STUDY OF PACKING EFFECTS ON SELF CONSOLIDATING CONCRETE (SCC) USING SECONDARY RAW MATERIALS (SRM)

By

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(2014-NUST-MS Ph.D-Str-17)

This thesis is submitted in partial fulfilment of
the requirements for the degree of

Master of Science

in

Structural Engineering

National Institute of Civil Engineering (NICE)

School of Civil & Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan

2017

This is to certify

that Thesis entitled

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Submitted by

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Has been accepted towards the partial fulfillment
of

the requirements
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Master of Science in Structural Engineering

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Feb 2017, Islamabad Pakistan

ACKNOWLEDGEMENTS

All praise to Almighty Allah who gave the courage and power to the author for completing this research work.

I am heartily thankful to my supervisor Prof. Dr. Ing. Syed Ali Rizwan, HoD Structural engineering department, NUST Institute of Civil Engineering (NICE), for giving me time and support from initial to final level made it possible for me to complete this work especially in the compilation of this manuscript and discussions.

I must not forget the supporting role of my friends and especially Engr. Siraj ud din, Engr. Hasnian Khan, Engr Haseeb Taj and Engr Muhammad Ali Janjua, student of Ms. Structural engineering at NICE, NUST and laboratory staff at NICE, for providing the technical assistance and cooperation during the reported research work.

Thanks due to DAAD for providing F-Cal 8000 Field Calorimeter and Modified Schwindrine Shrinkage Apparatus to NICE/NUST under an International Research Project.

I appreciate the support provided to me by my parents and my family as this research work that would not have completed without their prayers and whole hearted encouragement and support.

ABSTRACT

The classical idea of particle packing is based on Apollonian concept, in which the smaller sized particles fit into the voids left by larger particles. Well graded fine and coarse aggregates having greater range of particle size will reduce the voids in concrete and hence the paste required to fill those voids. Fine to coarse aggregate ratio can be adjusted by trials to have maximum packing density of granular mix with reduced voids between them. Crushed aggregate particles are very irregular in shape and pack more poorly together than naturally formed gravel. Aggregate voids increases the paste demand in the mix and this can be countered by use of very fine sized Secondary Raw Materials (SRM) to partially replace cement without adversely affecting the properties of concrete.

Present study focuses on determination of optimum fine to coarse aggregate ratio to have a maximum packing density of granular phase of Self Consolidating Concrete (SCC). SRMs including Fly Ash (FA) and Limestone Powder (LSP) were also utilized to further improve the packing of mix. Flow, volume stability, heat of hydration and mechanical characteristics of Self Consolidating Concrete made with and without SRM were studied and compared to the mix formulation designed using EMMA based on Modified Andreasen and Andersen (MAA) approach. The ratio of fine to coarse aggregate was varied in 20-80% range, as a trial process, to see the effect in the degree of packing of aggregates in the SCC. The packing density and compressive strengths were found to be optimum when fine to coarse aggregate ratio was 50:50 in terms of weights in trial mixes while that based on MAA approach this ratio was around 51:49 with distribution modulus “q” equal to 0.25.

Results showed that SCC prepared using SRMs (Modified Mixes) possesses higher packing density than that of SCC mixes in comparison to Control Mixes (CM) having no SRM. Modified Mixes (MM) show increased SP demand for target flow, higher flow times, better strengths, reduced total linear shrinkages and reduced heat peaks in calorimetry coupled with reduced air content. While MAA approach saves the time and materials needed in SCC mix design in trial process.

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CHAPTER 1: INTRODUCTION

1.1. General

Concrete is considered to be the most utilized material on earth after water. Concrete can be made up by mixing water with cementitious materials, aggregates and sometimes with chemical or mineral admixtures depending on the desired properties.

In concrete, voids of larger particles (coarse aggregates) are filled by smaller particles (fine aggregates) and the voids still left are then filled by paste (Powder + Water). Concrete is a three component system namely Paste, Mortar and Concrete as explained below.

Paste = Powder + Water	Single component system
Mortar = Paste+ Fine Aggregate	Two component system
Concrete = Mortar + Coarse Aggregate	Three component system

Concrete due to its strength is also known as man-made rock. The strength of concrete has been worked in various dimensions by different researchers around the globe by using different materials as its component like steel fibers, silica fume, fly ash etc [1] and also by reducing voids using different packing models. In 1900's structural engineers and material technologists tried to optimize the strength of concrete and with the passage of time rise in the strength of concrete was observed due to their efforts and the term "High strength" was under constant revision. Lower w/c ratio is critical to increase the strength of concrete while maintaining the workability of mix. In high strength concrete mixes, it is not necessary to hydrate every particle of cement, due to lower w/c ratios a portion of cement is left unhydrated so Secondary Raw Materials (SRM) of finer particle size is used as a partial cement replacement to not only densify the mixture but to enhance the strength due to its pozzolanic reactivity. In 1970's compressive strength of concrete surpassed the value of 41MPa (6000 Psi) at 28 days age and was labelled as high strength concrete by American Concrete Institute (ACI) [2]. Figure 1.1 shows the increase in strength of concrete with the passage of time.

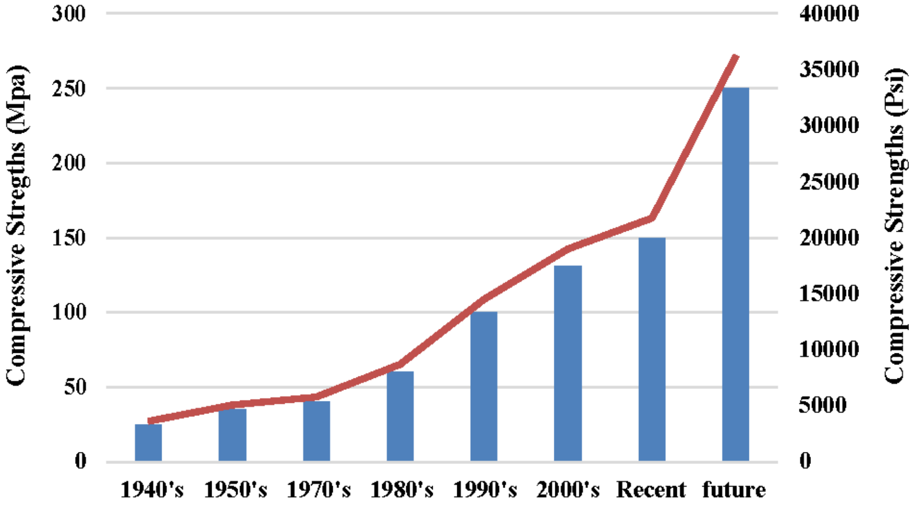

Figure 1.1: Development of compressive strength of concrete over time

Invention of super plasticizer in early 80’s in Germany and Japan is considered to be a great achievement in concrete industry. Use of superplasticiser made it possible to develop a concrete with low w/c ratio and adequate workability. This invention lead to the development of high strength concrete having a compressive strength of 60-100 MPa which is used commercially to build long span bridges and high rise buildings containing heavily reinforced sections [3]. Later, Ultra high performance concrete having compressive strength greater than 150 MPa (21750Psi) was developed and it’s not over yet, researchers are still looking forward to make the optimum use of concrete by increasing its strength to the maximum possible level and to date, specified maximum compressive strength achieved is 800Mpa (116,000 Psi) [4]. This new Ultra High Performance Concrete (UHPC) is also termed as Reactive Powder Concrete (RPC). It consists of a sand as its largest sized aggregates and fine steel fibers are distributed within the concrete.

Due to advancement in concrete technology, many other types of concrete like High Performance Concrete (HPC), High strength concrete (HSC) and Self-Compacting concrete (SCC) have been developed and are now replacing the conventional concrete due to its obvious limitations. Prof. J Francis of university of Illinois has developed a strength classification of concrete as shown below [5].

Table 1.1: Strength classification of concrete [5]

Paramete	**Conventional concrete**	**High-strength concrete**	**Very-high strength**	**Ultra-high strength**
Strength MPa (Psi)	< 50 (7250)	50-100 (7250-14,500)	100-150 (14,500-21,750)	> 150 (21,750)
Water-cement ratio	> 0.45	0.45-0.30	0.30-0.25	< 0.25
Chemical admixtures	Not necessary	WRA/HRWR*	HRWR*	HRWR*
Mineral admixtures	Not necessary	Fly ash	Silica fume**	Silica fume**
Permeability coefficient (cm/s)	$> 10^{-10}$	$> 10^{-11}$	$> 10^{-12}$	$> 10^{-13}$
Freeze-thaw protection	Needs air entrainment	Needs air entrainment	Needs air entrainment	Needs air entrainment

* WRA = Water reducing admixture; HRWR = high-range water reducer

** May also contain fly ash

Strength of concrete can be improved by reducing the porosity, inhomogeneity and micro cracks in hydrated cement paste and the Interfacial Transition Zone (ITZ). Use of secondary raw materials reduces cement content and due to its pozzolanic reaction, it increases strength and durability of concrete. Silica in SRM reacts with Calcium hydroxide produced during hydration of cement to form cementitious products. This improves micro structure of the matrix by making it better packed and reducing pores which in turn enhances the strength with better economy [6].

1.2. Self-Compacting Concrete

Two milestones that caused great impact in lifting the construction industry were the invention of Super-Plasticizer (SP) [7] and Self-Compacting Concrete (SCC) in 1980s. ACI 237-07 defines SCC as "Highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation." [8]. It was developed by the Japanese researchers in University of Tokyo to cater the issues developing in the country due to the lack of skilled labour in 1980s. The work of Okamura [9] was extended under the supervision of Ozawa [10] to produce the first usable version of SCC in 1988. Since then, SCC is being used successfully in Japan [11] and other parts of the world for different construction projects including bridges, high rise buildings etc. SCC generally requires 34%-40% paste [6] which is greater than the conventional concrete, this makes SCC a bit uneconomical to be used in large scale construction projects. Also the higher amount of paste means higher will be the shrinkage and heat of hydration. To account for these issues different Secondary Raw Materials (SRMs) have been discovered and are being used in the world which are cheaply available, they not only increase the strength of the SCC but also helps in obtaining other desired properties of concrete [12, 13]. Most commonly used SRMs include Silica Fume (SF), Fly Ash (FA) and Limestone Powder (LSP), they help in enhancing the properties of SCC by their pozzolanic activities and by packing the binder phase of the mix. Since they are by product of industries which would have been wasted otherwise. Their use in concrete makes SCC an environmental friendly concrete.

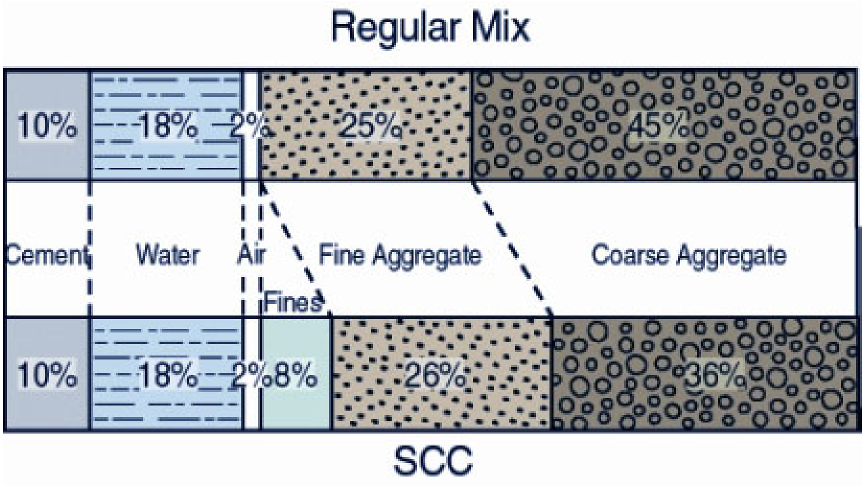

Figure 1.2: Comparison of conventional/regular and self-compacting mix

Self-Compacting Concrete is currently used in many projects due to its obvious advantages over conventional concrete. High durability, cost effectiveness and eco-friendliness are the driving forces behind the added value of SCC. Other applications of SCC involve placement in heavily reinforced sections, tunnel linings, rafts, bridge piers etc. Use of Secondary Raw Materials (SRM) in SCC have recently gained much popularity in construction industry. Due to the use of concrete at massive scale, it has caused great impact on environment due to emission of CO_2 in atmosphere. A study suggests that with the production of 1 Ton of cement, 0.8-1.3 Ton of CO_2 is emitted in air. According to the figures of All Pakistan Cement Manufacturer Association (APCMA) nearly 40 Million Ton of Cement is produced in the country during the last fiscal year [14]. This shows that only Pakistan has added around 52 Million Ton of CO_2 through its cement industry.

1.3. Secondary Raw Materials

Around 15 billion tons of concrete per annum is currently being produced around the world. This huge amount of concrete is contributing immensely in making the atmosphere polluted. It is estimated that in coming years around 10% of the total greenhouse gas emission on the planet will be due to concrete only [15]. In Europe, it is a common practice to replace clinker content in cement to reduce Carbon emission in atmosphere. This lead to the development of different classes of cements (CEM 1, CEM 2, CEM 3, CEM 4, CEM 5) as per European Norms (EN 197) by adding materials like slag as a replacement to clinker. This replacement concept was also used to partially replace cement content by industrial wastes like Silica Fume, Fly Ash, Limestone Powder, Baggase Ash etc. to make an environmental friendly concrete. Few of them proved to be very useful in increasing the strength and durability of concrete and potential of others is yet to be recognized. SCC containing secondary raw materials is an indirect way of reducing CO_2 footprint [16].

SRMs are mostly inorganic materials that show some pozzolanic activity when combined with cement and water. They modify the properties of concrete in fresh and hardened state when partially replaced with cement. ASTM C 125 defines pozzolanic materials as “A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (CH) produced by cement hydration at ordinary temperatures to form compounds possessing cementitious properties” [17].

SRMs when used separately have their own merits and demerits so researchers are now more interested in using their blends [18]. FA and LSP used as a blend to replace 30% of cement (15% each SRM) [19] in Self Compacting Paste (SCP) showed better properties than control mix. The same concept was used to produce a better packed and economical concrete in this research.

1.4. Packing Density of Concrete

In SCC, paste content majorly performs two important functions, one is to coat the aggregate particles to ensure good workability and strength, and secondly it fill the voids of aggregate in the mixture [20]. In order to reduce voids in the matrix, aggregates should be well packed and for that it is important to have a continuous grading of aggregates so that the voids left by bigger particles is filled by smaller ones. Thus packed system will require lesser amount of paste for producing SCC and will lead to better economy and durability.

