RATIONAL MIXTURE DESIGN OF SELF-COMPACTING CONCRETE

A THESIS

submitted by

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for the award of the degree

of

DOCTOR OF PHILOSOPHY

BUILDING TECHNOLOGY AND CONSTRUCTION MANAGEMENT DIVISION

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

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JULY 2009

This thesis is dedicated to my Parents

THESIS CERTIFICATE

This is to certify that the thesis entitled "**RATIONAL MIXTURE DESIGN OF SELF-COMPACTING CONCRETE**" submitted by **N. Prakash** to the Indian Institute of Technology Madras for the award of the degree of **Doctor of Philosophy** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

I express my deep sense of gratitude to my guide Dr. Manu Santhanam. His boundless energy and enthusiasm, willingness to spend long, endless hours on discussion whenever needed and his commitment to the job have been examples to emulate. Apart from that, he provided me all necessary facilities for doing research. His friendly nature and easy going attitude helps me in handling difficult situations. I wish to warmly thank him for all his guidance and support, which enabled me in the timely completion of this research work.

I would like to place on record my sincere appreciation for Prof. K. Rajagopal, Head of the Department of Civil Engineering, for all the administrative support and encouraging words. I am highly indebted to my Doctoral Committee members Prof. K. Ramamurthy, Dr. Abhijit P. Deshpande, Dr. Appa Rao, Prof. Krishnan Balasubramanian for their constructive suggestions at various stages of my research work. In particular, I would like to express a special thanks to Prof. K. Ramamurthy, who helped me in all aspects right from the date I joined IIT Madras.

I would like to thank all the faculty members of BT & CM division. In particular, I would like to express my sincere gratitude to Prof. Ravindra Gettu for his valuable ideas and constructive suggestions at all stages of my research.

I would like to extend my sincere thanks to Mr. S. Subramanian, Vishal Consult, Chennai who created the interest towards concrete in me and helped at the initial stages of my research. I would like to thank Prof. Harald S. Muller, Michael Haist and Jennifer Schyedt of Institute of Building Materials and Concrete Structures, University of Karlsruhe for their valuable technical support during my stay in

Germany. I would like to extend thanks to the DAAD (German Academic Exchange Service) for financially supporting me during my stay in Germany (April – Sep. 2006). A very special heartfelt thanks to Ashok and Eva Kunchiwala for their care and moral support during my stay in Karlsruhe, Germany. I extend my thanks to Dr. Murali Krishnan (IIT Madras) for his help with the viscometric studies. I also like to thank Prof. Paramanand Singh (IIT Madras) for his ideas related to aggregate studies and powder characterisation. Special thanks to Dr. Antony Vijesh (Indian Institute of Space Science and Technology, Trivandrum) for his help regarding interpolation.

I wish to thank the staff members of the concrete laboratory - Soundarapandian, Malarvizhi, Subramanium, Krishnan, Dhanasekar - who helped me to carryout the experiments. I would like to thank the project assistants Palani, Vijay Kumar, Prem Kumar, Prasath, Krishna, Prem Raj who admirably and unstintingly helped me physically through all the laboratory work and these people have a very special place in my heart for all the effort they put towards the successful completion of my work. I am also thankful to all office staff members of the Civil Engineering Department, especially Velayudham and Geetha.

I am thankful to all my fellow research scholars and hostel friends for their technical and moral support especially Sam, Ramesh, Manikandan, Jayasree, Sivakumar, Senthil, Saba, Ashok, Nambiar, Boeing, Cindy, Sundaraman, Ganesh, Glory, Geetha, Anu, Rajesh.

Above all, I wish to express my indebtedness to my father R. Nanthagopalan, my mother N. Rukmani, my sister N. Meenupriya and my wife P. Selva Karthica who have supported me in all possible ways.

N. PRAKASH

ABSTRACT

KEYWORDS: Rheology; Particle Packing; Self-Compacting Concrete; Mixture Design; Ternary Packing Diagram; Marble test.

