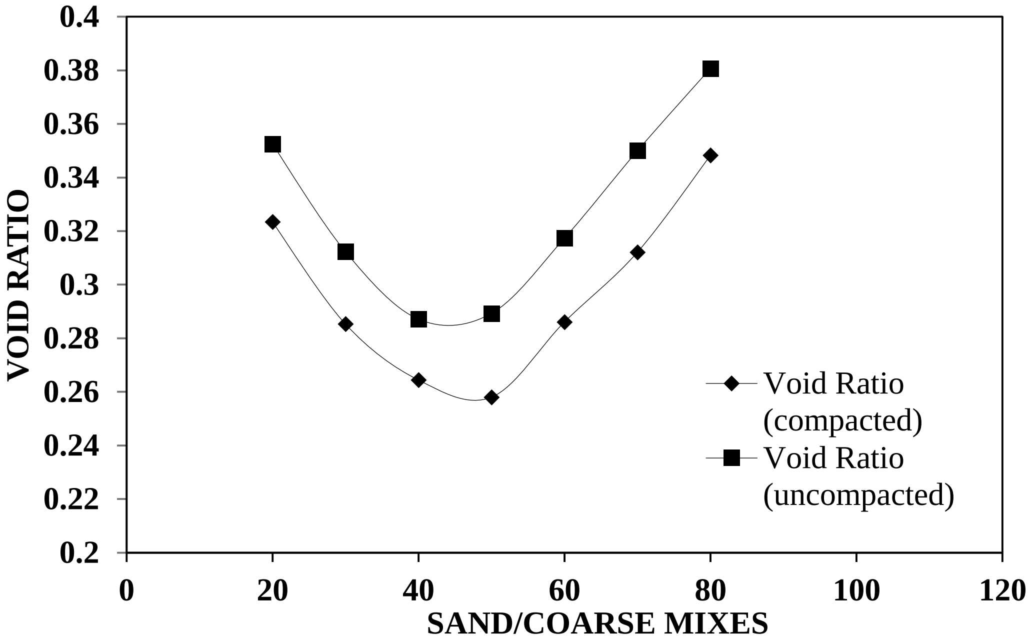

Figure 12: Void Ratio Curve

In

Figure 12, the relation between the sand/coarse mixes and void ration is shown both for loose and compacted state.

4.7.4 Specific Gravity of Coarse Aggregate

Following are the readings from the test:

Table 17: Specific Gravity of Coarse Aggregate (4-6 mm)

Weight of bucket (kg)	1053.5
Weight coarse aggregate (kg)	983
Weight of aggregate in water (kg)	559.7
Weight of aggregate in SSD (kg)	983
Bulk Specific Gravity	2.29
Apparent Specific Gravity	2.36
Percentage absorption (%)	

4.7.5 Rodded Bulk Density and Void Ratio

Summarized below are the result of bulk density and void ratio test on the above mentioned combinations.

Table 18: Rodded Bulk Density and Void Ratio

Combinations (C:S)	Aggregate + Mass of container	Mass of Aggregate in the container	Density kg/m^3	Density lb/ft^3	Specific Gravity	Void Ratio
60/40	13.67	8.971	1794.2	112.00	2.43	0.261
50/50	13.77	9.071	1814.2	113.25	2.46	0.262
40/60	13.66	8.961	1792.2	111.88	2.5	0.282

4.7.6 Un-Rodded Bulk Density and Void Ratio

Summarized below are the result of bulk density and void ratio test on the above mentioned combinations.

Table 19: Un-Rodded Bulk Density and Void Ratio

Combinations (C:S)	Aggregate + Mass of container	Mass of Aggregate in the container	Density kg/m^3	Density lb/ft^3	Specific Gravity	Void Ratio
60/40	13.26	8.561	1712.2	106.88	2.43	0.295
50/50	13.45	8.751	1750.2	109.26	2.46	0.288
40/60	13.16	8.461	1692.2	105.64	2.5	0.322

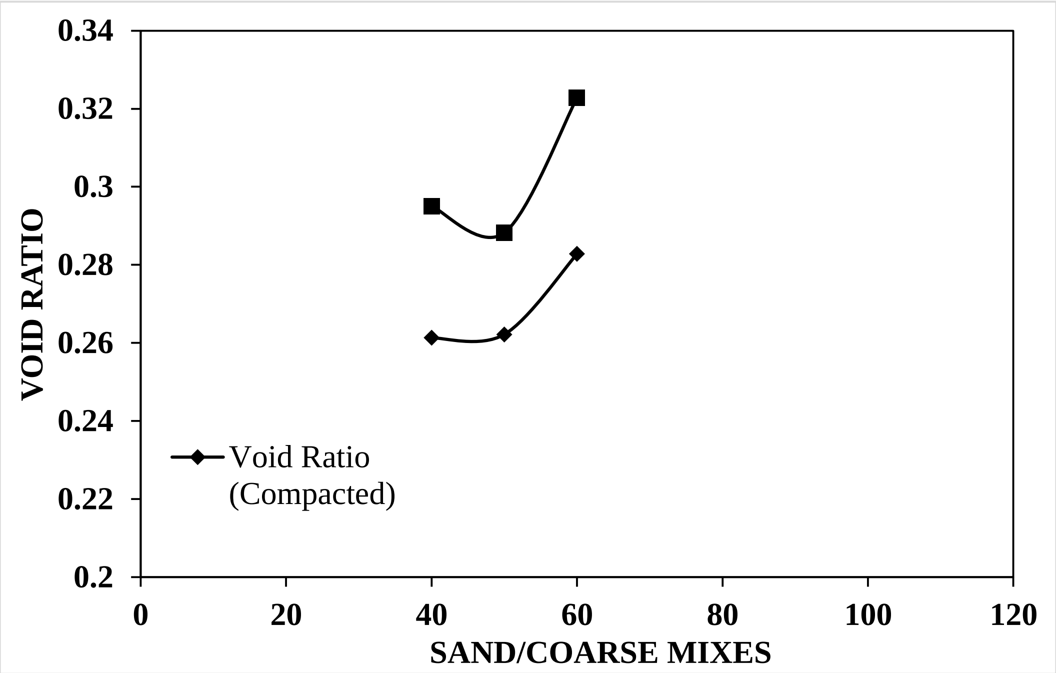

Figure 13: Void Ratio Curve

4.8 Flow Test

4.8.1 Hagerman Cone Test

The Hagerman's mini slump cone [ASTM C1437] was used to find the Superplasticiser demand for a target flow of 50 ± 1 cm. Percentage of SP demand by weight of cement in shown in Figure 14, spread flow time for a spread of 25 cm and 50 cm for all formulations of concrete are shown in Figure 15.