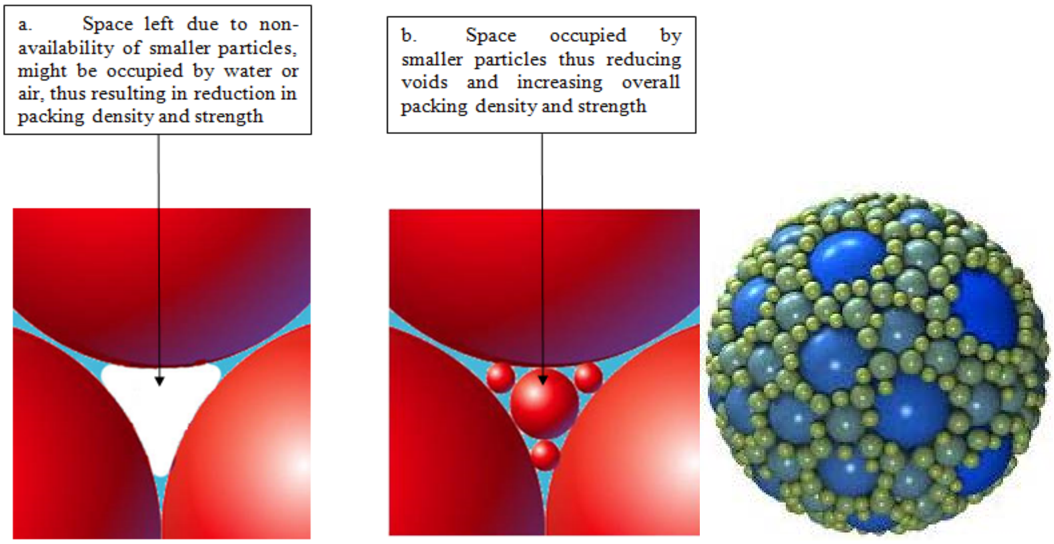

Figure 1.3: Filler effect of fine particles

Randomly packed equal sized particles can pack the system upto 64% at maximum [21]. Above figure shows how the bigger particles create voids that needs to be filled by smaller particles to increase the packing. Theoretically, packing density can approach to the value of 1 by using wide range of particles in large amount. In concrete, voids left by coarse aggregate is filled by smaller particles of fine aggregate and voids left by fine aggregate is filled by paste (powder and water). Powders are the materials having particle size less than 125 microns. Powders have a very critical role to play in SCC in terms of their filler effect and pozzolanic activity. They also play their part in modifying flowability depending on the nature of particle; its shape, surface and density.

Optimum packing in concrete mix can be achieved by packing the aggregate phase of the mix and then by packing the binder phase by using Secondary Cementitious Materials (SCMs) like LSP, FA, SF etc. Degree of packing of aggregate phase can be achieved by altering fine to coarse aggregate ratio by trials [22] or by using suitable packing model. There are different packing models proposed by researchers that can be followed to improve the packing density of concrete mix. Some of these models rely on ideal particle size distribution curves. Packing models that can predict packing density of the mixes generally considers only spherically shaped particles in their calculations. However, this contradicts the nature and practically it is not possible to have a perfectly spherical shaped particles throughout the mix. Packing models proposed by researchers are difficult to be followed accurately because of the involvement of sieving for all type of materials including coarse aggregate, fine aggregate and binding materials. However it has been observed in this research work that by using software based on particle packing approach, trial process can be eliminated to determine optimum fine to coarse aggregate ratio for greater packing of granular phase of the mix.

1.5. Research Objectives

Primarily the research is focused to attain the maximum packing density and study its effects on the mechanical and flow properties of self-compacting concrete with and without mineral admixtures. Detailed objectives are listed below:

a. Optimizing fine to coarse aggregate ratio by trials using locally available aggregates to get a mix of maximum packing density.

b. Using EMMA based on Modified A&A model to design an optimized mix of SCC having maximum packing density.

c. Using blends of FA and LSP (15% each by weight of cement) to partially replace cement to increase packing of binder phase of SCC. And conduct a comparative study to see the response of SCC developed with and without SRMs.

d. Compare the properties of SCC including mechanical strength, flow, volume stability, and microstructure of the optimized SCC mixes having different packing densities developed by trials and by using EMMA.

1.6. Scope of Research

Scope of the research is limited to study the properties of self-compacting concrete having different packing densities developed by adjusting fine to coarse aggregate ratios and by using EMMA based on Mod A&A particle packing approach. Maximum aggregate size was limited to 16mm for developing SCC. Limestone Powder and Fly Ash were used as a partial replacement of cement in equal amounts to replace 30% of cement by weight. Locally available aggregates (fine and coarse aggregates) were used in this project along with LSP manufactured locally using Margalla crush. Whereas FA was imported from Germany as it was not locally available.

CHAPTER 2: LITERATURE REVIEW

2.1. Self-Compacting Concrete

Self-Compacting Concrete is characterized by two important features; *deformability and segregation resistance*. Higher deformability is achieved mainly by using High Range Water Reducing Agents (HRWRA) commonly known as Super Plasticizer (SP) and limiting amount of coarse aggregate (50% of solid volume depending on its size). Segregation resistance is attained by controlling w/p ratio and using Viscosity Enhancing Agent (VEA). SCC contains higher amount of powders (having particle size < 125 micron) and low w/c ratio along with mineral admixtures like SF, FA etc that improves properties of SCC in fresh and hardened state through their filler effect and pozzolanic activities [23]. Enabling SCC to flow under its own weight through heavily reinforced sections while maintaining the stability of the mix requires preparing a mix design very carefully to ensure that every aggregate particle is get coated by the paste that helps in transporting them and also increasing the viscosity to prevent the separation of coarser particles from the matrix. Okamura and Ozawa [24, 10] proposed a simple technique to achieving self-compatibility as given below.

a. Increasing powder content
b. Reducing coarse aggregate (size and quantity)
c. Reducing w/c ratio
d. Using SP and VMA as required to make the mix stable and flowable.

ACI 237-07 also guides for proportioning of trial mix of SCC and lab tests to be performed to ensure the properties as desired, the summary of these guidelines is as follows.

Table 2.1: Proportioning Guidelines of ACI for SCC

Absolute volume of coarse aggregate*	28 to 32% (>1/2 in. [12mm] nominal maximum size)
Paste fraction (calculated on volume)	34 to 40% (total mixture volume)
Mortar fraction (calculated on volume)	68 to 72% (total mixture volume)
Typical *w/cm*	0.32 to 0.45
Typical cement (powder content)	650 to 800 lb/yd^3 (386 to 475 kg/m^3) (lower with a VMA)

*Up to 50% (3/8 in. [10 mm] nominal maximum size).

Greater w/c ratio is responsible for segregation and bleeding and also lowering the strength and durability. Increasing the paste content with reduced w/c ratio and lower amount of coarse aggregate causes significant decrease in internal friction and increases the flowability and passing ability of SCC through confined sections. To improve the viscosity of the mix in order to avoid any segregation, fine content in SCC is increased along with the use of VEA.

Elimination of use of any mechanical means to compact SCC and use of higher powder content makes the concrete homogenous and more durable. Higher amount of fines (mostly cement) make the concrete uneconomical and less feasible to be used on large scale, this issue is catered by utilizing SRM like SF, FA etc as a partial replacement of cement. This not only fills in the voids to reduce porosity but also helps in reducing shrinkage and improving strength. Researchers are now focusing to use blends of two or more SRMs and find their potential of complimenting each other. Rizwan et al, found that using FA and LSP individually may have few disadvantages like LSP due its porous and rough surface offers great resistance against the flow and increases SP demand while FA retards the hydration reaction [18]. Thus using them as a blend will improve the properties of concrete. Several combinations of FA and LSP have been tried already by researchers to find the optimum replacement level that gives better results. Rizwan et al, reported that using FA at 20% and LSP at 80%

performed better than other formulation in Paste system. Wahab [19] et al, reported LSP and FA used at (50%-50%) gives better results among the others by showing improvement in strength and flow with reduced shrinkage.

2.2. Packing Density

Volume occupied by solid particles in a unit volume of the mix is known as *packing density*. It gives an idea about how the particles are filled in a unit volume. It is represented as

$$\boldsymbol{\alpha = 1 - e}, \qquad (2.1)$$

$$\mathbf{e} = \frac{100 * [Gs * 62.4] - BulkDensity}{Gs * 62.4} \qquad (2.2)$$

Here α is packing density (%) of aggregates and e is % voids in aggregates (coarse and fine) and Gs is the specific gravity of aggregates.

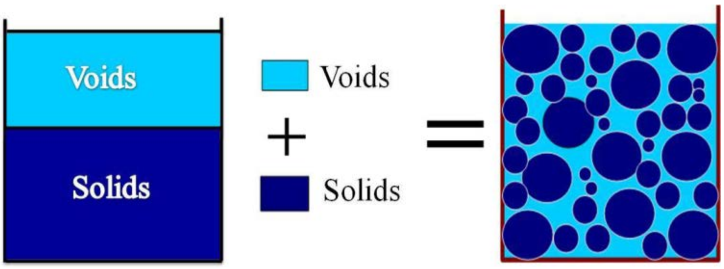

Figure 2.1: schematic of particle packing

From the above figure, it can be seen that packing density can also be represented as

$$\alpha = Vs/Vt = Vs/ (Vs + Vv) \qquad (2.3)$$

Here
Vs = Volume of solids
Vt = Total volume
Vv = Volume of voids

Packing density should not be confused with Bulk Density. Bulk density shows the mass filled in a unit volume while packing density shows the volume occupied by solids in a unit volume. Relation between the two is as below.

$$\alpha = \text{Bulk Density}/\ \rho_p = Mp/\ (\rho_p \times V) \qquad (2.4)$$

Here

Mp = mass of particles filled in a container

ρ_p = density of solid particles

V = volume of container

2.3. Factors affecting Packing Density

Concrete contains larger volume of natural materials which are not same everywhere. Natural materials differs in many aspects from each other due to their origin. Several factors that effects packing density includes particles density, particle porosity, shape of particles, particle stability, surface texture, particle size and their distribution in the mix. These factors are discussed in detail as under.

2.3.1. Particle Density

Particle density generally do not affect the degree of packing of mix having uniform sized particles, as packing is defined as the ratio of volume of solids to total volume. But in case of binary or ternary mixes where mix is composed of more than one material then Particle density comes into play. Due to large variation in specific gravity of particles, heavier ones settle down causing segregation in the mix [25]. This settling of heavier particles at the bottom of mix causes non-uniformity in the matrix and the idea of having well graded particle size distribution flops under such situations.

2.3.2. Particle Porosity

This is an important factor affecting the packing density of the mixture. Materials having porous particle nature will be having lower specific gravity and greater water absorption capacity. Open pores reduces the degree of packing in the matrix while closed pores reduces specific gravity. SRM is more critical when it comes to porosity, presence of open pores in SRM causes increase in water demand. Porous particle surface texture tends to accumulate water in them thus leaving less effective water behind. FA having lower specific gravity tends to come out of the mix specially during pumping. Thus viscosity enhancing agent is used to keep particles of FA in the mix.

2.3.3. Particle Size Distribution

Well graded particle size distribution contributes well enough in packing density of the mix. Particles of same size can pack the system upto 64% at maximum [18]. There can be different arrangements of spherical particles in a container which might be cubic, tetrahedron or octahedron.

In case of a particles of different sizes, cavities left by coarser particles are filled by finer particles. And ideally if having particles of every size in the mix, packing density can approach to a value of unity. Following figure elaborates how important it is for particles to fit in the voids left by bigger particles to enhance the packing density of the mixture.

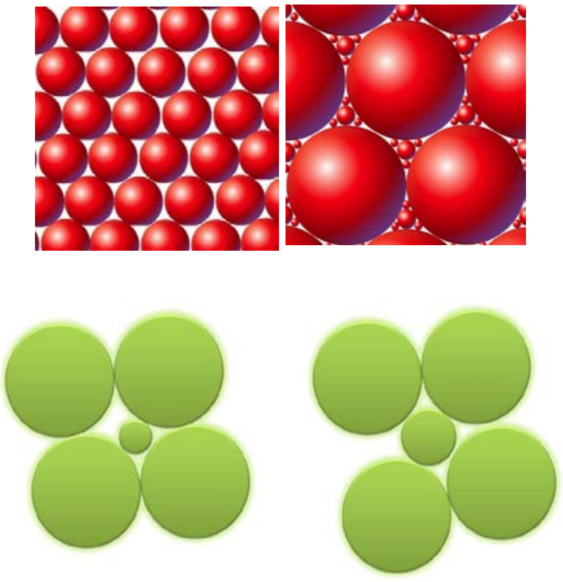

Figure 2.2: Effect of relative particle size on packing density of the system

2.3.4. Particle Shape

Workability of concrete is greatly affected by shape of aggregates, aggregates having sharp edges offers more resistance against the flow of mix while rounded aggregates ease the flow. Similarly packing is also affected by shape of particles, rounded aggregates may allow the finer particles to pass through them, on the other hand angular aggregate holds up the particles above them which might result in creating voids.

Aggregates are divided into five basic categories as follows [26]

Angular: Sharp edges
Sub Angular: Slightly wear on edges but surfaces are untouched
Sub Rounded: Significant wear on edges and faces
Rounded: Very little edges
Well Rounded: No or negligible edges

Ahn. N. prepared a chart for visual assessment of aggregate shapes [27] as shown below.