Self-Compacting Concrete (SCC) is a highly flowable concrete which gets compacted and fills the formwork completely under its own weight without any external vibration. The available mixture design methods for SCC have limited guidance for optimising the paste rheology. The criteria for selection of paste and aggregate content are not well defined. Some mixture design methods based on scientific concepts (Rheology and Particle packing) are either application specific or need proprietary software. The objective of this research study was to develop a mixture design for SCC for a wider range of strength and workability, using a simple and systematic approach based on the concepts of particle packing and rheology. For achieving the objective, the study involved optimisation of three phases namely, paste phase, aggregate phase and concrete phase.

The optimisation of paste phase included optimisation of (i) powder combinations, (ii) superplasticiser (SP) dosage, (iii) viscosity modifying agent (VMA) dosage and finally, viscometric studies for the cementitious pastes. The powder combinations were optimised using the concept of particle packing by Puntke test. A combination of Cement and Fly ash of 60: 40 (by volume) resulted in maximum packing density, and was selected for further investigations on cementitious paste. The SP dosage was optimised by using mini-slump cone test for different water to powder (w/p) ratios by volume and validated in SCC. The VMA dosage was optimised by using a newly developed test called Marble test. The optimum dosage of VMA was validated in SCC by using sieve segregation test. Viscometric studies were also conducted on

cementitious paste to understand the behaviour at different dosages of SP and VMA, and more specifically, at optimum dosages. The rheological parameters (yield stress and plastic viscosity) were compared with the empirical measures (spread and flow time) to validate the empirical test methods and the optimised dosages scientifically.

The aggregate phase included the development of a precise and practicable method for the determination of packing density of aggregates; this method eliminated the subjectivity encountered in the experiment. Based on the experimental data for packing density, a mathematical interpolation was performed to get adequate number of data points for developing a ternary packing diagram (TPD) of packing density of aggregates for Ready Mix Concrete plants. However, for an individual user, the TPD is not a viable solution as it involves exhaustive experimentation. Therefore, an attempt was made to establish an empirical relationship between the packing density and the particle size distribution (PSD) of the aggregates. An equation was proposed by using the coefficient of uniformity (C_u) to calculate the packing density of aggregates. In mixture proportioning of concrete, for designing the proportions of aggregates, this proposed relationship can be used for any gradation or any shape, as it depends on the combined particle size distribution of the particles alone without any predefined assumptions.

The influence of packing density on the properties of SCC was investigated by selecting three different packing densities (0.64, 0.66 and 0.68) of aggregates with constant paste composition and paste volume (388 litres). From the results, it was observed that the packing density has a positive influence on fresh and hardened SCC due to the reduction in void content. Studies were also conducted for different aggregate combinations having same packing density (0.68). The results reveal that selection of maximum packing density of aggregates alone should not be a criterion for the improved performance of the SCC; in addition, selection of aggregate combinations should also be considered as a criterion for obtaining the improved fresh concrete performance of the SCC. Based on the results, it was decided to use an aggregate combination of 50:20:30 (Fine agg. : Coarse agg. 12.5 mm: Coarse agg. 20 mm, by volume) giving maximum packing density (0.68), for further investigations on SCC.

Experiments were carried out on SCC with different powder contents (350 to 650 kg/m^3) and w/p ratios (0.7 to 1.7 by volume) with corresponding variation in the paste volume to investigate the influence of these parameters on properties of SCC. It is evident from the results that the slump flow increases with increase in paste volume. It is observed that a minimum of 50 to 70 litres of excess paste volume, on the top of the paste corresponding to the void content, is required for achieving the minimum slump flow of 550 mm. An empirical relation was proposed between the slump flow and excess paste volume based on the results obtained and it was used in the mixture design procedure. Based on the experimental results (implicitly involving concepts of rheology and particle packing), a simple and systematic mixture design procedure for SCC was developed. By using the proposed mixture design method, a compressive strength range of 20 MPa to 70 MPa with slump flow between 550 mm to 850 mm was achieved. It was also possible to produce SCC with powder content as low as 350 kg/m^3.