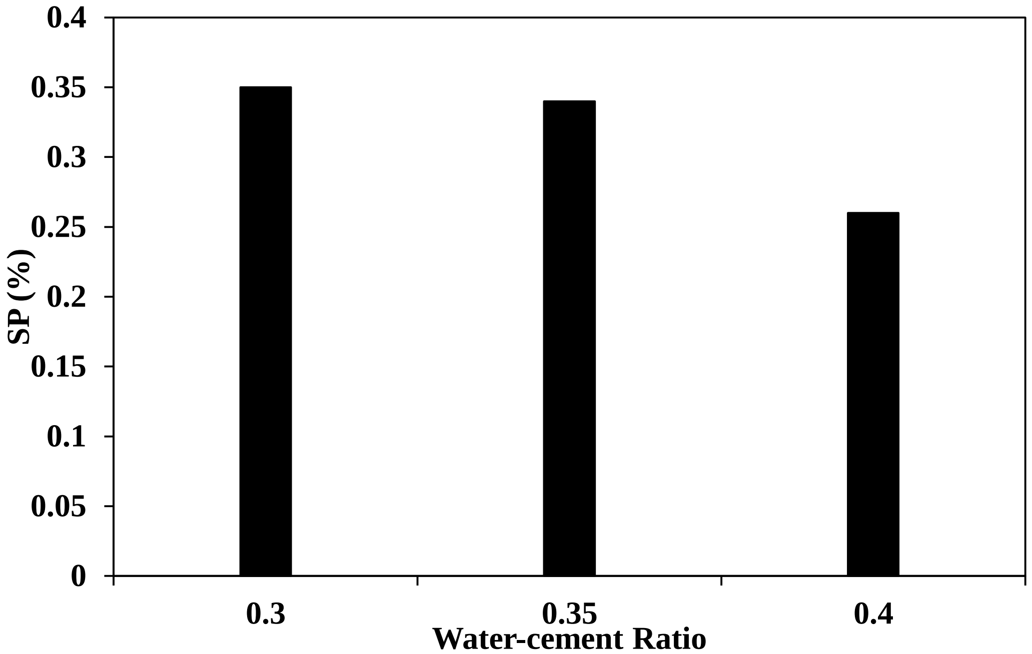

Figure 14: Superplasticiser demand for various water-cement ratio

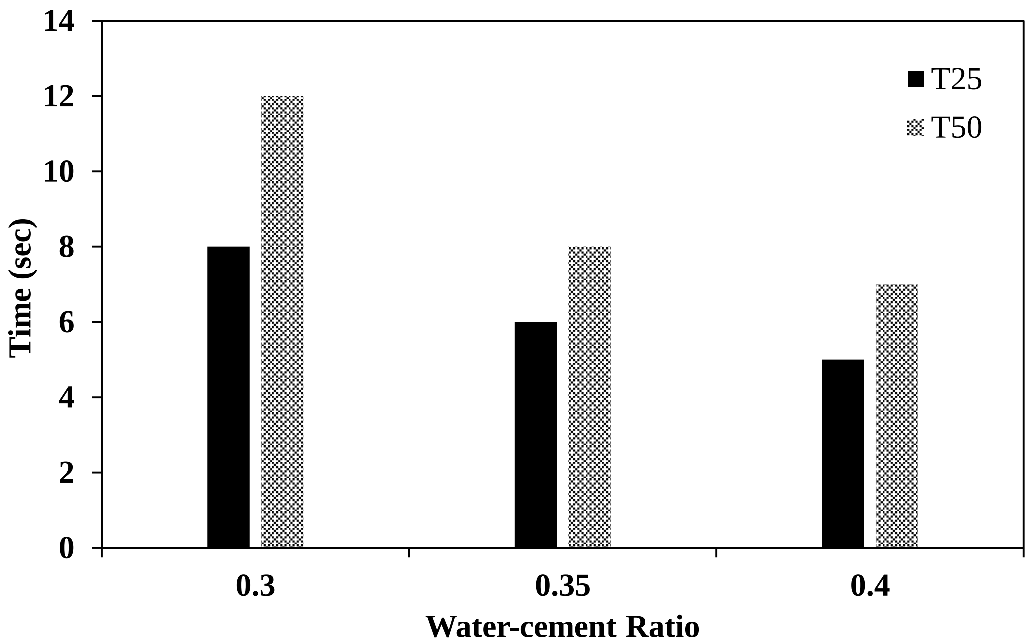

Figure 15: Flow time for mix having different water-cement ratio

4.8.2 Abraham Cone Test

The Abraham cone test [ASTM C1611] was used to find the Superplasticiser and Viscosity Enhancer Agent (VEA) demand for a target flow of 70 ± 1 cm. Percentage of SP and VEA demand by weight of cement in shown in **Error! Reference source not found.**, spread flow time for a spread of 50 cm and 70 cm for all formulations of concrete are shown in Figure 17**Error! Reference source not found.**.