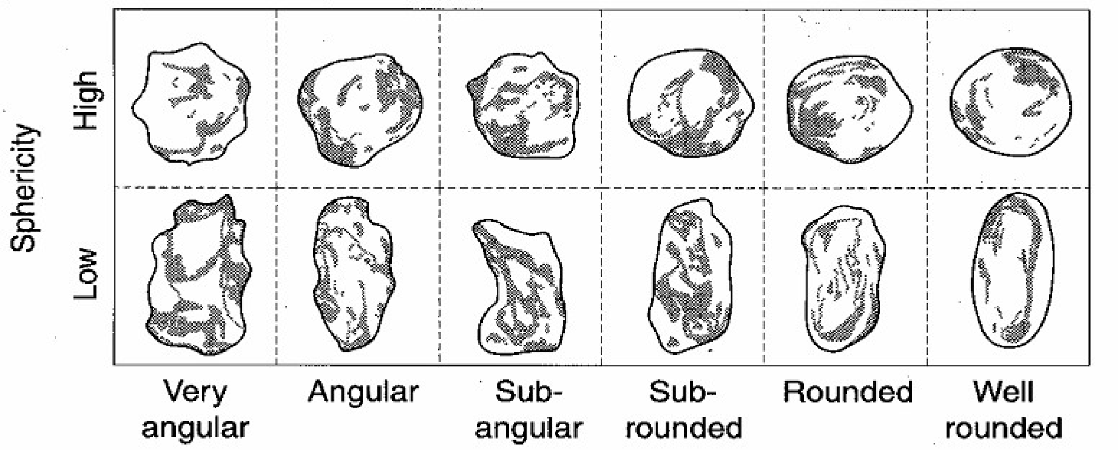

Figure 2.3: Visual assessment of particle shape

It should be noted that as we move from well-rounded to very angular shaped aggregates, packing density of a mix will decrease creating a mixture having high porosity.

2.3.5. Interparticle Forces

Interparticle force is the force of attraction between neighboring particles. It has a great influence on packing behavior of powders. Forces of attraction between the particles can be adhesion or non-bonded van der Waals forces. Interparticle forces and gravitational forces acts on the loose particles. Gravitational forces are directly related to the size of particles and they starts governing over the interparticle forces when particle size is nearly 100 micron [25]. Strong interparticle forces will adversely affect the packing density of the mix.

2.3.6. Particle Stability

The ability of a particle to change its shape under the influence of forces or any other stress like thermal stresses affects the degree of packing. If the particles are not stable against the forces, this will increase the packing density of the mix. Elastic and soft materials that can change their shape upon the application of any external force will tend to rearrange the particle distribution in a container and will try to close the gaps between the particles which leads to better packing. However, materials used in producing SCC are generally very hard and stable which do not change their shapes significantly due to application of forces.

2.4. Packing Density of Concrete

Particle packing has been suggested by some researchers as a scientific approach to mixture proportioning of concrete [28-31]. A review of common particle packing methods is provided elsewhere [32]. The concept of particle packing is borrowed from the ceramic industry. Here, the principle is to limit the void content of a dry granular mixture of all ingredients (including cement, fly ash and microsilica). This is done by the choice of appropriate sizes and gradation of aggregate.

O’Flannery and O’Mahony [33] have devised a method for shape characterization of coarse aggregate, which could assist in designing SCC mixtures having marginally unsuitable aggregates. The overall idea was to overcome local deficiencies in aggregate shape and to arrive at required packing characteristics irrespective of the aggregate.

Another deficiency in aggregates is poor gradation. Use of fillers (either reactive or inert) has been suggested as a means of overcoming this problem [34, 35]. At present, a trial and error approach is used to fix the type and amount of filler. Alternatively, particle packing models could be used to reduce the number of experimental trials [36]. Such models are discussed later.

Mix design proposed by Okamura and Ochi popularly known as Japanese method suggests that coarse aggregate content in concrete mix corresponds to 50% of its packing density and that in mortar fine aggregate corresponds to around 50% of its packed density. This independent consideration of coarse and fine aggregates results in SCC that has relatively high content of paste and so the higher strength than actually desired.

More recently, Su et al. [37] and Su and Miao [38] developed an alternative method for mix design of SCC, henceforth referred to as Chinese Method. This method starts with the packing of all aggregates (fine and coarse), and later with the filling of the aggregate voids with paste. Use of this approach for SCC mix design results in economical concrete by saving the most expensive ingredient, namely cement, without compromising on strength of concrete. This is also beneficial in terms of technical performance of concrete, as the greater content of coarse aggregate improves strength and stiffness while reducing permeability, creep and drying shrinkage of concrete.

2.5. Models Used for Packing of Concrete

Packing models can be characterized into two major groups; discrete models and continuous models. Discrete models assume the two or more groups of discrete sized particles arranged in a way to have a maximum packing between the particles. The other one is a more realistic approach that uses continuous particle size distribution in which particles of almost every possible sizes is considered. Following is the brief detail of few packing models proposed by researchers.

Furnas [39] is considered to be a pioneer in the field of packing density, he presented the very first model of particle packing that was applicable to binary mixes only. He then further extended his work to add subsequent sizes in his initial proposed model and in 1931 he presented an ideal particle size distribution curve aimed at providing the maximum packing density of granular mixes. Model proposed by Furnas is mathematically represented as follows

$$\text{Cumulative \% passing} = \frac{d_r^{\log d} - d_r^{\log dmin}}{d_r^{\log dmax} - d_r^{\log dmin}}$$

Here d_r = ratio between the consecutive aggregate sizes, d_{min} and d_{max} = minimum and maximum aggregate sizes respectively. Furnas curve assumes the diametric ratio “dr” equal to √2.

Another model which is widely used in design of concrete pavements was proposed by Fuller and Thompson in the beginning of the 20th century [40]. Fuller’s model was comparatively simpler and only includes maximum size of particle which is represented as dmax. Mathematically his model can be written as follows.

$$\text{Cumulative \% passing} = (d/dmax)^{0.5}$$

Fuller suggested, to achieve higher strength and workability of a mix, aggregates should be graded in sizes and combined with water to optimize the packing. Wig et al (1916) while working on particle packing found that by using Fuller’s model maximum density cannot be achieved if aggregates of any different nature was used.

Fuller’s model is actually a specific case of a more generalized model presented by Andreasen and Andersen (A&A) [41] which is as follows.

$$\text{Cumulative \% passing} = (d/dmax)^{q}$$

Here q is distribution modulus and its range was proposed to be between 0.33-0.5 instead of fixing it to 0.5. A&A made their efforts to improve the grading curve to produce the highly concentrated coal slurries with low viscosity. Value of distribution modulus depends on many factors including shape, texture, roundness, porosity and density of particles. In general finer the materials in a mix, lower will be the value of q to attain optimum packing density. Distribution modulus also varies with the workability requirements of the mix.

Work of Andersen was further modified by Funk and Dinger at the end of 20th century [42]. They considered the ground realities and incorporated minimum size of particles. As in nature there are some limitations on the PSD of naturally occurring materials, there cannot be infinitely small in size. Modified Andreasen and Andersen (MAA) model works great for ceramic industry but recently researchers are trying to explore its efficiency in concrete industry by proportioning aggregates according to the model and also by using secondary raw materials of fine particle sizes. Mod A&A model is as follows.

$$\text{Cumulative \% passing} = \frac{d^q - d^q_{min}}{d^q_{max} - d^q_{min}}$$

The value of q can varied in the range of 0.21 to 0.37 depending on workability required and nature of particles in the mix. The lower value of q indicates presence of fine particles and higher value shows coarse nature of the mix. For normal concrete it can be varied between 0.27-0.3 but for SCC it is advisable to use $q<0.27$ [32]. In SCC there is a need of higher slump than conventional concrete and also the mix for SCC contains more fines, this is why the value of q is lower for SCC than conventional concrete.

Mod A&A model gives a very smooth curve which is very capable of developing mix of high packing density. Issues with other models are already discussed, this model compared to others is more likely to gain popularity in concrete industry. Mod A&A model for different values of q is as shown below that validates the increase in finer content with the reduction in value of q.

Following figure shows different types of models proposed to date for predicting packing density of the mix including both discrete and continuous models.

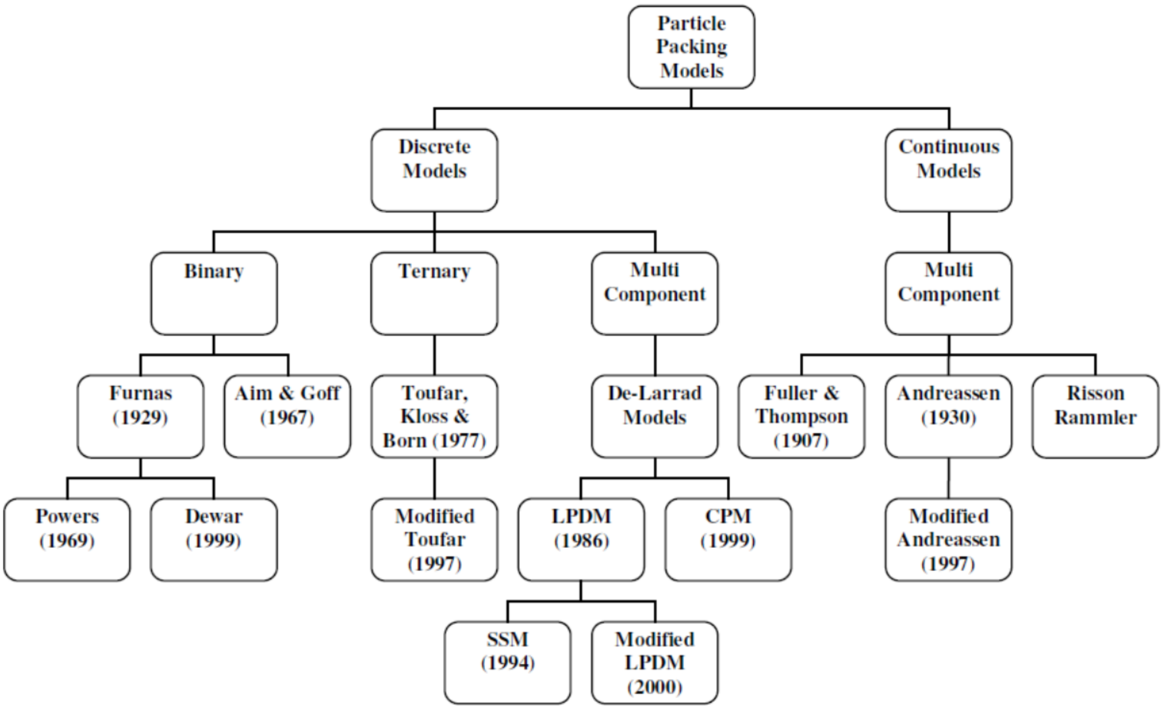

Figure 2.4: Particle packing models [43]

2.6. Computer Software for Particle Packing

There are several computer softwares available commercially that can predict packing density of mixes composed of different materials. Softwares like LISA, EMMA, 4C Packing, COST etc can be used to develop a mix having optimum degree of packing.

Elkem Materials Mixture Analyzer “EMMA” developed by ELKEM has been used successfully by the researchers to optimize the mix for conventional as well as Self Compacting Concrete [44]. EMMA is based on both A&A and Mod A&A particle packing model. It reduces the amount of effort and material required for trial process to determine mix of optimum packing density. Particle size distribution of materials is used to develop cumulative PSD curve of the mixture which is then compared with the ideal PSD curve. Contents of the mixture are then varied to alter the PSD curve and get it closer to the ideal one. EMMA, having a user friendly interface, is now gaining popularity to be used as a handy tool to optimize the mix to get maximum packing density without wasting time, materials and efforts on trials.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1. Materials

Materials used in this research work were obtained locally, however FA was imported from Germany. Powders were stored in plastic air tight containers to avoid any contact with moisture. Aggregates were taken in as available condition and were cleaned to remove impurities that might affect the properties when used in concrete. Following are the details of different materials that were part of this research work.

3.1.1. Cement

ASTM Type-1, Ordinary Portland Cement (OPC) manufactured by BESTWAY Cement Industry, confirming ASTM-C150, EN-196, CEM 1 42.5 N or Grade 53 and Pakistan Standards PS-232-2008 was used. Particle size distribution (PSD) of OPC was determined by using Mastersizer, a laser granulometer, which was available in Institute of Space Technology (IST), Islamabad. PSD curve of OPC is shown in figure 3.1 from which it can be seen that average particle size (D_{50}) of OPC used is 16.4 micron. X-Ray Fluoresce (XRF) results obtained from Geoscience lab, Islamabad are showing chemical composition of OPC (see table 3.1).

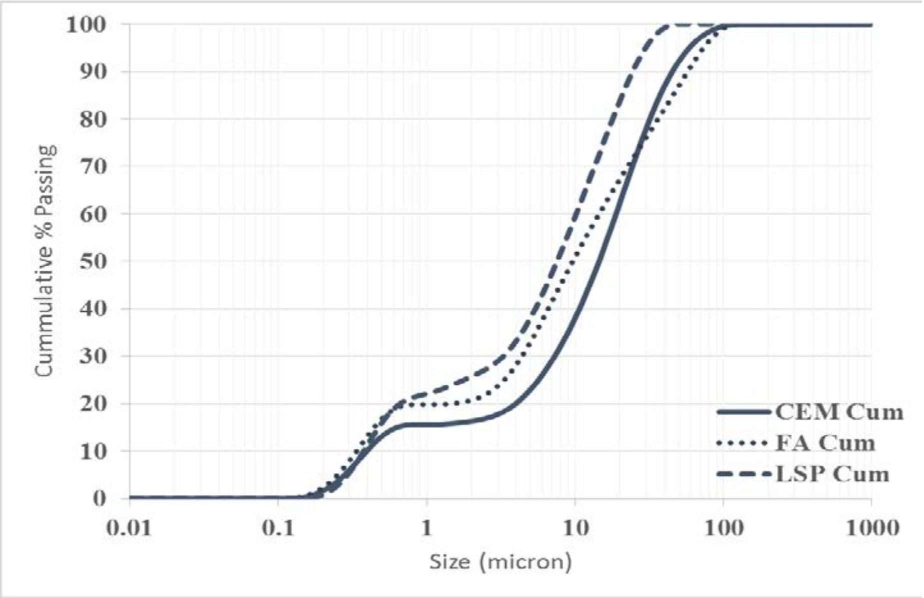

Figure 3.1 PSD of FA, LSP and OPC

Table: 3.1 Chemical and physical properties of Powders (FA, LSP and OPC)

Parameters	**OPC**	**FA**	**LSP**
SiO_2	19.19	59.06	3.00
TiO_2	0.29	1.58	0.04
Al_2O_3	4.97	27.58	0.69
Fe_2O_3	3.27	5.14	0.27
MnO	0.04	0.05	0.01
MgO	2.23	1.27	0.67
CaO	65.00	1.66	52.67
Na_2O	0.58	0.54	0.30
K_2O	0.51	1.59	0.10
P_2O_5	0.08	0.15	-
LOI	3.84	1.38	42.24
Particle Size (D_{50})	16.4	11.0	8.63
BET Surface Area (m^2/g)	0.822	1.61	4.97
Density (g/cm^3)	3.17	2.41	2.75

3.1.2. Secondary Raw Materials

The choice of SRMs to be used in this research work was based on previous researches conducted by Rizwan [18] and Wahab [19] that showed improved response in terms of flow and mechanical properties of Self Compacting Paste systems. Blends of FA and LSP were used in equal amounts by weight to partially replace 30% of cement. The properties of FA and LSP used are discussed in the following sections.