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GLOSSARY

Consistency	- The relative mobility or ability of freshly mixed concrete or mortar to flow
Flowability	- The ease of flow of fresh concrete when unconfined by formwork and/or reinforcement.
Lattice effect	- Grid of stable small and mid-size particles prevent the sinking of big particles.
Packing density	- The volume fraction of a system occupied by solids.
Particle packing	- The inherent property of the material to pack in a given volume.
Passing ability	- The ability of fresh concrete to flow through tight openings, such as spaces between the steel reinforcing bars, without blocking.
Plastic Viscosity	- Resistance to flow of a material.
Powder	- Particles finer than 125 microns (Cement and Fly ash).
Pseudo plastic	- A decrease in viscosity with increasing shear rate during steady flow.
Rheology	- Science of deformation and flow of matter. It investigates the relationship between stress, strain and time.
Segregation	- Separation of either paste phase from concrete or water from cement paste.
Segregation resistance	- The ability of the concrete to remain homogeneous in composition while in its fresh state.
Shear thickening	- An increase in viscosity with increasing rate of shear in steady flow.
Shear thinning	- A reduction of viscosity with increasing rate of shear in steady flow.
Thixotropy	- A decrease of the apparent viscosity under shear stress, followed by a gradual recovery when the stress is removed. The effect is time-independent.
Slump	- The height of subsidence of fresh concrete, using a slump cone as per ASTM C 143
Slump flow	- The spread of fresh concrete, from a slump cone as per ASTM C 143
Yield stress	- The minimum shear stress required to initiate the flow.

NOTATIONS

Φ_p	Packing density
V_w	Volume of water
V_p	Volume of solid particles
F_b	Buoyancy force
F_d	Drag force
mg	Gravitational attraction
V_c	Volume of the container (m^3)
M_1, M_2, M_3	Mass of aggregate types (kg)
S_1, S_2, S_3	Specific gravity of aggregate types
C_u	Coefficient of uniformity
τ	Shear Stress (Pa)
τ_0	Yield stress (Pa)
μ	Plastic Viscosity (Pa s)
$\dot{\gamma}$	Shear rate
K	Consistency
r	Radius of the sphere (m)
d	Diameter of the sphere (m)
V	Terminal velocity of the sphere (m/s)
ρ	Density of the liquid (kg/m^3)
w/p	water powder ratio
T_{500}	Time taken to reach 500 mm of slump flow (s)
bwoc	By weight of cementitious materials

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Proper compaction is essential for adequate strength and durability of concrete. For compaction of concrete, external energy has to be provided by means of vibration (using internal and external vibrators). Vibration makes the entrapped air to rise to the surface and escape from the mixture. Generally, skilled labourers are necessary for adequate compaction of concrete to achieve durable concrete. However, vibration on site is not always carried out as it should be, resulting in reduced strength and durability of the concrete structure (Schutter *et al*., 2008). On the other hand, compaction by means of vibration produces undesirable noise, increases construction time and labour, and is harmful to the construction workers (sometimes leading to diseases such as 'white fingers'). Primarily to address these issues, Japanese researchers developed a special high performance concrete, later named as Self-Compacting Concrete (Okamura *et al*., 1993).

Self-Compacting Concrete (SCC) is a highly flowable concrete which does not segregate and can spread into place, fill the formwork with heavily congested reinforcement, and encapsulate the reinforcement without any mechanical vibration (ACI 237 R, 2007). Further, it holds good in areas of difficult accessibility and complicated structural forms while maintaining the homogeneity of the mixture (Okamura and Ouchi, 1999). Self-compactability is achieved by limiting the coarse aggregate content, adopting low water powder ratio and using a suitable superplasticiser. Limited coarse aggregate content will help in reducing the internal stresses arising due to the friction between the aggregates particles causing blockage when the concrete is deformed. Added to that, the blockage of coarse aggregates can be avoided by using high viscous paste. Low water powder ratio coupled with the use of superplasticiser is required to achieve high deformability concrete (Okamura and Ouchi, 2003).