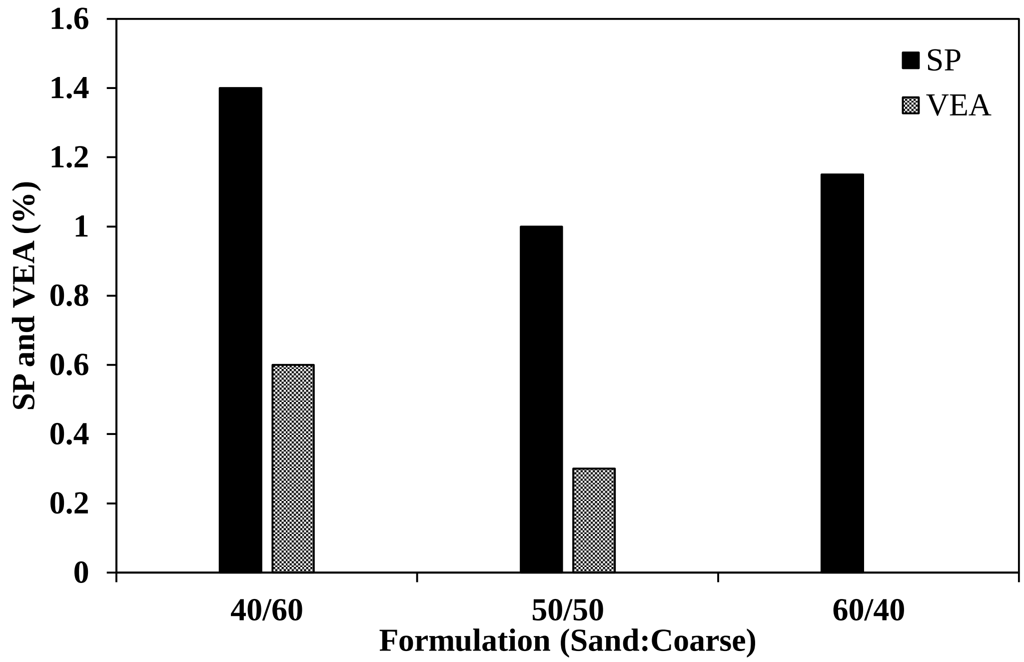

Figure 16: SP and VEA demand for different formulations of cubes

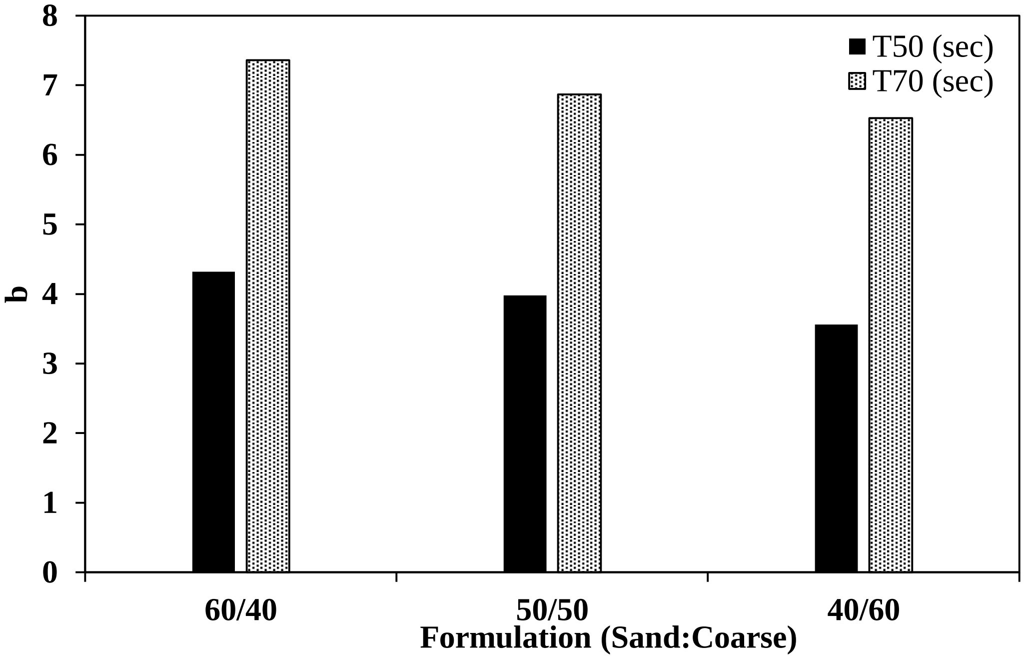

Figure 17: Flow test for different SSCS formulations

4.8.3 V-Funnel Test of Concrete System

V-Funnel [BS EN 12350-9] times for various formulations of concrete are in shown in Figure 18.

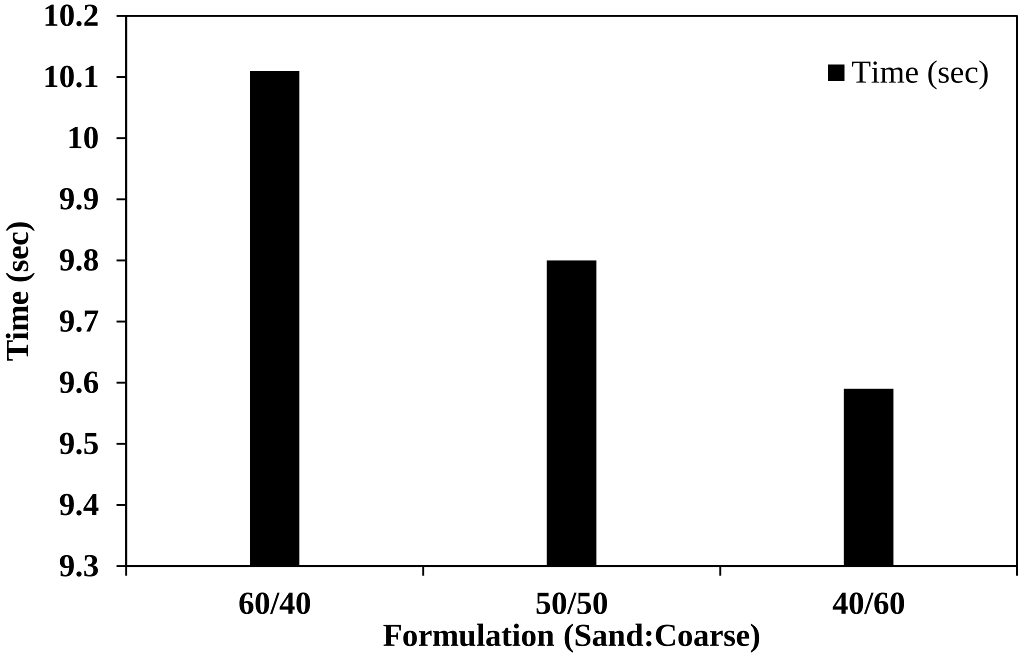

Figure 18: V-Funnel time for Concrete Formulations

4.9 Compressive and Tensile Strength Results

4.9.1 Compression and tensile strength test results of Prisms

The following graphs are of concrete prisms casted for three different water-cement ratio:

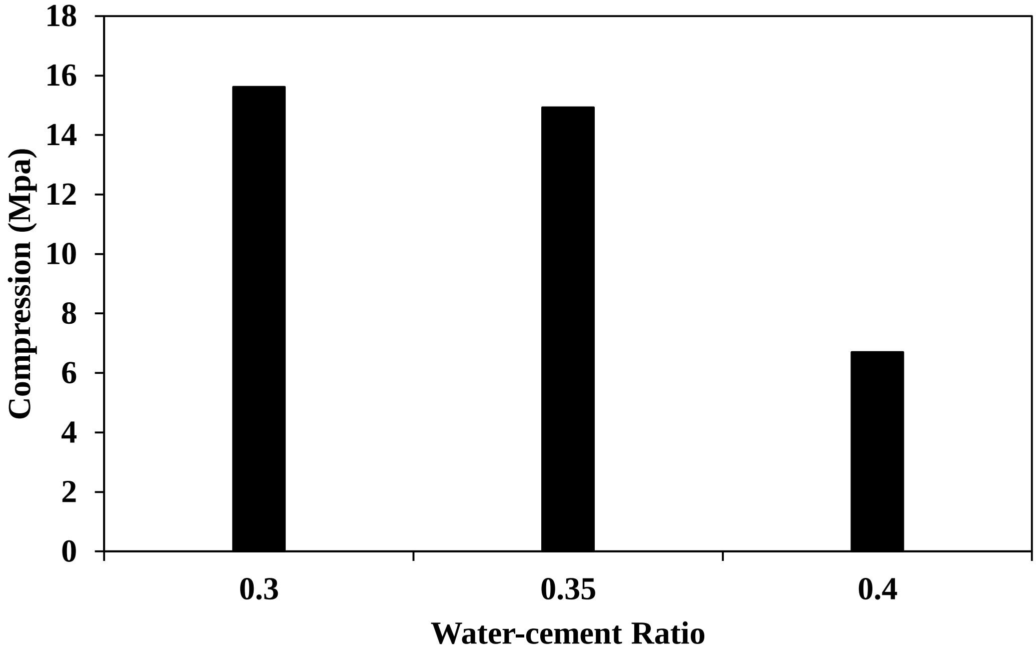

Figure 19: Day 1 Compression test of prisms

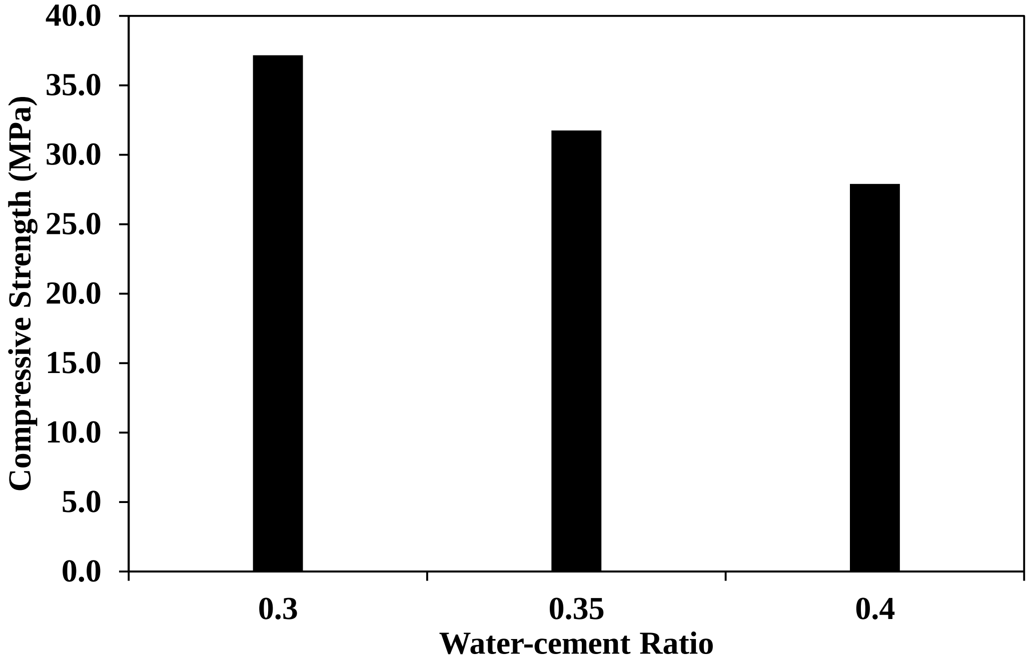

Figure 20: Day 7 Compression Strength of prisms

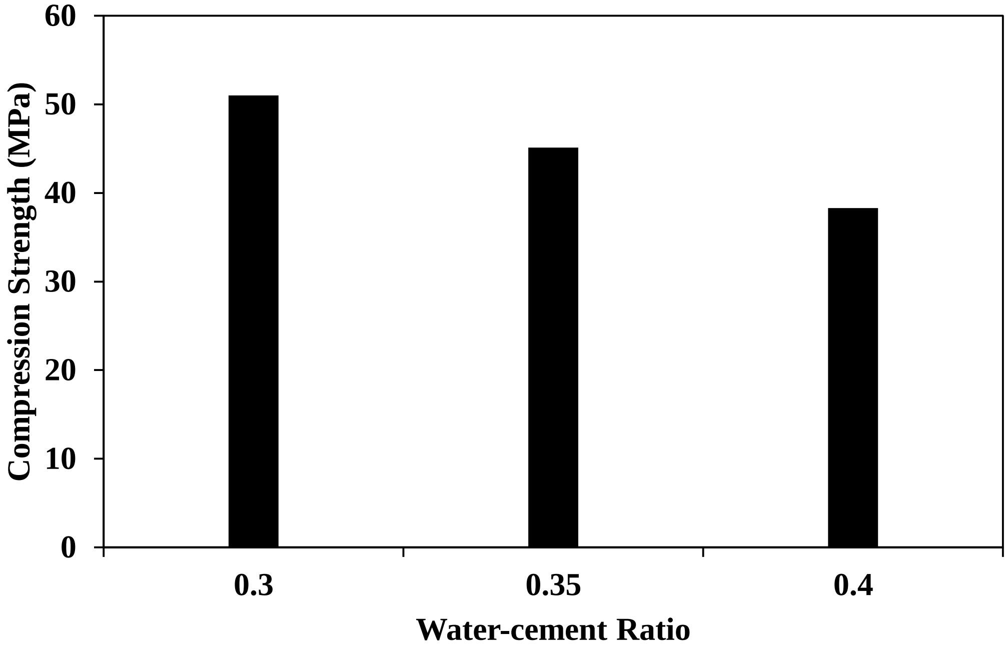

Figure 21: Day 28 Compression Strength of prisms

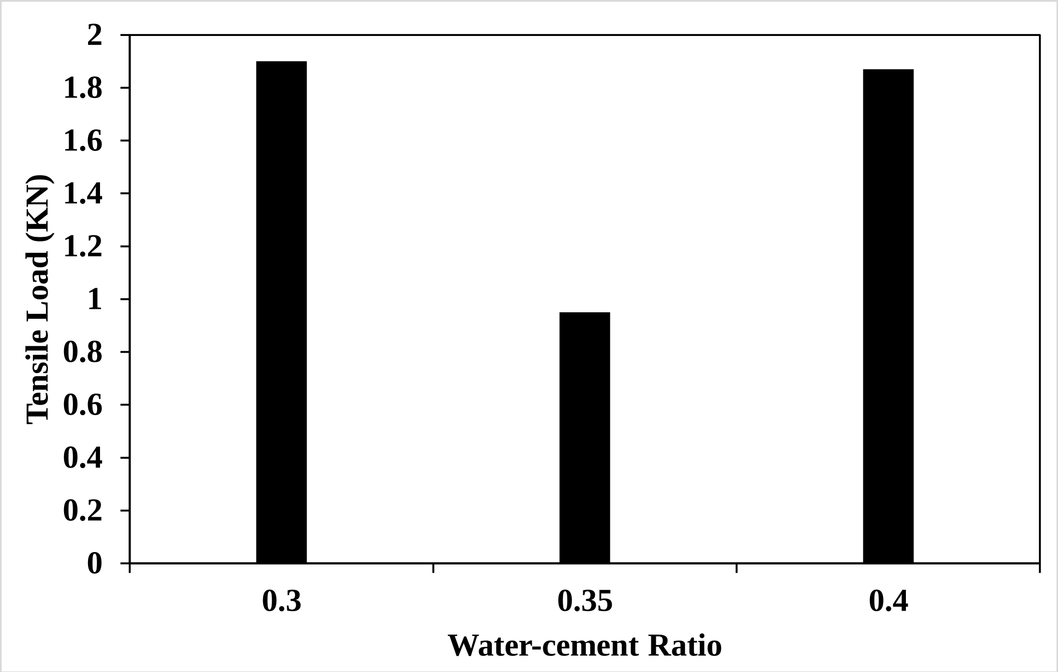

Figure 22: Day 1 Tensile Load of prisms