3.1.2.1. Fly Ash

FA is a by-product obtained from the combustion of coal in the thermal power plants. Due to the presence of higher amount of silicon dioxide (SiO_2), it shows pozzolanic activity when mixed with cement and water. Its reactivity also depends on the particle size, the smaller the particle greater will be the reactivity [45]. FA has got a spherical shape and glassy surface as can be seen in SEM images (figure 3.2). This glossy surface and low particle density of FA also aids in flow of SCC. SEM images of FA particles are as shown in figure 3.3.

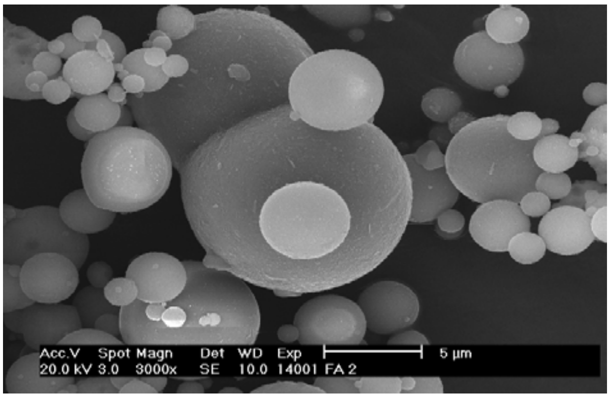

Figure 3.2: SEM presentation of FA [46]

FA used in this research work was imported from Germany and its average particle size was found to be 11 micron as can be seen in Figure 3.1. Other chemical and physical properties of FA are shown in Table: 3.1.

3.1.2.2. Limestone Powder

LSP was manufactured by grinding the Margalla crush in locally available china made grinding plant. Before grinding, Margalla crush was washed and cleaned to ensure the removal of impurities and then oven dried to a constant mass. The grinding process was observed very keenly to avoid inclusion of any impurities and to have the particles of smallest possible size. LSP obtained after grinding was passed through sieve having aperture of 45 micron (BS-410 #350/ ASTM E-11 #325). After manufacturing, LSP was analyzed for the physical and chemical properties as shown in Table 3.1 respectively. D_{50} of LSP was found to be around 7 micron.

LSP is inert in nature and do not show any reactivity but due to its rough surface, it offers nucleation sites for growth of hydration products [18]. Rough surface texture of LSP also offers resistance against the flow of SCC and delays the flow times (T_{50} and T_{70}). However, due to synergic effects of using blends of FA and LSP as a partial replacement of OPC, an overall improved response is observed in flow and mechanical properties of SCC as can be seen later in this thesis. SEM images of LSP showing its rough surface texture can be in figure 3.3.

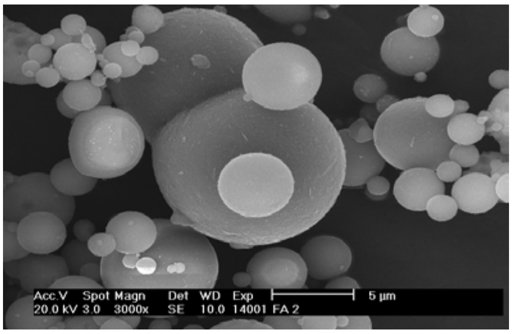

Figure 3.3 SEM presentation of LSP

3.1.3. Fine Aggregate

Sand used for this research work was obtained from the sand deposits of Lawrencepur. It was properly cleaned before use to remove any organic matters. Fineness Modulus (FM) of the sand was found to be 2.01, determined as per ASTM C-136. FM of Lawrencepur sand is observed to be lower than the specified range of 2.3-3.2, as given in ASTM C-33 which results in increased porosity in the mixture. Sieve analysis results of fine aggregate used can be seen in Figure 3.4.

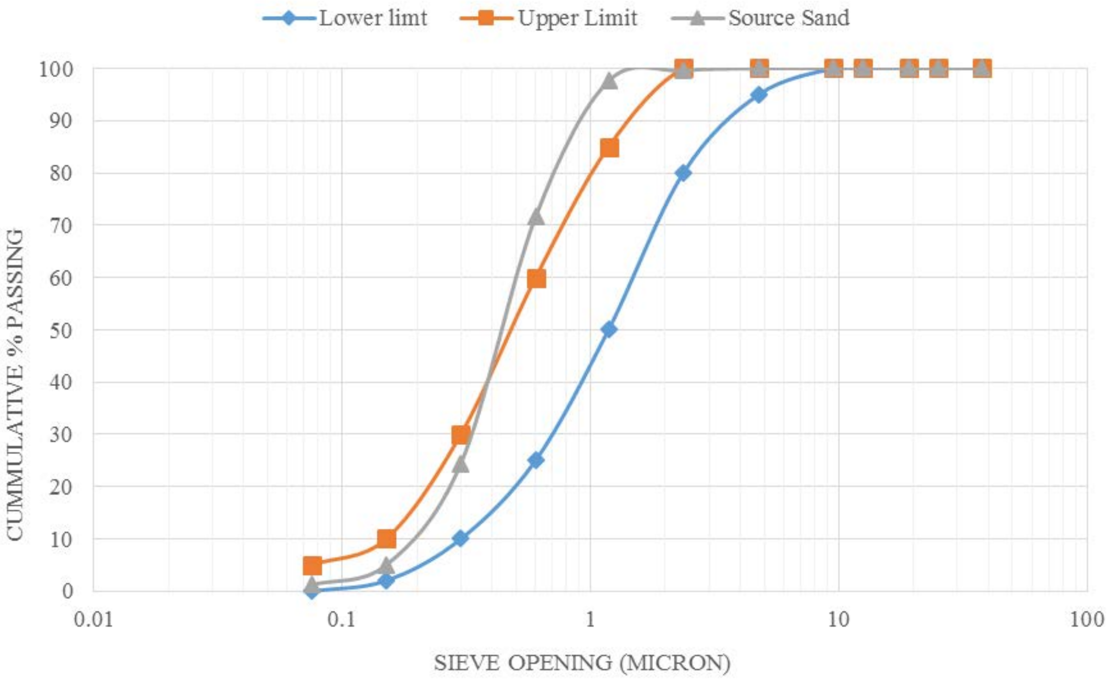

Figure 3.4: Particle Size Distribution of fine aggregate

It can be seen in the above figure that the sand is finer than the allowed limits of ASTM C-33 standards. PSD of Lawrencepur sand lies within the limits till particle size of 0.3mm afterwards it contains finer particles.

3.1.4. Coarse Aggregate

Coarse aggregate has a great influence on the properties of self-compacting concrete in terms of flowability and strength. For SCC maximum size of coarse aggregate was restricted to 16mm. Aggregate of smaller size shows good rheological properties but have adverse effects on strength. So generally 12 to 16mm is used to have a mix of good workability and strength.

Angular and rough particles of coarse aggregate also increases the mechanical properties of concrete but workability is compromised due to increased internal friction which can be catered by using chemical admixtures if required. Coarse aggregate for this research work was collected from Margalla hills situated in Islamabad. Maximum size of coarse aggregate was restricted to 16mm. Gradation of coarse aggregate was done as per ASTM C136 and can be seen in Figure: 3.5. Gradation of coarse aggregate is the most important parameter to study the packing density as they are the biggest particles in the mix and the voids created by these particles need to be filled by the available amount of fine aggregate and paste.

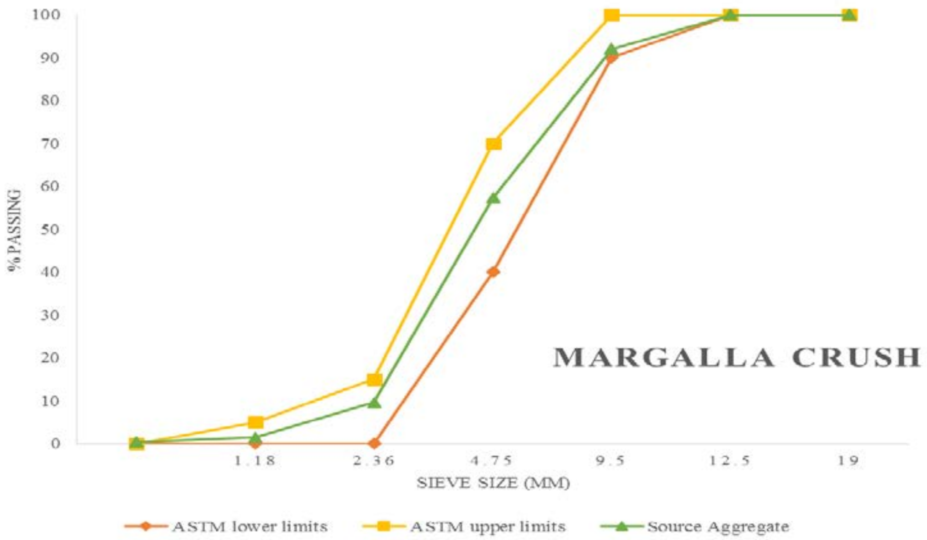

Figure 3.5: Particle size distribution of coarse aggregate

3.1.5. Super Plasticizer

Super plasticizer is the chemical admixture used to increase the flow of SCC, it reduces the additional amount of water required to make the concrete flow under its weight. Thus increasing the strength and durability of concrete. It is also known as high range water reducing agent (HRWRA). A newer type of SP, which is based on Polycarboxylate ethers (PCE) is found to be more effective and requires lesser dosage as compared to older sulfonated melamine (SMF) or naphthalene (SNF) formaldehyde. For this research work third generation High performance PEC based superplasticiser, ViscoCrete 20-HE, manufactured by Sika was used. The technical information regarding the product is shown in table 3.2.

Table 3.2: Technical data of ViscoCrete 20-HE

Physical Form	Liquid
Appearance	Light brownish
Density (Kg/lt) at 25ºC	1.08
PH Value	3.4 approx.
Dosage Recommendation (%)	1.0 to 2.0

3.1.6. Viscosity Modifying Agent

Segregation and bleeding are most devastating problems for SCC. Bleeding can be easily identified by the presence of water layer on top of the fresh concrete due to its lower density in the mix. Stability of SCC was formerly improved by using high amounts of inert powders but now viscosity modifying agents (VMAs) are more likely in use and they give very similar flow properties.

MasterMatrix 110 (formerly known as RheoMATRIX 110) manufactured by BASF chemicals was used in the research work. It is an aqueous solution of a high-molecular weight synthetic copolymer. It increases the viscosity of mix also enabling acceptable balance between the passing ability, fluidity and resistance to segregation. Typical properties of VMA are given in table 3.3.

Table 3.3: Technical Data of MasterMatrix 110

Physical Form	Viscous Liquid
Appearance	Light brown to dark brown liquid
Specific gravity	1.009 g/cu-cm
PH Value @ 25ºC	9.5
Chloride content	< 0.1%
Dosage recommendation (%)	0.1-0.5

3.2. Experimental Program

Experimental program was conducted with great care to achieve maximum accuracy. Standards procedures of DIN, ASTM and BS were followed for experiments as described below.

Table 3.4: Experimental Detail and corresponding standards

	Experiments	**Tests Standard**	**Measured Values**	**Property Assessed**
Paste	Water Demand	EN-196	% by weight of Cement	Consistency
	Setting Time	EN-196/3	Time (sec)	Initial and Final Setting
Concrete	Slump Spread Test	EN- 12350/8	Spread (cm)	Flowability
			Time (sec) for 50cm dia	Viscosity
	V-Funnel	EN- 12350/9	Time (sec)	Viscosity
	L-Box	EN- 12350/10	Time (sec)	Passing ability
	J-Ring	EN- 12350/12	Spread (cm)	Passing ability
	Strength	EN- 12390	Load (KN)	Compressive Strength

3.2.1. Water Demand and Setting Time of OPC & Blends

Water demand is amount of water required to produce a paste of standard consistency. European guidelines EN 196 were followed for determination of water demand and setting time of OPC and blends of FA & LSP. Standard consistency can be described as the state that allows the penetration of standard VICAT plunger in the paste up to 33-35mm from top or 5-7mm from bottom of the surface. Water demand and setting times are greatly influenced by the certain factors like mixing water temperature, room temperature and relative humidity. Hobart mixer was used to prepare the cement paste for determination of water demand and setting times of OPC and blends of FA and LSP used as partial replacement of cement.

3.2.2. Packing Density of Naturally Occurring Aggregates

In order to determine packing density of aggregate mixes having different fine to coarse aggregate ratios, naturally occurring fine and coarse aggregates were used. Fine to coarse aggregate ratio was varied in 80-20% range (i.e. 20/80, 30/70, 40/60, 50/50, 70/30 and 80/20) as trials to obtain the optimized ratio having maximum packing density. Packing density of these mixes of aggregate was determined by following standards guidelines of BS-812. Both compacted and uncompacted densities were determined by filling the aggregate mixes in container of 5 dm^3 capacity. For compacted density of aggregate mixes, container was filled in three layers and each layer was given 25 blows. Upon completely filling the container, extra material on top of container was removed using straight edge.

Figure 3.6: Container used for determining packing density

3.2.3. Packing density using MAA

Modified Andreasen and Andersen model was also utilized to develop aggregate mixes having reduced voids. As mentioned above in the literature that value of distribution modulus for SCC ranges from 0.22 to 0.28, so SCC mixes were designed using q = 0.22, 0.25 and 0.28.

EMMA was utilized to develop SCC mix design based on MAA approach. EMMA is very handy tool that can be used easily to develop mixes that follows Mod A&A model. Particle size distribution and particle density were used as input and then on trial basis quantity of materials is adjusted to follow the ideal curve of Mod A&A model.

In order to follow Modified A&A model, aggregates were sieved and stored in separate containers according to their sizes. Maximum and minimum aggregate size was decided to be 16mm and 0.075mm respectively. Details of different aggregate sizes are as shown in table 3.5.