Self-Compacting Concrete has many advantages (Bui *et al*., 2002a). To mention a few, it helps in

(1) Reducing construction period by increasing the casting speed.
(2) Reducing usage of labour.
(3) Assuring compaction in the structure especially in confined zones (e.g. Beam column joint) when compaction by vibrator is difficult.
(4) Eliminating noise due to vibration.
(5) Saving in cost and energy due to compaction.
(6) Resulting in highly durable concrete.
(7) Minimising health-related problems for construction workers.
(8) Large utilization of industrial by-products.

The first practical application of SCC was in a building in 1990 and in 1991, SCC was used in large scale in the towers of a prestressed concrete cable-stayed bridge (Sakamoto *et al*., 1991). In 1992, lightweight SCC was used in the main girder of a cable-stayed bridge (Ohno *et al*., 1993). In 1998, SCC was used in the anchorages of Akashi - Kaikyo suspension bridge with a span of 1991 meters (Kashima *et al*., 1999). In 1998, SCC was used for a wall of a large LNG tank belonging to Osaka Gas Company (Kitamura *et al*., 1999). SCC technology has also been widely used in Europe and United States. A range of practical applications all over the world can be found elsewhere (Domone, 2006). In India, SCC was used in a water pump house in Tarapur Atomic Power Project (Mittal *et al*., 2004), nuclear power project at Kaiga

(Bapat *et al.*, 2004), Engineering Design building and air conditioning unit at IIT Madras, Chennai. It can be used for all applications like bridges, box culverts, concrete filled steel columns, tunnels, dams, concrete products (blocks, culverts, walls and slabs), diaphragm walls, roofs, piles, tanks, etc.

1.2 PROBLEM STATEMENT

Review of literature indicates that tremendous amount of research in SCC has been performed in the past 20 years. However, the applications based on SCC are far behind the pace of the research, especially in India. This is due to the lack of standard testing methods and standard mixture proportioning methods with scientific emphasis. The specific shortcomings of the mixture proportioning methods are listed below:

- Most of the available mixture design methods either have restrictions in the selection of coarse and fine aggregate content or are primarily intended for high strength concrete.

- Approaches suggested for the calculations of materials are computationally intensive and the developed statistical models are specific only to the materials used and the range of proportions considered.

- Little guidance is given for selection of various factors used for the optimisation of paste and aggregate phases. The experimental methods developed for the optimisation of paste and aggregate phases may not yield reliable results.

- The mixture design methods using scientific concepts (such as Rheology and Particle packing) are either application specific or need proprietary software.

- The methods of calculation of the void content of aggregates differ for each mixture design method. Most of the methods have unrealistic assumptions. Some other methods assume additional factors like surface area, angularity etc. to measure the void content. The reliability of these methods is questionable. For example, a rounded aggregate and crushed aggregate having same surface area would result in much different workability.

- Limited guidance is available for optimising the paste rheology.

- The criteria for selection of paste and aggregate content are not well defined.

- VMA dosage optimisation is not addressed in any of the studies.

In this context, an in-depth investigation on the development of mixture design based on the concepts of particle packing and rheology is deemed necessary. Specifically, methods for the optimisation of paste, aggregate and concrete phases need to be developed, which are simple, well defined, and have a sound scientific basis.

1.3 OBJECTIVES, SCOPE AND METHODOLOGY

The primary objective of this study is to develop a mixture design procedure for Self-Compacting Concrete based on the concepts of rheology and particle packing. In order to achieve this, the following specific aims are outlined:

(1) To optimise the use of mineral admixture (fly ash) and chemical admixtures (superplasticiser and viscosity modifying agent) in cementitious paste for different w/p ratio of Self-Compacting Concrete

(2) To develop a practicable and precise method for the determination of packing density of aggregates and to optimise aggregate combinations based on the packing density

(3) To understand the influence of packing density (of aggregates) on the performance of Self-Compacting Concrete

The scope of the study is limited to the following with respect to raw materials used and the test methods adopted:

(1) Study includes Class F fly ash, one superplasticiser (polycarboxylic ether based) and one Viscosity Modifying Agent (microbial polysaccharide - powder form).