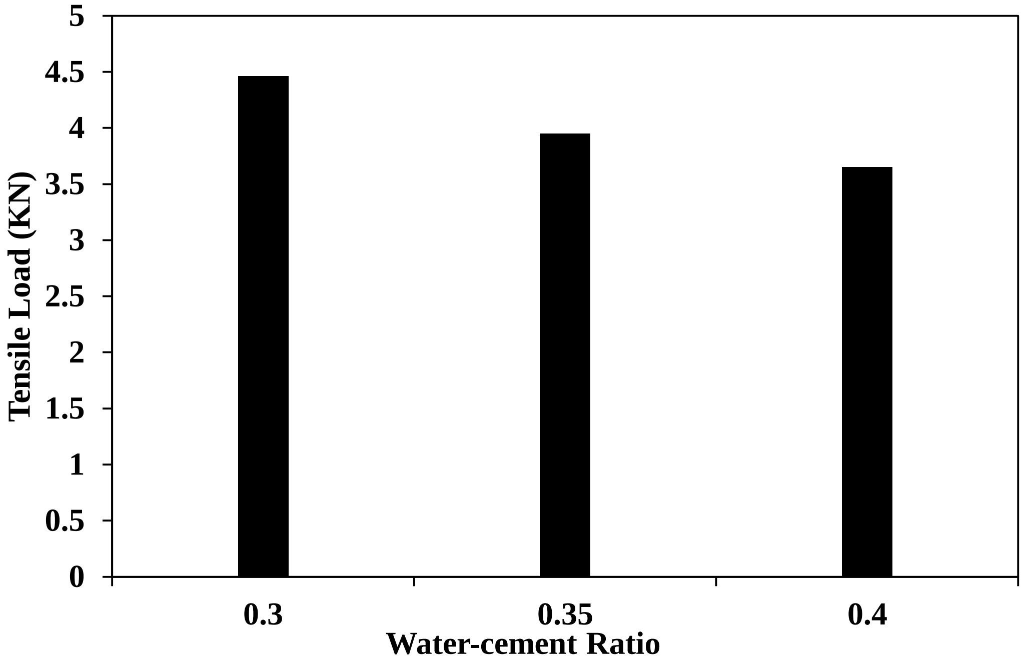

Figure 23: Day 7 Tensile Load of prisms

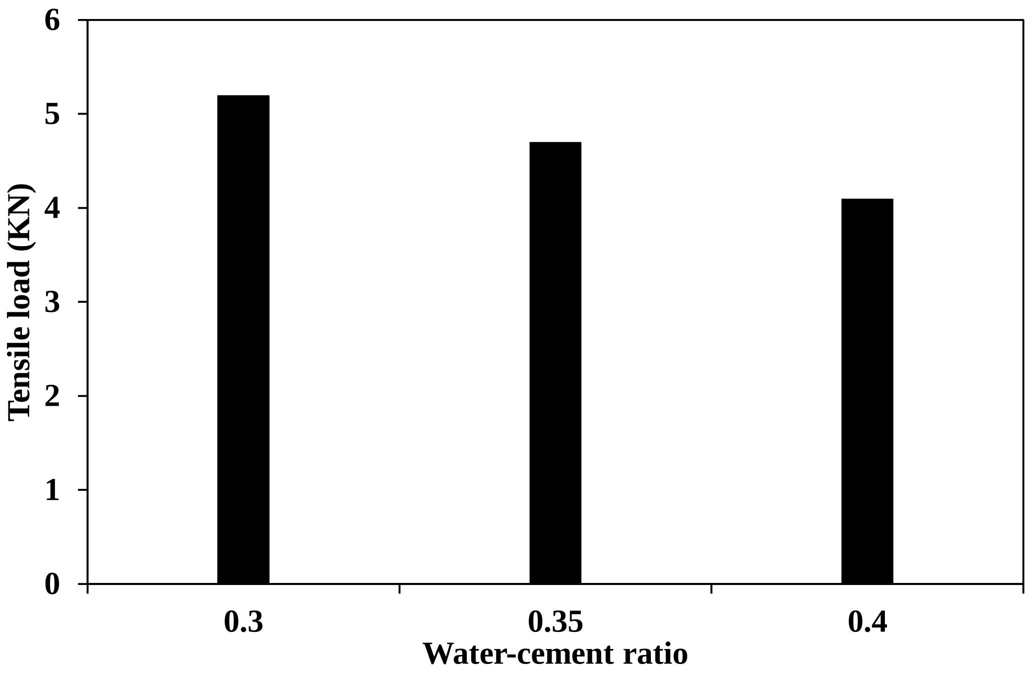

Figure 24: Day 28 Tensile Load of prisms

4.9.2 Compression and tensile strength test results of Cubes

The following graphs are of concrete cubes casted for three formulations having different sand to coarse ratio.