Table 3.5: Different sizes of aggregates obtained after sieving

Notation	Retained on sieve	Max size (mm)	Min size (mm)
A1	1/2"	16	12
A2	3/8”	12	9.5
A3	1/4"	9.5	6.35
A4	#4	6.35	4.75
A5	#8	4.75	2.36
A6	#16	2.36	1.18
A7	#30	1.18	0.6
A8	#50	0.6	0.3
A9	#100	0.3	0.15
A10	#200	0.15	0.075

The above mentioned aggregates were used to prepare mixes based on MAA approach, having distribution modulus equal to 0.22, 0.25 and 0.28.

Similar procedure as described above was followed to determine packing density of aggregates based on Mod A&A approach.

3.2.4. SCC Composition

On the basis of results obtained from packing density of aggregate mixes using both naturally occurring and based on MAA approach, SCC formulations were decided that were subjected to further investigation on flow and mechanical properties. Based on earlier studies [46], water to cement ratio equal to 0.42 and binder to aggregate ratio equal to 1:3 were kept constant for all formulations. SP demand for all the formulations were decided to have a target flow of 70±1 cm using Abraham’s slump cone and VEA was used for formulations showing signs of bleeding.

3.2.5. Mixing Regime

Pan mixer of 50 Liter capacity was utilized and a total of 5 minutes mixing was done for all SCC formulations. Initially dry mixing of powders and aggregates was done for 1 minute at rpm. After that 70% water was added in the dry mix and mixing was continued for 1 minute. Chemical admixtures including SP and VEA were then added with remaining 30% water and mixing was done for 3 further minutes. SCC generally requires greater mixing time compared to conventional concrete, this is to ensure activation of super plasticizer to produce a uniform mix of SCC [7].

3.2.6. Flow Measurements

Basic experimentations done on SCC to determine its various properties in fresh state are explained is this section. These tests were performed in the very facility of Structural lab, NICE, NUST. Flow tests were performed according to EN 12350 standards.

Sequence of flow tests for SCC starts with allowing the mix to stand for around 1 minute after mixing and then slump spread test was carried out. After that V-funnel tests and L-box test is performed and lastly J-ring test was conducted. Concrete was mixed in the mixer for 30 seconds before conducting each flow test. Casting was done using a fresh batch of SCC having same mix that satisfies the flow test requirements.

3.2.6.1. Slump Flow Spread Test

Slump flow test is performed to investigate the filling ability of SCC. It is the simplest test that can be used in the labs or on site for assessing filling ability of SCC in fresh state. No temping or additional vibration is required in this test. Slump flow spread is influenced by several factors including SP dosage, w/c ratio and quantity of fines in the mix. Two major parameters that are to be observed in slump flow test are total flow and flow times (T_{50}, T_{70}) that indicates the rate of deformation and unrestricted flow of SCC.

SCC is allowed to stay in the mixer for around 1 minute. Cone and base plate are wetted using sponge to avoid any absorption of water or friction between the surface of cone/base plate and concrete. SCC is then filled in the slump cone with narrow end up using a bucket in one go. The cone is then lifted in single movement and time required for SCC to reach 50cm dia mark (T_{50}) is noted along with the time for total spread which in this case was 70cm i.e T_{70}. Once the SCC stops to flow, its dia is noted from two perpendicular directions and its average is reported as total spread.

This test is also used to determine SP demand for a target flow which for this particular project was decided to be 70cm, keeping the other materials constant in a mix addition of SP will increase the Total spread. Thus amount of SP added was so adjusted by trials that total slump spread of all the mixes should be 70±1cm. Standard dimensions of cone and base plate used for this experiment are as shown below.

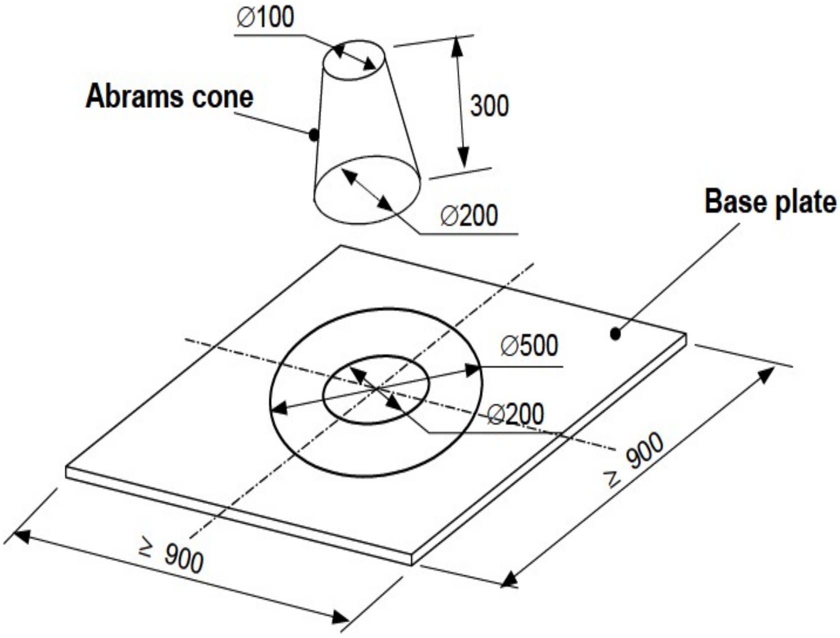

Figure 3.7: Abraham’s Slump Flow apparatus

3.2.6.2. V-Funnel Test

V-Funnel test is used to assess viscosity in the mix which is dependent on amount of fines in the mix. V-Funnel is placed on a leveled surface to avoid any external factor disturbing the results. Before filling the funnel, it wetted using a sponge and opening at the bottom is closed. SCC is then poured in the funnel using bucket in one go and SCC is allowed to stay for nearly 10 ± 2 seconds. Bottom gate is then opened to allow concrete to flow through it under its weight and time is noted till clear space becomes visible through the funnel opening. Stopwatch reading is recorded as V-Funnel flow time. Standard dimensions of V-Funnel are as shown below.

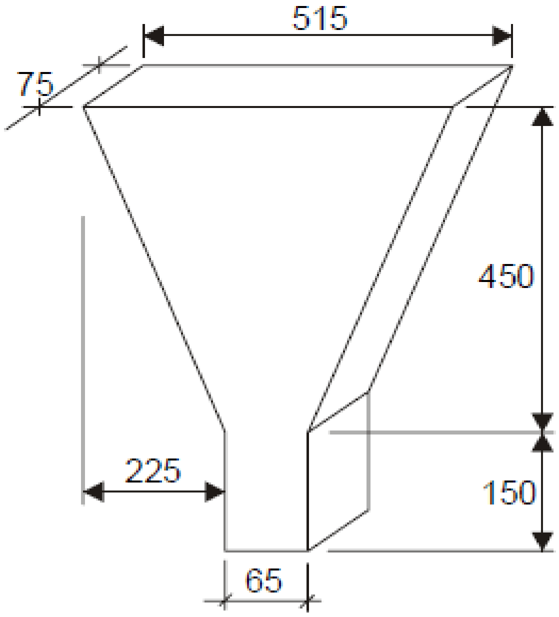

Figure 3.8: V-Funnel Apparatus

3.2.6.3. L-Box Test

SCC is known for its passing ability through heavily reinforced concrete sections without application of any external vibration. L-Box is used to investigate the passing ability of concrete mix through reinforcement. L-Box as shown in figure below have 3 steel bars at the bottom section of box to replicate steel reinforcement. L- Box is wetted before pouring SCC to avoid any moisture absorption from SCC. SCC is poured from the top of L-Box to fill the vertical section of the box in one go. SCC is allowed to stay for around 10 ± 2 seconds and then gate is opened that allows the SCC to pass through the reinforcement into the horizontal section of the L-Box. The height of SCC in the vertical and horizontal section is noted at the instant when concrete becomes stationary. Height of concrete in vertical section (H_1) and horizontal section (H_2) is reported as ΔH (H_2/H_1) along with flow time at three positions in horizontal section at 20cm, 40cm and 60cm as T_{20}, T_{40} and T_{60} respectively. Details of L-Box is as shown below.

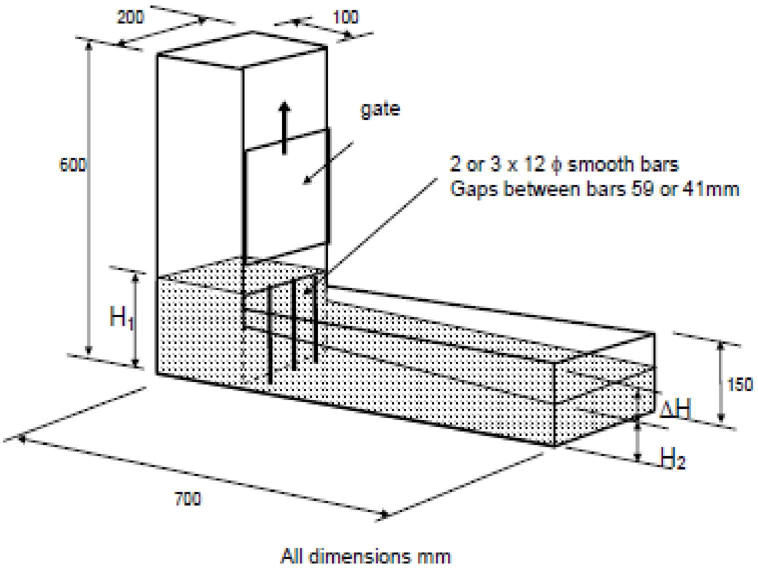

Figure 3.9: L-Box Apparatus

3.2.6.4. J-Ring Test

J-Ring is used to investigate two important properties of SCC namely passing ability and filling ability. J- Ring test measures four parameters: total spread of SCC, time required for total spread (T_{Total}), T_{50} and height difference of SCC between the center of J-Ring and outside the ring which is represented as Bj.

$$Bj = \frac{H_1+H_2}{2} - Ho \times 10$$

Here H_1 and H_2 are the height of SCC at the edges of J-Ring and Ho is height of SCC at the center of J-Ring.

Main factors influencing passing ability are the coarse aggregate content, flowability, segregation resistance and ratio of clear spacing between rebars to maximum aggregate size [47].

After mixing is completed, inner surface of the cone and base plate is wetted using sponge and cone is placed inside the ring within 200mm circle of the base plate. Cone is filled with SCC using bucket in single movement and allowed to stay in the cone for around 10 ± 2 seconds. The cone is then lifted and SCC is allowed to flow under its weight. Time required for SCC to reach 50mm dia, total spread and T_T is noted. Also height of SCC at the center of ring and edges of ring is noted. Details of J-ring apparatus is as shown below.

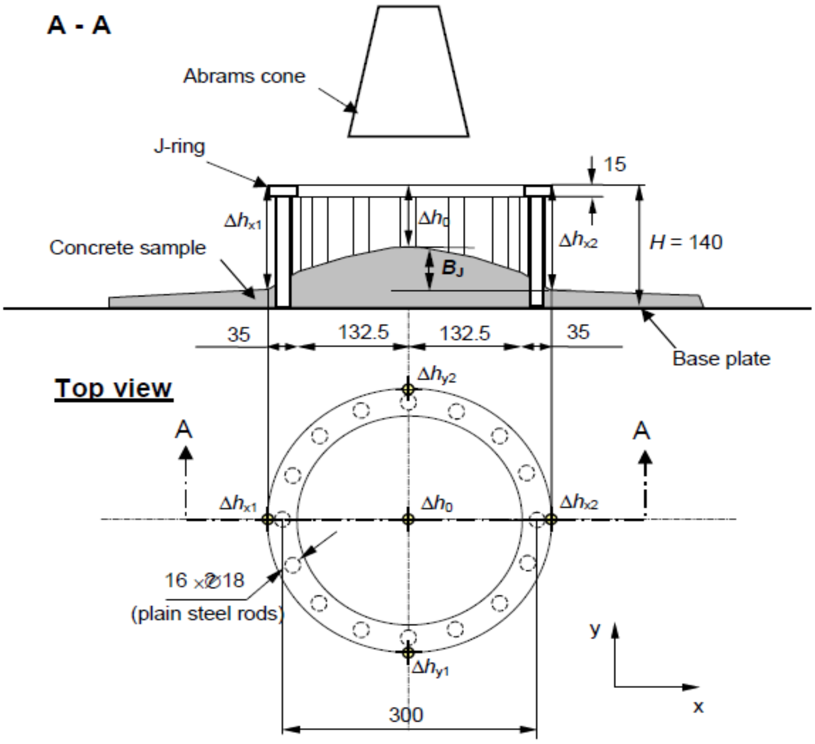

Figure 3.10: J-Ring Apparatus

3.2.7. Recommended limits for SCC Flow Tests

Following table shows the typical limits for SCC with maximum coarse aggregate size >12mm [47].

Table 3.6: Recommended limits for SCC flow tests

S.No.	Method	Unit	Typical range of values	
			Minimum	Maximum
1	Slump flow by Abrams cone	mm	650	800
2	T50cmslumpflow	Sec	2	5
3	J-ring	mm	0	10
4	V-funnel	Sec	6	12
6	L box	H_2/H_1	0.8	1.0

3.2.8. Casting and Curing

EN 12390-1 was used as a guideline for casting and curing of test specimens for strength evaluation. After adjusting the mix to satisfy properties of SCC in fresh state. A fresh batch of SCC is prepared and casted in cube having dimensions 4in x 4in x 4in. Minimum 4 samples of each formulation were casted to increase the reliability of the results. A total of 120 samples were casted at a temperature of 25°C and relative humidity of 40%. Casted samples were covered by plastic sheets to avoid any loss of moisture in the atmosphere. Curing was done in plastic containers filled with water and it was ensured that water is in contact with the samples from all the 6 faces.

3.2.9. Compressive strength of concrete

Cubes were tested at the age of 3, 7, 14 and 28 days. BS EN 12390-1 standard was followed for evaluating compressive strength of SCC cubes. Samples showing large deviation from the average value were not considered in calculations. Broken pieces of the tested samples were preserved for Scanning electron microscopy (SEM) images.

3.2.10. Shrinkage

Volumetric stability of SCC should be considered while designing a mix. SCC, as it contains greater quantity of cement and other SRMs, is more vulnerable to shrinkage problems. A Modified German Shwindrine apparatus having dimensions of $4x6x25cm^3$ was utilized for linear shrinkage measurement. This apparatus is equipped with sensors having sensitivity of 0.31 microns. Shrinkage tests were conducted at room temperature of 25°C and relative humidity of 40%. Mortar passing through sieve having aperture of 2mm was poured in the shrinkage channel.