(2) Studies on fresh concrete tests include Slump flow, J ring, V funnel, and the hardened property measured is compressive strength.

A flowchart depicting the research methodology is presented in Fig. 1.1. The methodology involves 3 phases namely, the paste phase, the aggregate phase and the concrete phase. The paste phase includes the optimisation of powder combinations (cement and fly ash), superplasticiser dosage, viscosity modifying agent dosage and viscometric studies on the cementitious paste for different w/p ratios (0.8 to 1.2 by volume). The aggregate phase includes the development of ternary packing diagram of aggregates (River sand, coarse aggregates 12.5 mm max. size and 20 mm max. size), followed by the establishment of an empirical relationship between the particle size distribution and the packing density of aggregates.

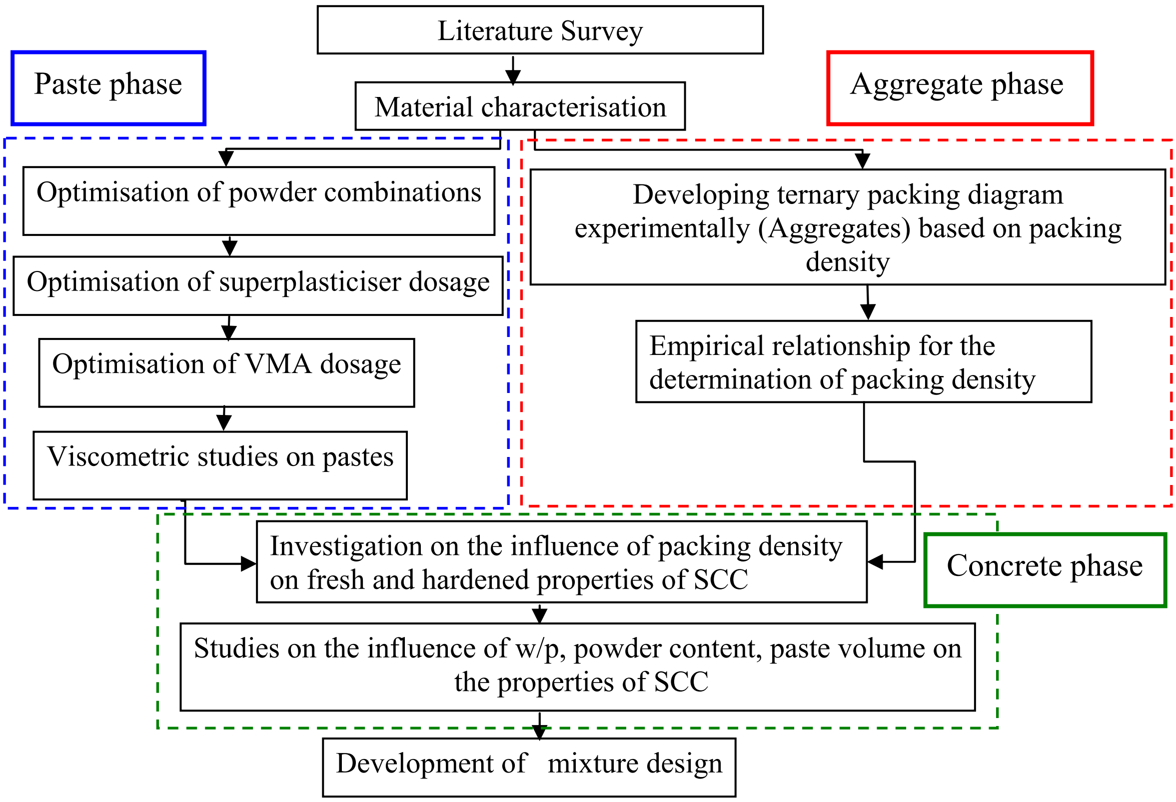


Fig. 1.1 Methodology of research

In the concrete phase, the influence of the packing density of aggregates on the fresh and hardened concrete properties of SCC is investigated. The combination of aggregates giving the maximum packing density combined with optimum proportion of aggregates is chosen for the further investigations on the self-compacting concrete. Studies are conducted to evaluate the effect of influence of w/p (0.8 to 1.2 by volume), powder content (350 – 650 kg/m^3) and corresponding paste volume on the fresh and hardened properties of SCC. Based on the results, a rational mixture design procedure for SCC is developed.