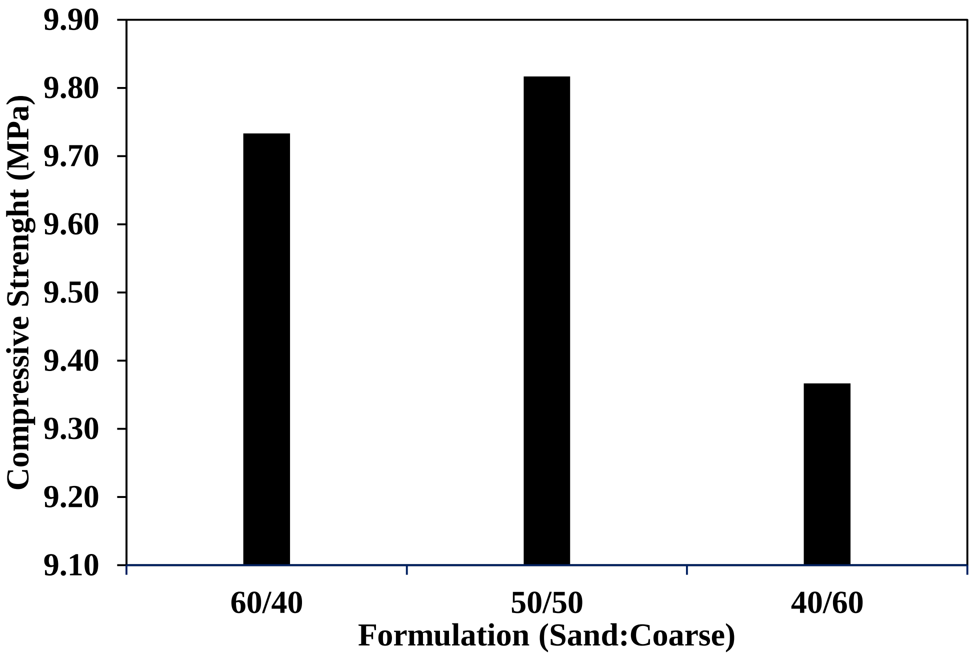

Figure 25: Day 1 Compressive strength of cubes

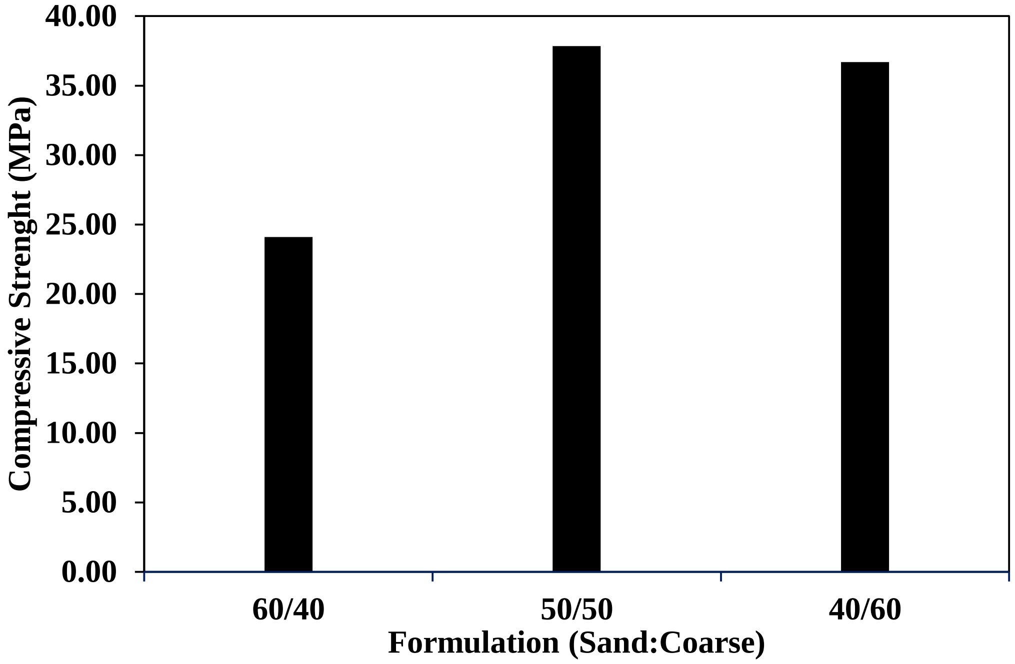

Figure 27: Day 7 Compressive strength of cubes

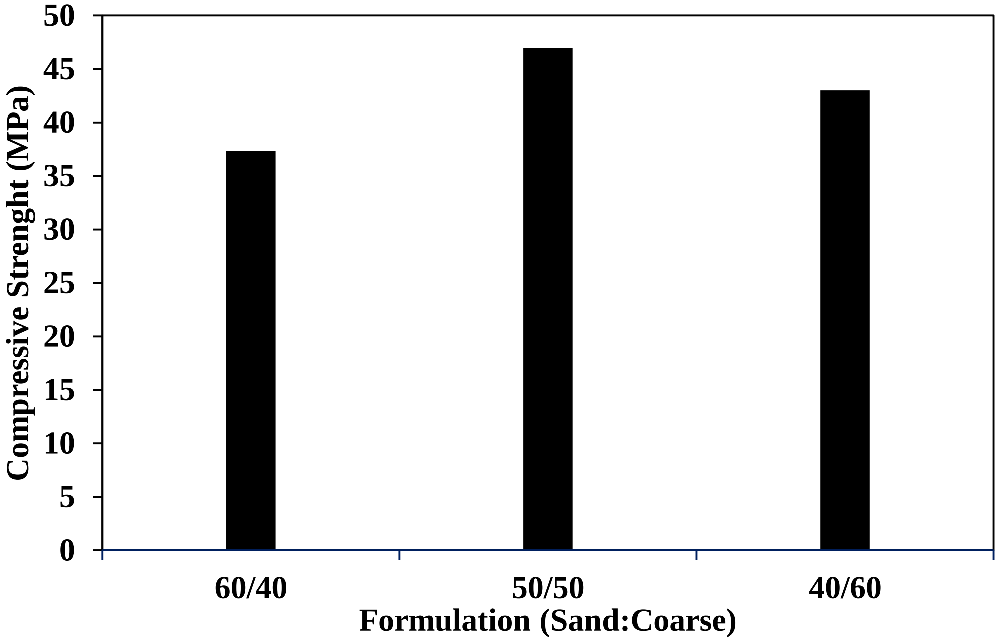

Figure 26: Day 28 Compressive strength of cubes

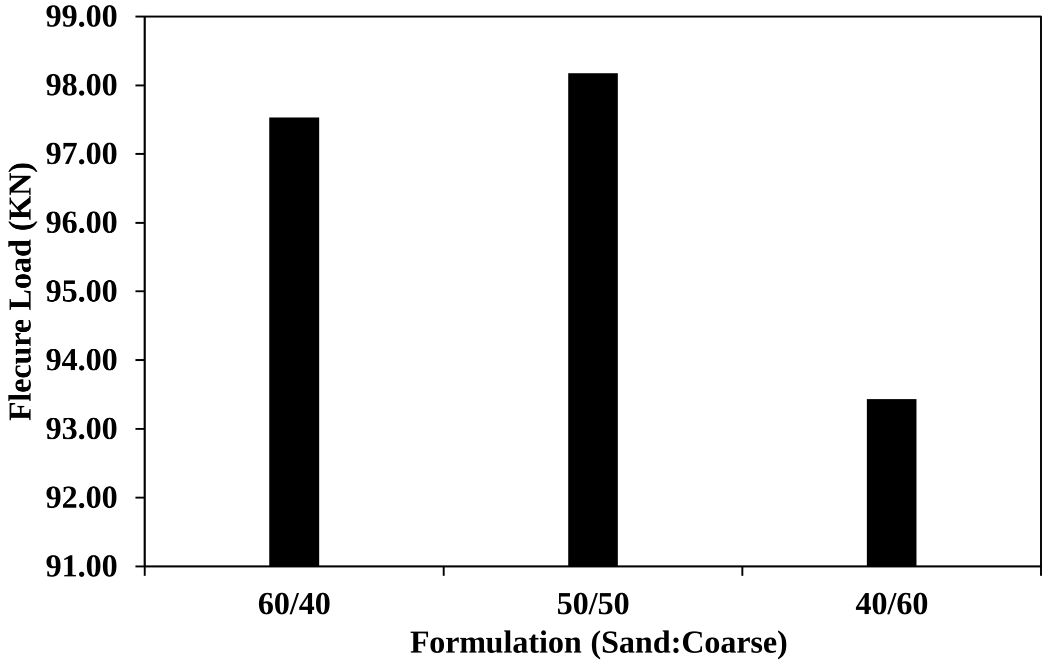

Figure 28: Day 1 Tensile Strength of cubes

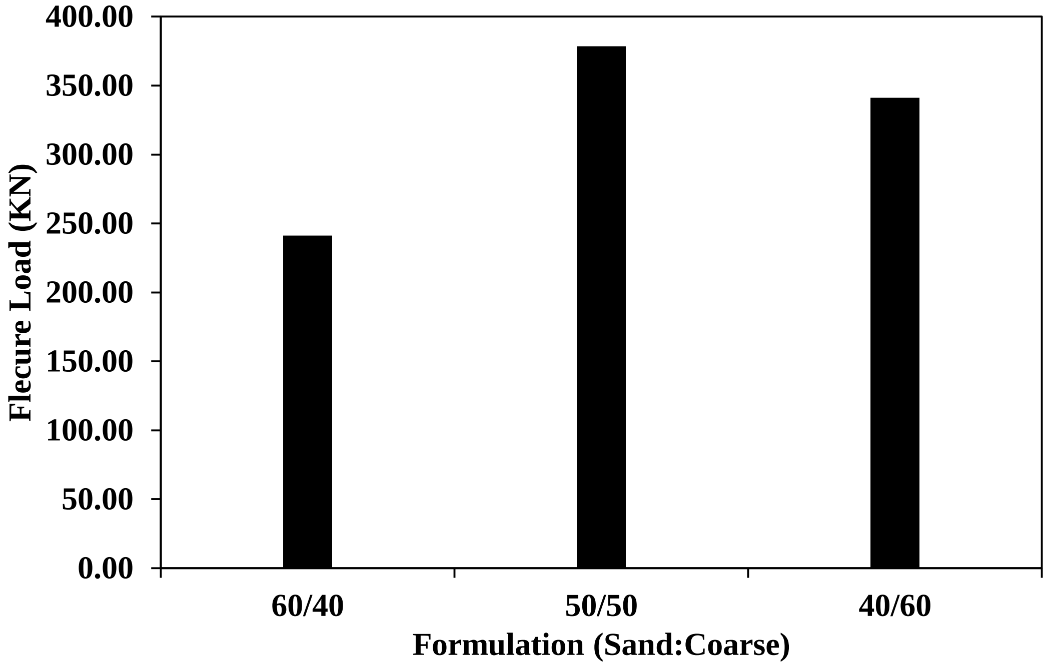

Figure 29: Day 7 Tensile Strength of cubes

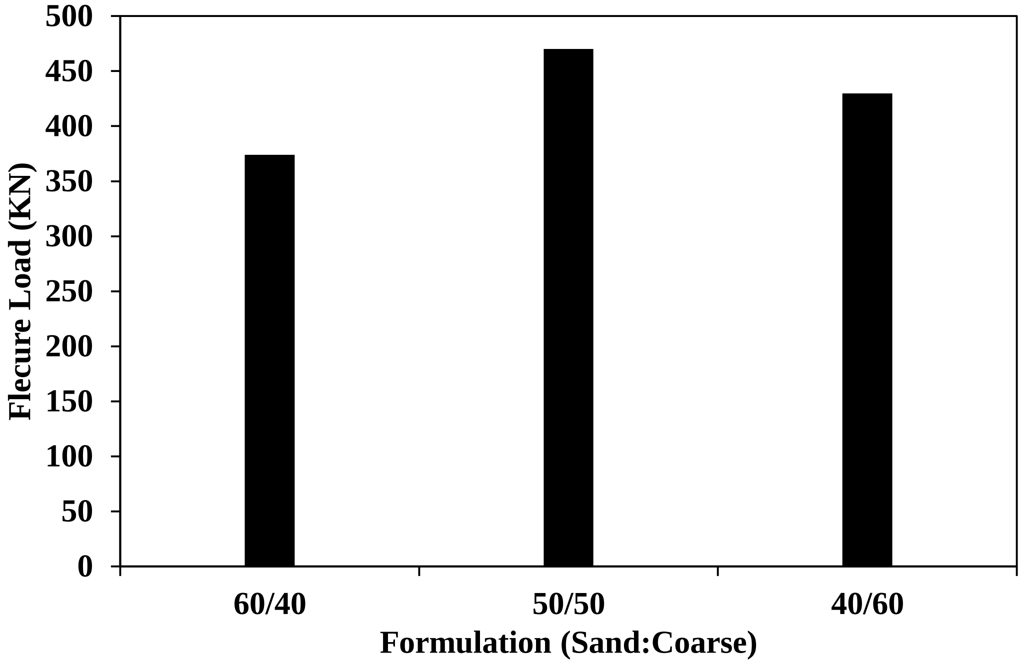

Figure 30: Day 28 Tensile Strength of cubes

Chapter 5

Discussion on Results

The present thesis contains the results regarding the investigations carried out to see the effects of packing density on the performance of self-consolidating mortar systems. Therefore the discussion about the effects of packing is given in following paragraphs.

5.1 Relation of void ratio with packing density

The maximum packing of particles is achieved when the voids in the mix are completely filled with the particles. The distribution of particles is such that the voids created by coarse particles are filled by the finer particles. This arrangement of particles results in minimum void ratio of the mix.

To determine the minimum void ratio or maximum particle densities, various mixes were formulated containing different percentages of coarse and fine particles. The composition of these formulations is given in the Table 15: Rodded Bulk Density and Void RatioTable 15 and Table 16 for Rodded and Un-rodded density test. These test conclude that the density of the mix increases up to a certain limit and then starts to decrease. The maximum density or minimum void ratio is maximum for the mix containing 50% of coarse particle and 50% of fine particles. The mix containing more sand particles than coarse particles can be supposed as a sea of fine particles and the embedding large particles in it. The individual packing density of fine particles is lower as compared to the packing density of coarse particles hence the resultant packing density of the mix becomes lower due to concentration of small size particles. On the other hand when a mix contain more coarse particles than fine particles, the voids in the packed structure increases and the reduced fine particles results in more unoccupied voids in the mix. The result shows that the optimum packing is achieved when an equal amount of fine particles are present in the mix to fill the void created by the same quantity of coarse particles.

5.2 Packing Density of Sand Mixes for Mortar and Concrete

For various distribution modulus, sand mixes were prepared comprising different sand components S_1 to S_5 with the percentages given by Modified Andreasen & Andersen model, which were then used in making the mortar and concrete samples.

Studies infer that with the increase in the distribution modulus, the packing density of sand mixes increases and at distribution modulus of 0.35, maximum packing density occurs after which it starts decreasing.

By relating the fineness modulus of the sand mixes and their distribution modulus of Modified Andreasen & Andersen model, the relationship of packing density and distribution modulus can be easily understood. As the fineness modulus of the sand mixes increases, the distribution modulus also increases which shows that the sand becomes coarser with the increase in distribution modulus. The sand contains more fine particles as compared to the coarse particles at the distribution modulus of 0.20. The packing density of the mix becomes lower at this distribution modulus because the individual packing density of fine sand is less as compared to the packing density of large size sand particles. The content of fine sand decreases as the distribution modulus increases. On the other hand, the content of coarser sand content increases resulting in increased packing density of the mix.