Figure 3.11: Modified German Shwindrine Shrinkage Apparatus

3.2.11. Calorimetry

Hydration kinetics of SCC systems is very important to be investigated as it has an influence on deciding curing time for a particular mix and also forecasts the setting times. F-Cal 8000 field calorimetry was utilized to study the hydration kinetics of cement based system for around 48 hours for each formulation. Similar to the process done for shrinkage measurements, mortar passing through sieve having aperture of 2mm was poured in the container that was then placed in calorimeter to determine heat of hydration peaks.

CHAPTER 4: EXPERIMENTAL RESULTS

4.1. Water Demand and Setting Times

Water demand and setting time of OPC and blends of FA and LSP (15% each by weight of cement) were determined by preparing cement paste in Hobart mixer. Powders were initially dry mixed for 30 seconds, 70% water is then added and mixing is done for 1 minute at 145rpm. After that Hobart mixer was stopped and bowl was cleaned with the remaining 30% water and mixing was done for 2 minutes at 285rpm. Room Temperature at the time of experiment was 29°C, Relative Humidity was 70% and mixing water temperature was 28°C. Results of water demand and setting time are as shown in table 4.1.

Table 4.1: Water Demand and Setting Time of OPC and Blends of FA and LSP

	OPC	Blends (15% FA, 15% LSP)
Water Demand (w/c)	27.5	36.7
Initial Setting (min)	162	178
Final Setting (min)	186	210

4.2. Investigation of Aggregates

Locally available aggregates were used in this research, fine aggregate was obtained from sand deposits of Lawrencepur and coarse aggregate was obtained from Margalla hills. Specific gravity and water absorption capacity of these aggregates were determined and details are discussed in the following sections.

4.1.1. Specific gravity of aggregate components

ASTM C-127 and C-128 were followed for determining specific gravity of coarse and fine aggregate components respectively. Details of these aggregate components can be seen in table 3.5. For fine aggregates, pycnometer of 250ml was utilized and sand sample of around 100gm was used. For coarse aggregate standard bucket was used and 2kg coarse aggregate sample was taken.

Results are as shown in figure 4.1 which indicates increase in specific gravity due to decrease in particle size of aggregates. Also it has been noted that there is uniform trend in these values, no large deviation is observed between the two components. Literature suggests that there is a risk of segregation when there is large deviation in specific gravity of particles [20].

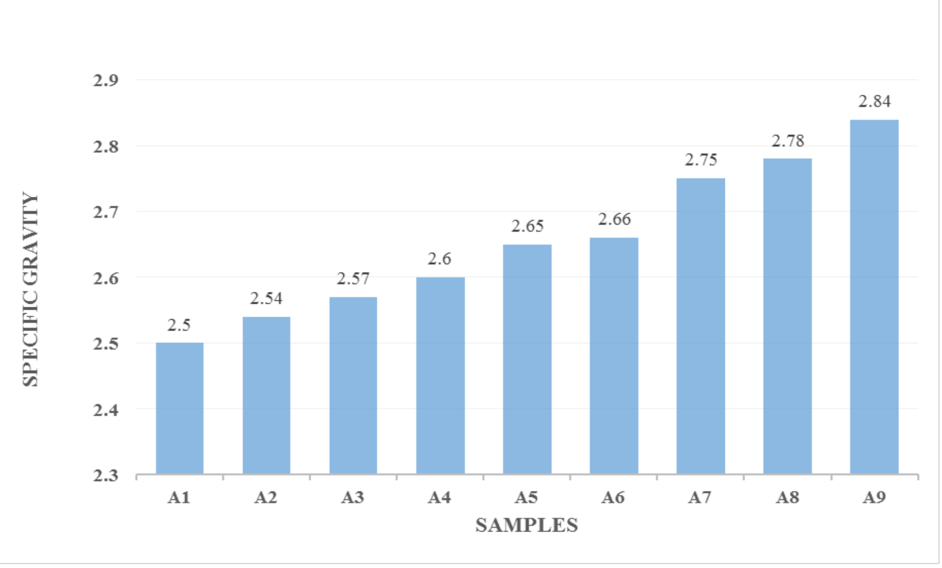

Figure 4.1: Specific gravity of aggregate components

4.1.2. Water absorption of aggregate components

For determining water absorption capacity, ASTM standards C-127 and C-128 were followed for coarse and fine aggregates respectively. Water absorption is the ability of particle to accumulate water in itself, it is represented in percentage by weight of sample. Several factors that affect water absorption capacity includes porosity of particles, surface area, permeability etc. Water absorption capacity of aggregate samples were determined at Saturated Surface Dry (SSD) condition. Samples were kept in water for 24hrs and then SSD condition of these samples were achieved by following standard procedures of ASTM. After that samples were oven dried to constant mass to determine their water absorption capacity. Figure 4.2 shows the results of water absorption capacity that increases with the decrease in particle size.

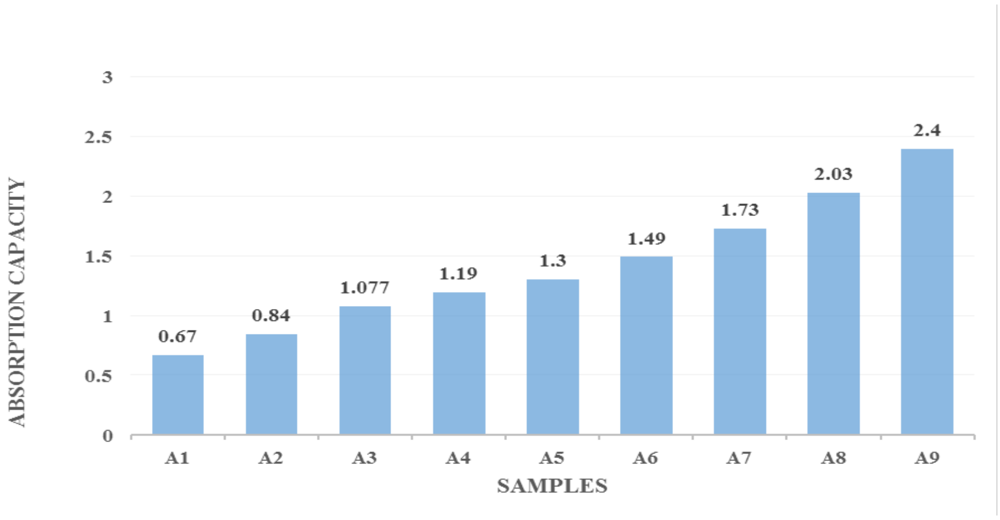

Figure 4.2: Water absorption capacity of aggregate components

4.3. Packing Density of aggregate mixes (based on fine to coarse aggregate ratio)

Packing density of seven naturally occurring aggregate mixes were determined. Fine to coarse aggregate ratio was varied in 80-20% range. Container having 5000ml volume capacity was used to determine the packing density of these aggregate mixes. Eq 2.1 was used in accordance with BS-812 to determine compacted and uncompacted packing density and the results are as shown in figure 4.3.

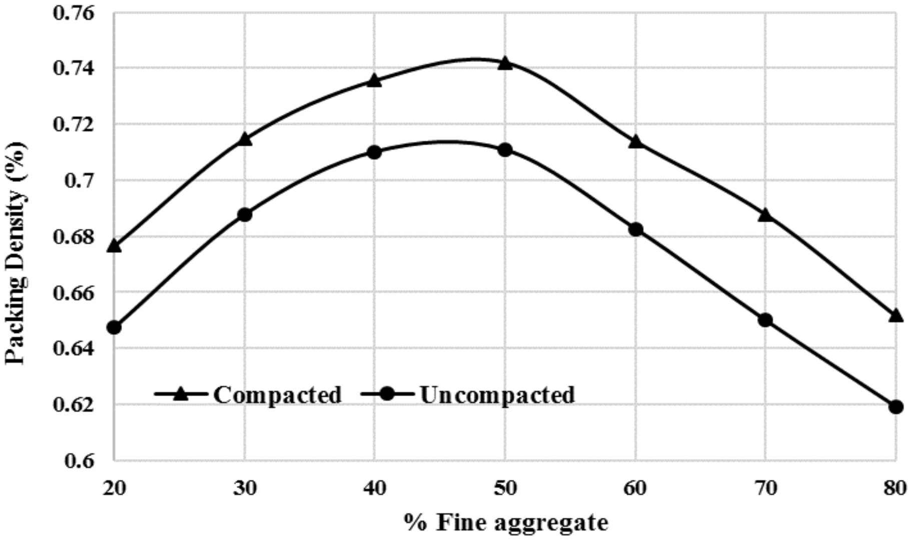

Figure 4.3: Packing density of aggregate mixes

Results showed that maximum packing density is obtained when fine to coarse aggregate ratio of 50/50 was used. It will be more economical to develop concrete using fine to coarse aggregate ratio of 50/50 because of reduced void content. Thus less amount of cement paste will be required to fill the voids and greater effective paste will be available to aid in flow. On the basis of results shown in figure 4.3, three aggregate mixes i.e 40/60, 50/50 and 60/40 will be used to develop SCC that will be subjected to further investigation for its flow and mechanical properties.

4.4. Packing density of aggregates (Based on Modified A&A model)

EMMA software was used to develop SCC mixes having distribution modulus equal to 0.22, 0.25 and 0.28. Packing density of aggregate mixes developed using Modified A&A approach was determined using similar container of 5000ml volume. Only compacted packing density was determined for these mixes and the results are as shown in figure 4.4.

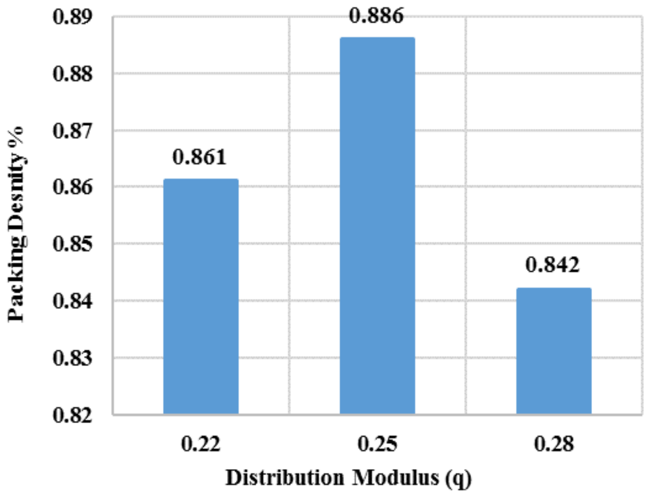

Figure 4.4: Compacted Packing density of aggregate mixes developed using MAA

It can be seen in the above figure that maximum packing density is obtained when mix is developed having distribution modulus equal to 0.25. It is noted that SCC mix developed using MAA approach having q equal to 0.25 have fine to coarse aggregate ratio of 51/49. This ratio is quite similar to the one obtained using trails as shown in figure 4.3. Thus on the basis of results shown in figure 4.3 and 4.4, it can be said that using EMMA based on MAA approach can be useful to obtain optimum fine to coarse aggregate ratio in terms of maximum packing density without going through the process of trials. For further investigation of SCC mix developed using MAA approach, mix showing maximum packing density was selected. That is MAA mix having q equal to 0.25 was selected to develop SCC mix to determine its flow and mechanical properties.

4.5. SCC Formulations

To study the effect of packing density on properties of SCC along with partial replacement of OPC with blends of FA and LSP (15% each by weight of cement), a total of seven mixtures were investigated as shown in table 4.2. These formulations were selected on the basis of results as shown in figure 4.3 and 4.4. Three out of seven aggregate mixes (based on fine to coarse aggregate ratio) and one out three aggregate mixes (based on Modified A&A approach) showing maximum packing density were selected for further investigation on flow and mechanical properties. Considering the mix design proposed by Rizwan [46], binder to aggregate ratio of 1:3 and w/c ratio = 0.42 was maintained for all the formulations except the one designed using MAA approach. Mixing water temperature was kept constant to 25°C for making SCC. Formulations having no SRMs were denoted as "CM", Control Mixes, and those having blends of FA and LSP were denoted as "MM", Modified Mixes. While digits shows the percentages of fine and coarse aggregates respectively. For example a mix CM 64 means that Control Mix having 60% fine aggregates and 40% coarse aggregates of the total amount of aggregates. Other formulations can be understood on similar lines.

Optimized formulation that was designed using MAA approach having maximum aggregate size of 16mm and minimum aggregate size of 0.75mm. MAA formulation having distribution modulus of 0.25 have binder to aggregate ratio of 1:3.89. While w/c was kept constant which was equal to 0.42. Details of SCC formulations are as shown in table 4.2. The quantities shown in table 4.2 were used to prepare SCC mix for flow tests. Casting for strength evaluation was done using fresh batch of SCC.

Table 4.2: Details of SCC Formulations

Materials/ Mixes	**Fine/coarse aggregate ratio**	**Binder to Aggregate ratio**	**OPC (Kg)**	**FA (15%) (Kg)**	**LSP (15%) (Kg)**	**Fine Agg (Kg)**	**Coarse Agg (Kg)**	**w/c=0.42 (Kg)**	**SP (%)**	**VEA (%)**
CM64	60/40	1:3	10	-	-	18	12	4.2	1.15	-
CM55	50/50	1:3	10	-	-	15	15	4.2	1	0.4
CM46	40/60	1:3	10	-	-	12	18	4.2	1.4	0.6
MM64	60/40	1:3	7	1.5	1.5	18	12	2.94	1.7	-
MM55	50/50	1:3	7	1.5	1.5	15	15	2.94	1.61	-
MM46	40/60	1:3	7	1.5	1.5	12	18	2.94	1.65	-
MAA (51/49)	51/49	1:3.89	5.4	1.156	1.156	15.3	14.7	2.268	1.58	-

4.6. Flow response of SCC Formulations

To investigate the flow response of SCC in terms of packing density, seven formulations having different packing densities were subjected to routine SCC flow tests including slump flow spread, L-box, V-Funnel and J-Ring test as per EN 12350 standard and are discussed below.

4.6.1. SP Demand and Slump Flow Spread of SCC Formulations

Abraham’s slump cone with narrow end up was utilized to determine the SP content (demand), of SCC for target flow of 70 ± 1 cm, as shown in Figure 4.5. Viscosity and deformability in terms of T_{50} cm time and T_{70} cm time respectively were also evaluated for the mixes and the results are as shown in Figure 4.6.