1.4 ORGANISATION OF THE THESIS

A critical review of literature on self-compacting concrete with a special emphasis on the mixture proportioning methods, rheology and particle packing concepts, test methods, fresh and hardened concrete properties, is presented in Chapter 2.

Chapter 3 presents the physical and chemical properties of the materials used for the experimental investigations in the present study.

Chapter 4 describes the experimental methods for optimising the mineral admixture (fly ash) and chemical admixtures (Superplasticiser (SP) and Viscosity Modifying Agent (VMA)) of the cementitious pastes for different w/p by volume. This chapter also discusses the viscometric studies conducted for the all the cementitious pastes. The validation of the optimum dosages of the SP and VMA in concrete is also explained in the relevant section of this chapter.

The experimental determination of packing density of aggregates is described in Chapter 5. The first part of the chapter covers the description of the experimental procedure adopted for the determining the packing density of aggregates and the development of the ternary packing diagram of the aggregates based on the experimental and interpolated data. The second part of the chapter deals with the experimental investigations on the influence of the packing density of aggregates on the fresh and hardened concrete properties of self-compacting concrete. This is followed by the investigation of the influence of different proportions of aggregates having same packing density on the properties of SCC.

Chapter 6 deals with the investigations on the influence of different parameters such as w/p ratio, paste volume, powder volume, water content etc., on the fresh and hardened properties of SCC. Finally, a detailed mixture design procedure based on the experimental results supported by scientific concepts is explained.

A general discussion of the experimental findings, and their relevance to the science of SCC, is included in Chapter 7.

The conclusions drawn from the present research work and recommendations for further studies form Chapter 8.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

A review of the development and the current scenario of Self-Compacting Concrete (SCC) is described in first part of this chapter. A detailed description of the existing mixture proportioning methods for SCC is then presented. This is followed by discussions on the concepts of particle packing and rheology in general and their applicability to the optimisation of the paste composition and proportioning of aggregates for SCC. Finally, a brief account of the fresh concrete test methods and hardened concrete properties is provided.

2.2 DEVELOPMENT AND PRESENT SCENARIO OF SELF-COMPACTING CONCRETE

In the 1980s, the Japanese construction industry faced serious problems of poor durability of concrete structures, owing to decline in the quality of work. This was due to the reduction in the number of skilled workers responsible for sufficient compaction. This led to the development of Self-Compacting Concrete (SCC) in Japan in 1988 (Okamura and Ouchi, 1999). Apart from assured compaction, which enhances the durability of structures, the SCC technology has many other tangible advantages like reducing construction period, reducing the man power, effective elimination of noise, less harm to construction workers etc. Self-Compacting Concrete can be achieved by a combination of (i) limiting the aggregate content to reduce the frequency of collision between the aggregate particles, which decreases the internal stresses when concrete is deformed and provides more resistance to segregation, (ii) adopting low water to powder ratio, which results in high viscous paste essential for avoiding the segregation of coarse aggregates, and (iii) the use of an effective superplasticiser, which is inevitable for high deformability (Okmaura *et al.*, 1993).

The volume of research in SCC within a short span of time (~ 20 years) has been steadily increasing and spreading throughout the world, which is evident from the substantial number of publications in journals and major conferences. Domone (2006) conducted an extensive analysis of 68 case studies of the use of SCC around the world for 11 years from 1993 to 2003. SCC is being used in all types of structural elements. Table 2.1 was formulated from the case studies and it gives an idea of the maximum and minimum amount of ingredients used for the production of SCC.