If the content of coarser sand is further increased, it reaches a limiting value at which the content of fine sand is just enough to fill the voids in the packed structure of coarse sand particles. Sand mix has the maximum density at that point and the distribution modulus at that point is 0.35. If the distribution modulus is further increased, it results in the two results on the packing density of the mix. Firstly, reduction in the fine sand particles will produce more unoccupied voids in the mix and secondly, the coarse sand particles will be increased and thus, the voids will be increased in the packed structure which are to be filled by the sand. Therefore, by increasing the distribution modulus from 0.35, it results in the decreased packing density.

5.3 Water-cement ratio Effects on the Flow and SP Demand of SCC with constant distribution modulus

The flow test results of SCM and SCC show that the flow of SCM and SCC systems is directly related to the packing density of aggregate in the mix. The mix having a distribution modulus of 0.35 produced the highest flow. This is because of the higher packing density of the mix requires least amount of paste to fill up the voids in the matrix of fine and coarse aggregate and remaining paste is available to provide high workability / flow-ability.

Keeping the distribution modulus of 0.35, water-cement ratio was varied for the same formulation of mix obtained from Modified Andresean model. The SP demand for each water cement ratio was obtained by performing Hagerman Mini-Slump cone test [] and the results are shown in the **Error! Reference source not found.**. The graph shows that as the water-cement ratio increases, SP demand decreases. This is because at high water-cement ratio, the amount of water for flow-ability is greater and therefore less SP content is required to obtain self-consolidating system.

5.4 The effect of formulations on viscosity

Literature suggests that the T_{70} cm time and the V-funnel times are related to the viscosity of the SCC systems. The SCC formulations were tested for T_{70} cm time and V-funnel time and it was found that the T_{70} cm time increases as the percentage of coarse particle in the mix decreases while the V-funnel time show some relation with the packing density of the mixes. The T_{70} cm time increases because higher fine particle content makes the mix more cohesive and it creeps slowly requiring more time for its flow. The trend of V-funnel time is shown in the Figure 18, indicating as the coarse particles in the mix increases, V-funnel time decreases and the need to use VEA arises. On the other hand, VEA content is not required when the amount of fine particles is greater than coarse particles.

5.5 Flexural and Compressive Strength of Mixes

To analyse the effects of the packing density of aggregates and the water cement ratio on the mechanical properties of SCM and SCC systems, compressive ad flexural strength tests were performed. It is inferred from the results that compressive and flexural strengths are increased with higher packing density and comparatively lower water-cement ratio. With the optimum value of the distribution modulus i.e. 0.35, increasing the water cement-ratio results in lower compressive and flexural strength. Three type of samples were prepared at the water-cement ratio of 0.30, 0.35 and 0.40. Sample 1, with the lowest water cement ratio of 0.30 and the distribution modulus 0.35, gives the maximum compressive and flexural strength. On the other hand, sample 3 with the water-cement ratio of 0.40 and the optimum distribution modulus 0.35 results in the lowest compressive and flexural strength. Therefore, SCM and SCC mixtures with lower water-cement ratio and higher packing density give compressive and flexural higher strength.