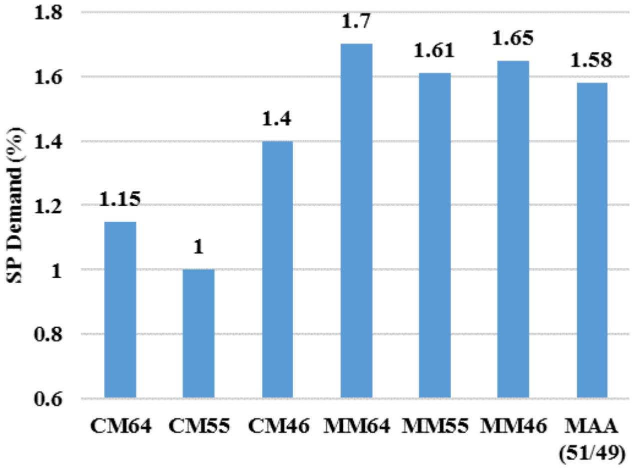

Figure 4.5: SP Demand of SCCs

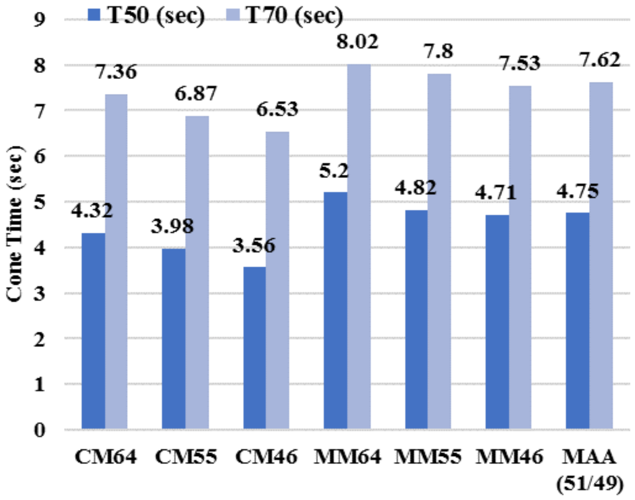

Figure 4.6: T50 and T70 of SCCs

4.6.2. V-Funnel Test on SCC Formulations

V-funnel apparatus was used to know the cone times of SCC formulations. It is reported in the literature [48] that this is a manifestation of plastic viscosity of the SCC system. The results are shown in Fig 4.7. T_{50} cm cone time is also dependent on plastic viscosity of SCC systems [32]. Both times were plotted in figure 4.8 and a reasonable linear relation is obtained verifying the above statements.

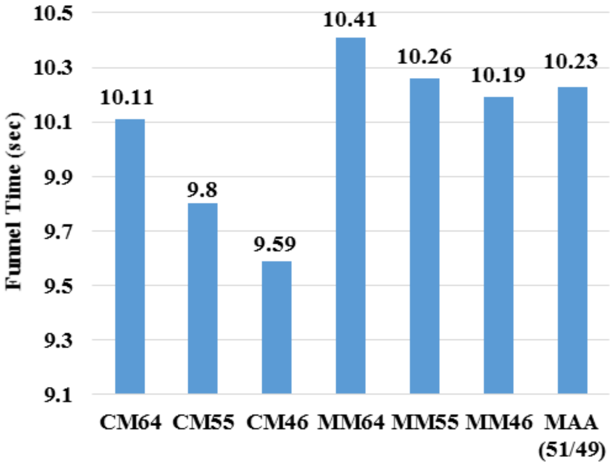

Figure 4.7: V-Funnel Time of SCCs

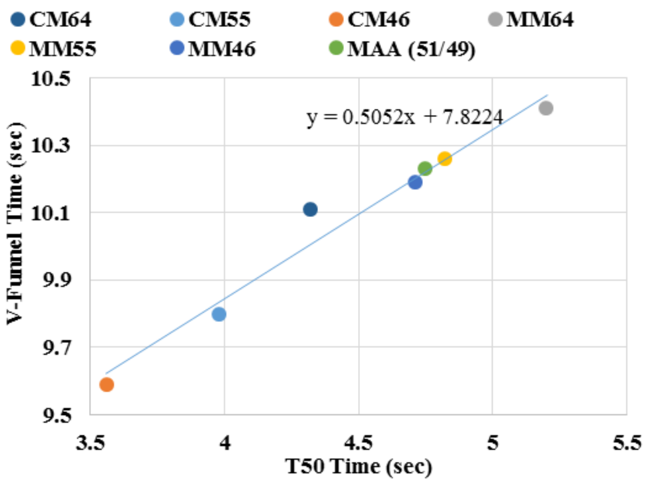

Figure 4.8: V-Funnel Time vs T50 time of SCCs

4.6.3. L-Box Test Flow Tests on SCC Formulations

L-box apparatus simulates the field conditions for SCC and gives some indications about passing ability of SCC. Time required (T_{20}, T_{40} and T_{60}) for SCC to cover the distance of 20cm, 40cm and 60cm at the horizontal section of L-Box after passing through reinforcements were noted. Also the ratio of height (H2/H1) is shown in Figure 4.9. A higher H2/H1 shows higher passing ability.

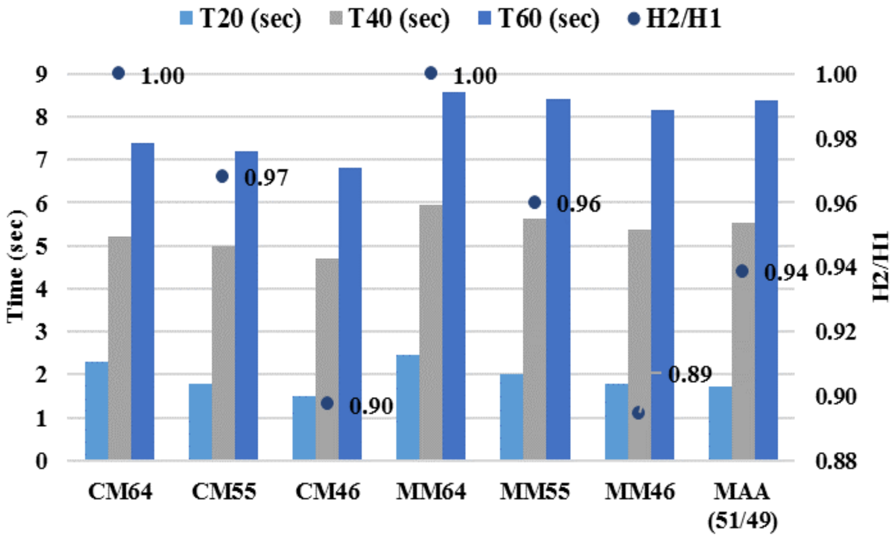

Figure 4.9: Flow Time of SCC formulations using L-Box (T20, T40 and T60 cm time and H2/H1)

4.6.4. J-Ring Test on SCC Formulations

Total spread of SCC through J ring and T_{50} cm time of J-Ring along with height difference (Bj-height of concrete at the center and at the far end after J-Ring has been lifted) of concrete before and after passing through the J-Ring was noted. High is the Bj value, lower is the passing ability. J-Ring response of SCC formulations are as shown in Figure 4.10 while Figure 4.11 shows the relation between L-box T_{60} cm time and J ring total spread time. A reasonably linear trend line relation is obtained indicating the usefulness of assessing passing ability by these two methods.

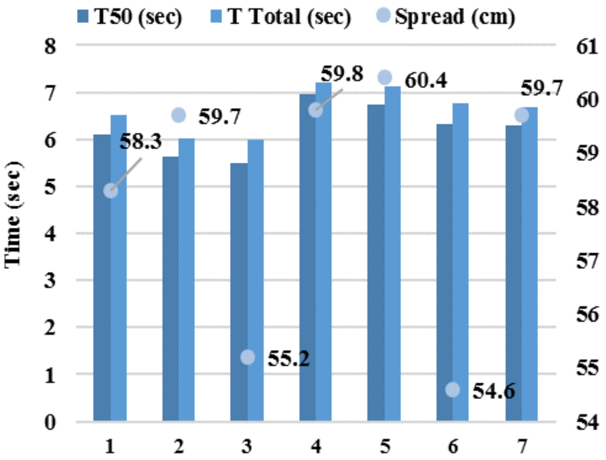

Figure 4.10: Flow Time for J-Ring (T_{50}, T total and Total Spread)

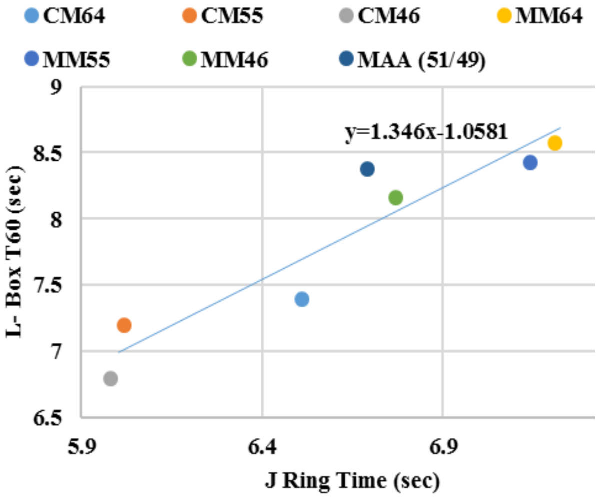

Figure 4.11: J-Ring Time vs L-Box T_{60} Time

Figure 4.12 shows the height differences (Bj) at middle and edge of J-Ring for SCC formulations studied. A higher **Bj** value gives reduced passing ability of SCC formulation.

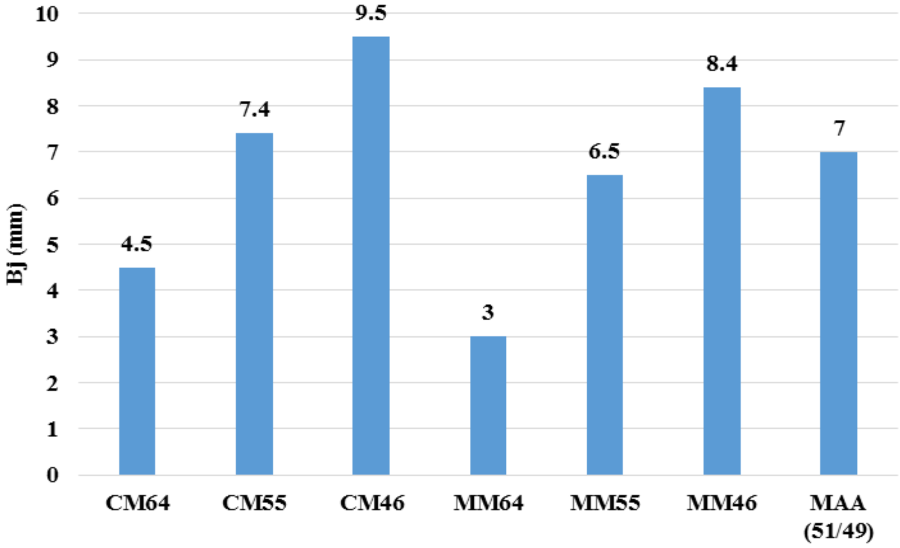

Figure 4.12: J-Ring Passing ability Parameter (Bj) for Various SCC formulations

4.7. Shrinkage Response of SCC Formulations

Early age total linear shrinkage response was measured using Modified German Shwindrine apparatus of 4x6x25 cm^3 dimensions with a sensitivity of 0.31 microns for first 45 hours approximately. Shwindrine channels were filled with the fresh SCMs obtained from SCC after passing through 2mm sieve and the channel was then covered with plastic sheet to avoid any exchange of moisture with environment. Total Linear early Shrinkage response of studied formulations is shown in Figure 4.13.

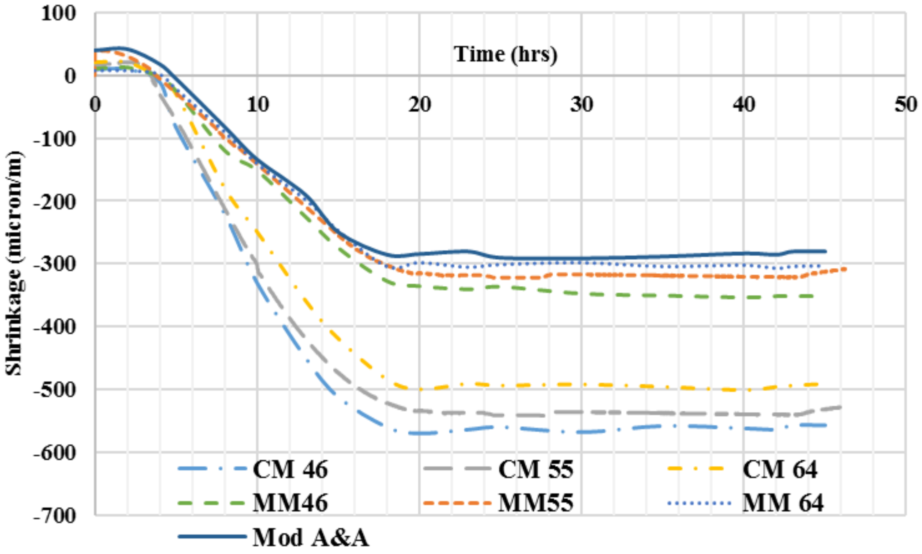

Figure 4.13: Simulation of Total linear Shrinkage Response of SCC formulations

4.8. Calorimetry of SCC Formulations

Hydration kinetics of SCC formulations was studied using F-CAL 8000 field Calorimeter which is a semi adiabatic calorimeter. Sample of fresh SCM was obtained from SCC by sieving through 2mm sieve. The sample obtained was filled in apparatus channels having inner lining of plastic sheets for 72 hours. Figure 4.14 shows the calorimetric response of SCC formulations.