Table 2.1 Case study details

Ingredients	Minimum	Maximum
Coarse aggregate (% volume)	28	38
Powder content (kg/m^3)	438	625
Water content (kg/m^3)	159	226
Paste volume (% volume)	320	420
Volume of fine agg. / Volume of mortar (%)	38.1	65.4
Water/powder ratio (by weight)	0.26	0.48

The studies indicate that overall grading of aggregates is a more important factor than size or type of aggregate. From the studies reported, mostly limestone powder was used along with Portland cement. Limited studies were done on SCC incorporating Viscosity Modifying Agent (VMA). From this analysis, it was deduced that coarse aggregate content, paste content and fine aggregate content are more critical for successful SCC when compared to powder content and water to powder ratio. The studies indicate that there is considerable scope for optimising SCC mixes by minimising powder content and for developing mixes for wider range of applications.

Self compacting concrete has a promising future in onsite construction and in prefabrication (Gettu and Pacios, 2004). SCC technology is being used increasingly in the precast concrete industry, where there is a considerable scope for complicated design of structural elements, and to have a firm control over the quality of the concrete products (Humehara *et al*., 1999). In the future, SCC will be widely used as standard concrete rather than as a special concrete.

2.3 MIXTURE DESIGN METHODS

The mixture design of any concrete should begin with the selection of required properties. It is definitely possible to develop mixture proportioning based on previous experience and then following the trial and error method to arrive at the required properties. However, it is advantageous to use a more systematic approach based on knowledge of the effect of various parameters on the mixture properties. The following sections present a brief account of 12 mixture design methods for SCC.

2.3.1 Rational Mixture Design Method

A simple step by step mixture proportioning system was proposed by (Okamura and Ozawa, 1995) based on extensive work on SCC at the University of Tokyo. The method consisted of limiting the coarse aggregate content to 50 % of solid volume of concrete. The fine aggregate was fixed at 40 % of the mortar volume; all particles larger than 90 microns were considered as aggregates and particles less than 90 microns were considered as powders. It was assumed that moderate heat Portland cement or belite-rich Portland cement was the only source of powdered materials. The water to powder (w/p) ratio and SP dosage were determined by spread and V-funnel tests on paste and mortar. The spread was measured in terms of relative flow area (change in the flow area to the original flow area) and plotted against w/p ratio. The intercept on the w/p ratio axis (retained w/p) indicates the water content just sufficient to initiate the flow. The experiments were carried out on mortar with an initial w/p ratio of 0.85 and SP dosage was varied. The w/p ratio and the SP dosage were adjusted to achieve V-funnel flow time of 9 – 11 s and relative flow area of 5 (no units). These results formed the basis for the tests on concrete. Finally, tests were performed on trial batches of concrete to finalise the mixture proportions. A slump flow of 650 mm, V funnel flow time of 10 – 20 s and a final height of 300 mm in the U box test was considered to be adequate for SCC. Generally, a w/p ratio of 0.9 to 1.0 (by volume) with proper superplasticiser dosage was required to ensure self-compactability. The schematic representation of the mixture design is presented in Fig. 2.1.