Chapter 7

Conclusion

Based on the research work following conclusions have been drawn.

- The size and shape of the fine and coarse aggregate particles are the two governing factors determining the packing density of the aggregate mix. Packing density is greatly affected by the proportioning of the varying size components of fine and coarse aggregates.
- In SCM and SCC systems, enhanced packing density of the aggregates results in improved workability and less requirement of cement paste. This is because of the lower void ratio of the system and thus, with the same amount of cement, extra cement paste enhances the workability.
- To optimize the aggregate gradation for higher packing density in SCM and SCC systems, Modified Andreasen model can be followed. It is inferred from the results that the highest packing density is achieved at the distribution modulus of '0.35'. Therefore, by varying other factors and keeping the distribution modulus of '0.35' the design of SCM and SCC systems can be optimized.
- At a constant distribution modulus, higher the water-cement ratio lower the strength of SCM and SCC systems. Moreover, the higher water-cement ratio also reduces the SP content required to attain the optimum workability.
- In SCC systems the aggregate comprising equal amount of coarse and fine particles results in maximum particle density which subsequently reduces the void ratio. Moreover, the strength is also greatly enhanced by keeping the ratio (1:1) of sand to coarse particles in the mix.
- As the amount of fine particles in the SCC systems increases, the required quantity of VEA decreases because of the enhanced viscosity due to the fine particles. Similarly, due to the effect of internal friction indicating higher viscosity, proposed T 25 cm time increases as the amount of fine particles increases.

- As the packing density of the aggregates in SCM and SCC systems increases, the required strength is achieved at a lower quantity of cement, SP and VEA, thus, making the mixes more economical.

- The compact arrangement of aggregate particles in a mix with high packing density results in more compressive and flexural strength.

- The addition of finer particles in the mix, according to the gradation curve, to ameliorate the degree of packing caters for the adverse results of extra effective water available in the packed system due to the inter particular forces between fine particles which are not significant on micro level but very significant in the whole system.

Recommendations

- Research can be carried out by adding different quantities of SRMs (limestone, fly ash etc.) and observing their effect on the properties of SCC systems.
- Different deposit of natural aggregates can be used to achieve packing density and their relation with the distribution modulus can be studied

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APPENDIX

Annexure- A: Material Characterization

Table 20: ASTM limits of fine aggregate

Fine aggregate limits (ASTM C33)			
sieve size		% passing	
	micro meter	lower limit	upper limit
1 1/2"	37500	100	100
1"	25000	100	100
3/4"	19000	100	100
1/2"	12500	100	100
3/8"	9500	100	100
#4	4750	95	100
#8	2360	80	100
#16	1180	50	85
#30	600	25	60
#50	300	10	30
#100	150	2	10
#200	74	0	5
Pan	0	0	0

Table 21: ASTM limits of coarse aggregate

Coarse aggregate limits (ASTM C33)			
sieve size		% passing	
	micro meter	lower limit	upper limit
1 1/2"	37500	95	100
1"	25000	50	85
3/4"	19000	35	70
1/2"	12500	20	50
3/8"	9500	10	30
#4	4750	0	5
#8	2360	0	0
#16	1180	0	0
#30	600	0	0
#50	300	0	0
#100	150	0	0
#200	74	0	0
Pan	0	0	0

Annexure- B: Flow Test Results

Table 22: Abraham cone flow test results

Abraham Cone						
	Without SRMs			With FA & LSP		
Formulations	**60/40**	**50/50**	**40/60**	**M64**	**M55**	**M46**
Spread (cm)	70	70	70	70	70	70
T50 (sec)	4.32	3.98	3.56	5.2	4.82	4.71
T70 (sec)	7.36	6.87	6.53	8.02	7.8	7.53

Table 23: V-Funnel flow test results

V-Funnel						
	Without SRMs			With FA & LSP		
Formulations	**60/40**	**50/50**	**40/60**	**M64**	**M55**	**M46**
Time (sec)	10.11	9.8	9.59	11	10.26	10.19

Table 24: J-Ring flow test results

J-Ring						
	Without SRMs			With FA & LSP		
Formulations	**CM64**	**CM55**	**CM46**	**M64**	**M55**	**M46**
T50 (sec)	6.1	5.62	5.5	6.97	6.73	6.32
T Total (sec)	6.51	6.02	5.98	7.21	7.14	6.77
Spread (cm)	58.3	59.7	55.2	59.8	60.4	54.6
Ho (cm)	13.8	13.5	12.4	13.5	13.2	12.9
Hx1 (cm)	14.5	13.9	13.8	13.8	14.2	14.1
Hx2 (cm)	14.2	13.6	14.5	14.8	13.5	14.6

Table 25: L-Box flow test results

L-Box						
	Without SRMs			With FA & LSP		
Formulations	**CM64**	**CM55**	**CM46**	**M64**	**M55**	**M46**
T20 (sec)	2.3	1.8	1.5	2.47	2.01	1.78
T40 (sec)	5.2	5	4.7	5.96	5.62	5.37
T60 (sec)	7.4	7.2	6.8	8.57	8.43	8.16
H1 (cm)	49.2	50.3	52.8	49.2	50.3	52.8
H2 (cm)	52	48.7	47.4	52	48.7	47.4

Annexure- C: Strength Test Results

Table 26: Strength test results of concrete cubes

C:A	S:C	Formulations	w/c	SP %	VEA %	Day 1 Results		Day 7 Results		Day 28 Results	
						Load	Strength	Load	Strength	Load	Strength
		C:S:C				(KN)	(Mpa)	(KN)	(Mpa)	(KN)	(Mpa)
1:3	60/40	1:1.8:1.2	0.42	1.15	0	97.53	9.73	241.2	24.10	373.93	37.37
1:3	50/50	1:1.5:1.5	0.42	1	0.3	98.18	9.82	378.5	37.83	470.03	47
1:3	40/60	1:1.2:1.8	0.42	1.4	0.6	93.43	9.37	341.1	36.70	429.9	43.0

Table 27: Strength test results of concrete prisms

C:A	w/c	SP %	Day 1 Results		Day 7 Results		Day 28 Results	
			Load	Strength	Load	Strength	Load	Strength
			(KN)	(Mpa)	(KN)	(Mpa)	(KN)	(Mpa)
1:1.33	0.3	0.35	1.9	15.62	4.46	37.2	5.2	51
1:1.33	0.35	0.34	0.95	14.925	3.95	31.8	4.7	45.1
1:1.33	0.4	0.26	1.87	6.7	3.65	27.9	4.1	38.28

Table 28: Strength test results of mortar prisms

C:A	w/c	SP %	Day 1 Results		Day 7 Results		Day 28 Results	
			Load	Strength	Load	Strength	Load	Strength
			(KN)	(Mpa)	(KN)	(Mpa)	(KN)	(Mpa)
1:1.33	0.30	1	1.3	16.4	4.8	41.7	5.43	47.8
1:1.33	0.35	0.45	1.2	11.12	4.6	32.4	5.25	41.7
1:1.33	0.4	0.3	1.87	7.58	4.4	27.025	5.05	35.6