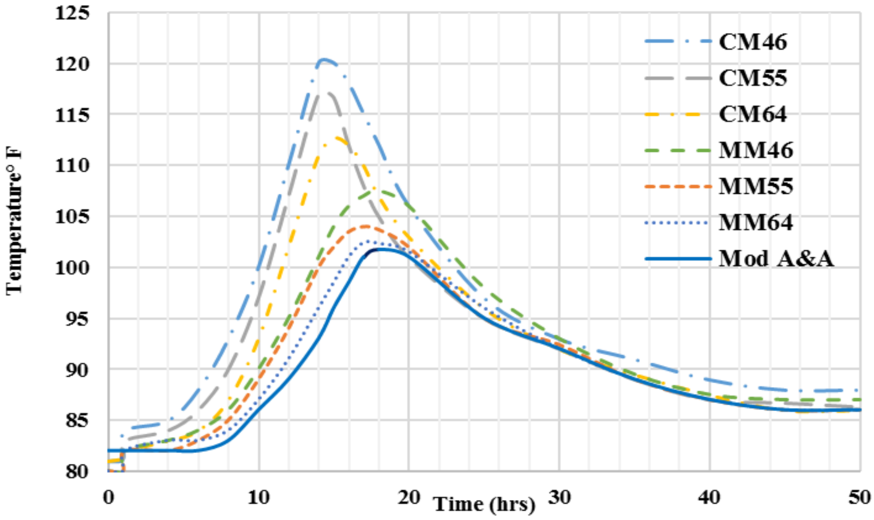

Figure 4.14: Calorimetry of SCC Formulations

4.9. Compressive Strength of SCC Formulations

Compressive strength of concrete samples dimensioning 4x4x4 inch^3 was determined according to EN 12390 standard guidelines. Samples were water cured till test age and were tested in SSD condition at 1, 7, 14 and 28 days. The results are as shown in Figure 4.15.

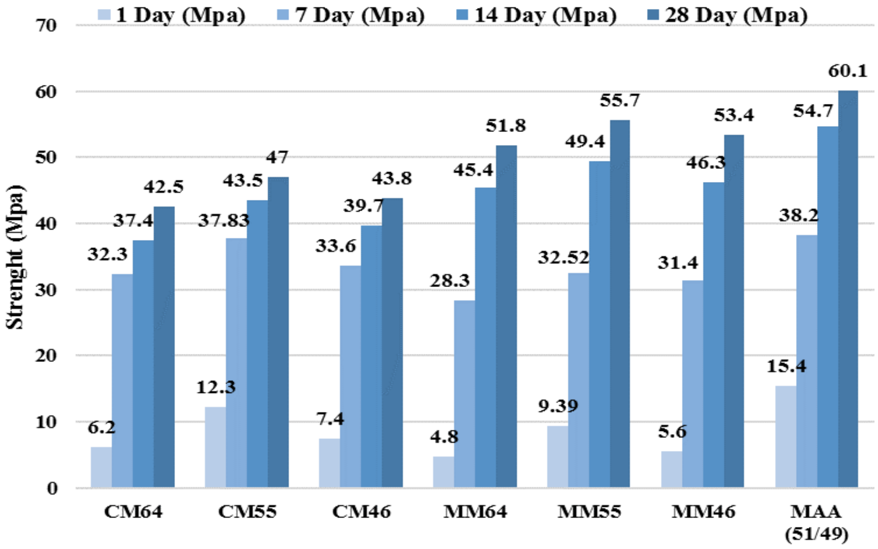

Figure 4.15: Compressive Strength of SCCs

4.10. Air Content

Figure 4.16 shows air content of SCC formulations determined by following ASTM C-231 standard guidelines. It can be seen that MM SCC mixes show less air content in fresh state than CM SCC mixes due to filler effect of SRMs which is one of the factors in strength enhancement of corresponding SCC mixes.

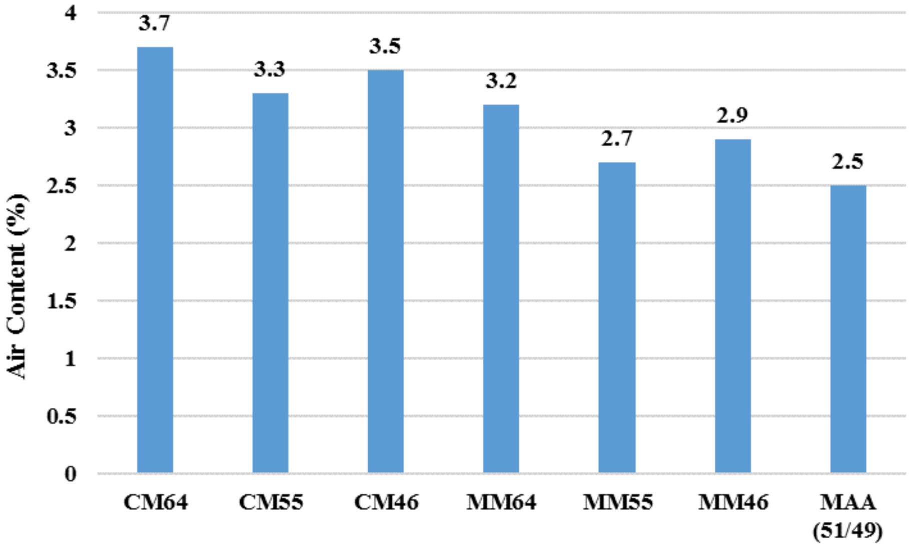

Figure 4.16: Air content of SCCs

4.11. SEM Analysis for Microstructure

Microstructure and hydration products especially CH content were studied using SEM images obtained from JEOL JSM5910 Scanning Electron Microscope available at Central Research Laboratory of University of Peshawar. Figure 4.17 shows the hexagonal CH crystals of SCC formulations at 28 days age developed due to the hydration reaction. SEM image of MM55 shows smaller CH crystals due availability of lesser space for growth of hydration products [6] caused by higher packing density.

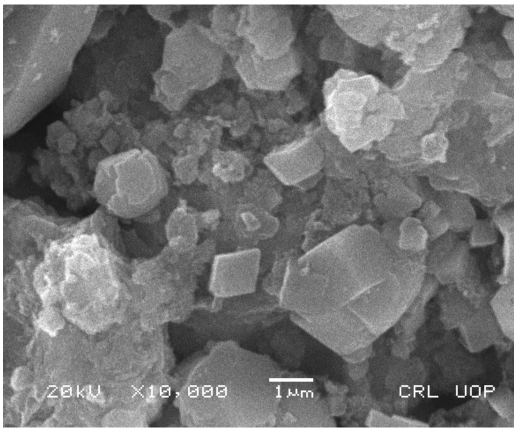

Figure 4.17(a): SEM Image of CM55-Open Microstructure showing bigger CH crystals

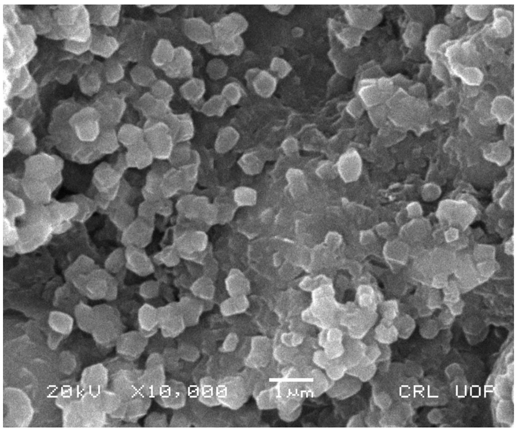

Figure 4.17(b): SEM Image of MM55-Dense Microstructure showing smaller CH crystals

CHAPTER 5: DISCUSSION

This chapter includes discussion on the different experimental results obtained during the research.

5.1. Packing Density of Mixes

Packing density of mixtures depends on various factors including particle density, particle porosity, surface texture and PSD. Figure 4.3 shows that by increasing the amount of fine aggregate, packing density of aggregate mix increases till it reaches its peak value at fine to coarse aggregate ratio of 50/50. Further increasing the amount of fine aggregate will decrease the degree of packing of aggregate mixes. Use of blends of FA and LSP as a partial replacement of cement will increase the packing of binder phase of SCC mixes thus resulting in greater degree of packing of SCC mixture. FA and LSP due to their finer size increases the packing density of mixes by filler effect.

Mixes prepared using Mod A&A model having different values of q gives optimum packing density at q = 0.25 as shown in figure 4.4. For lower values of q, fineness of mix decreases which indicates the presence of coarse particles. MAA mix having q equal to 0.25 showed maximum packing density and it had fine to coarse aggregate ratio of 51/49 which is quite closer to the one obtained from trails. However using Mod A&A approach greater packing density was obtained with the similar fine to coarse aggregate ratio as that from trails. This is because of the better particle size distribution in MAA mix resulting in reduced porosity. However great amount of effort is needed for sieving aggregates in accordance to their size to prepare a mix that exactly follows the Modified A&A approach. However EMMA software based on MA&A approach can be used to obtain fine to coarse aggregate ratio for better packing and thus extra efforts needed for trails can be reduced.

5.2. Water Demand and setting time

Water demand and setting times of paste was determined using standard VICAT's Apparatus. Use of blends of FA and LSP causes increase in water demand and setting times. Greater the specific surface area, higher is the water demand. Water demand is also influenced by the surface morphology of powders. LSP seems to absorb water in its porous surface and thus shows greater water demand. FA having glossy surface texture and being spherical in shape generally do not require greater amount of water. But when used in combination with LSP, water demand increases due to the increased internal friction caused by rough surface morphology of LSP.

LSP being inert in nature do not take part in hydration reaction, however it provides space for hydration products to grow. Literature suggests that LSP reacts with C_3A phase of OPC and produces ettringite [15] thus setting time is reduced and dormant period is shortened causing acceleration in hydration process at early stages. While FA being glossy in nature, retards the hydration kinetics and delays the setting. Thus it can be seen form the results that replacing OPC with blends of FA and LSP causes increased setting times and water demand.

5.3. SP Demand and cone times (T50 & T70) of SCC Mixes

SP demand of control mixes (having no SRMs) is lesser than the corresponding modified mixes (having blends of FA and LSP). This is because of the reason that modified mixes are densely packed due to the presence of fine SRMs and also increased internal friction and rough surface texture of LSP particles. Effect of glossy and smooth surfaced particles of FA is reduced when blends of FA and LSP are used. Thus mixes having greater packing density shows SP demand because of the increased internal friction between particles.

Flow times T50 and T70 shows the rheological properties of SCC in terms of plastic viscosity and yield stress respectively [32]. Flow times are directly related to the amount of effective water available, particle characterization and amount of fines in the mix. Modified mixes shows increased cone times due to greater packing density and presence of higher amount of fines in the mixture. Also presence of blends of LSP and FA causes greater internal friction and resists the flow due to rough surface texture of LSP particles. LSP particles also tend to absorb water in its porous surface resulting in decreased amount of effective water left to aid in flow.

5.4. Flow measurements of SCC Mixes

Slump flow and V-funnel tests are generally performed to investigate flow characteristics of SCC mixes. Slump flow T50 time and V-funnel time shows the plastic viscosity of SCC mixture. Both are directly related to each other and this can be justified through figure 4.8 that shows a reasonable linear relationship between T50 and V-funnel times of different SCC mixes. Viscosity of SCC mix having blends of FA and LSP is increased due to the greater degree of packing and also due to the presence of more fines in the mix. Also the effect of amount of fine aggregate can also be seen in figure 4.7 which shows that viscosity of the mix is increased by increasing the amount of fine aggregate.

Passing ability of SCC was assessed by L-box test that replicates the scenario of SCC passing through the reinforcements. FA and LSP caused the delay in T20, T40 and T60 times due to greater amount of fines and higher internal friction between the particles. Passing ability is also greatly influenced by the size and amount of coarse aggregate in the mixture. Mixes having greater amount of coarse aggregate showed the lower values of H2/H1 that indicates lower passing ability of the SCC mixes as can be seen in figure 4.9.

J-Ring test is also used to access the passing ability of SCC mixes. Control mixes having no SRMs showed greater value of Bj as shown in figure 4.12 which shows that control mixes have reduced passing ability as compared to corresponding modified mixes. Figure 4.11 shows a linear trendline obtained between J-Ring and L-box times. This figure shows the usefulness of investigating passing ability by these two methods. Modified Mixes shows higher flow times coupled with lower Bj values, indicating better cohesion in such mixes.

5.5. Strength of SCCS

Compression tests for 1, 7, 14 and 28 days were performed on 4 samples of each formulation to improve reliability of results. FA and LSP due to their dilution effect decreased the strength at early ages but later on at 28 days age, it showed greater strength than control mixes. It is due to their pozzolanic reactivity, FA reacts with hydration products of OPC to produce CSH that improves the micro structure of the mix by densifying it thus improving the strength. LSP being inert do not take part in hydration reaction, however it do provide space for development of hydration products.

Another finding was observed which shows that even decreased binder content in SCC, strength of MAA formulation was increased. This is due to the better packing of mix. Less porous matrix resulted in better performance when mechanically tested. Particles are more intact to each other thus internal friction and particle to particle stress transformation helped to bear additional load.

5.6. Shrinkage of SCC Mixes

Early expansion of few formulations is caused by the sedimentation process. Shrinkage starts nearly at final setting time of a formulation when water is consumed in hydration reaction. Modified Mixes showed lower shrinkage due to better packing between particles and also due to retarding effect of FA.

Similarly CM mixes having lower packing density showed higher heat of hydration due to higher cement content. Dilution effect caused by presence of blends of SRMs in modified mixes resulted in reduced heat of hydration and thus reduced linear shrinkage.

CHAPTER 6: CONCLUSIONS

1. Fine to coarse aggregate ratio of one yields the maximum packing density of granular phase of SCC mixes prepared using aggregates in as obtained condition (natural condition) with maximum aggregate size of 16mm.

2. Maximum Packing density of the mixes prepared using Modified A&A approach is obtained at q equal to 0.25. At this value of q fine to coarse aggregate ratio is equal to 51/49 which is quite closer to value obtained from trails.

3. EMMA software can be used to determine the proportioning of ingredients of SCC to obtain mixture having maximum packing density.

4. EMMA can also be utilized conveniently to determine fine to coarse aggregate ratio to obtain maximum packing density for granular mix having particular maximum aggregate size. This will save the time and material required for trails.

5. Flow times and SP demand of SCC mixes having greater packing density is increased because of the presence of FA and LSP.

6. Passing ability of SCC is greatly affected by the amount of coarse aggregates in the mixture. Greater the amount of coarse aggregate, lower will be the passing ability of SCC through the reinforcements.

7. Higher packing density of SCC mixes decreases the maximum heat of hydration of the formulation and thus reduces the linear shrinkage as measured using modified Schwindrine shrinkage measuring apparatus.

8. Strength of SCC increases with increase in packing density due to greater interparticle friction, reduced porosity and greater amount of paste available to contribute in strength enhancement.

9. Blends of FA and LSP also contributes in increasing mechanical strength of SCC through their synergic effect and pozzolanic activity which is more dominant after 14 days age of concrete.

10. Increasing the packing density of SCC mixes results in more economical and environmental friendly concrete by reducing the amount of cement paste required to fill the voids.

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