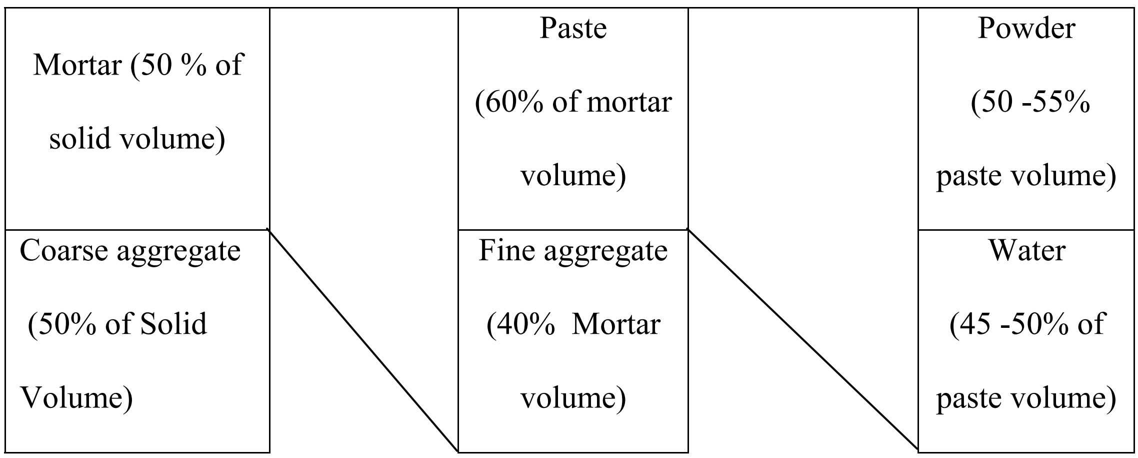


Fig. 2.1 Schematic representation of the mixture design procedure proposed by Okamura (1993)

This mixture design method restricts the coarse and fine aggregates contents which may not result in required workability. It establishes target paste flow properties. The resulting proportions may not be optimal in concrete. Moreover, the strength criterion is not discussed; however, some control over the strength could be achieved by selecting suitable powder combinations and w/c ratio based on experience.

Later, this method was modified further by Edamatsu *et al*. (1999) and Ouchi *et al*. (1998) for satisfactory combination of w/p ratio and SP dosage, minimising the number of tests required.

2.3.2 CBI Mixture Design Method

A mixture design method for self-compacting concrete was proposed by Petersson *et al*. (1996). This method, popularly known as CBI method, assumes concrete as a 2 phase material including the solid fractions, which consist of particles greater than 0.125 mm, and micro-mortar fraction consisting of particles smaller than 0.125 mm (including water, admixtures and air). This method consists of two principal stages:

1. Selection of the maximum aggregate content (minimum paste content) based on the blocking criterion ensuring sufficient passing ability (blocking greatly depends on the ratio of reinforcement gap size to particle diameter and to a lesser extent on the particle shape).
2. Selection of micro-mortar composition and volume to give required hardened properties and adequate flow through the reinforcement without any blocking respectively.

The determination of the fines, water and superplasticiser contents constituting the micro-mortar was based on tests with rheometer. The minimum paste volume for avoiding blocking was selected and it was greater than the minimum void content in the aggregate. The advantage of this method is that it considers the overall grading and also takes into account the practical placing conditions. This method gives no recommendation for the design of mixes containing a viscosity agent. Results from a series of tests based on the mix design indicate that satisfactory SCC had a yield stress less than 12 Pa and plastic viscosity of about 150 – 250 Pa s. The limitation of the method is that the proposed criteria for the selection of micro-mortar rheology and the volume of micro-mortar are not well-established. Strength criterion was also not discussed.

Van and Montgomery (1999) proposed liquid phase criterion for the calculation of the minimum paste volume in addition to the blocking criterion proposed in CBI method. The proposed method ensures that there is adequate paste volume to provide sufficient spacing between the aggregates. Here the aggregates are assumed to be spherical particles, and no suggestions are given for the usage of viscosity agent in the mixes.

2.3.3 LCPC Mixture Design Method

A mixture design procedure for SCC was developed by Sedran *et al*. (1996) based on characterisation of the rheological behaviour of concrete by using a new type of rheometer and adopting a numerical model called compressible packing model (an extension of a previous model called "Solid Suspension Model") for determining a compact aggregate system with minimum voids, taking into account wall effect and the degree of confinement exerted by the form and the reinforcement to the mixture. Moreover, in this method, packing analysis was included to achieve the optimal particle size distribution of aggregates and powders as well. In this model, equations were computed for the determination of concrete yield stress, plastic viscosity and segregation resistance. The superplasticiser dosage was chosen for different combination of fines using Marsh cone test. The water and superplasticiser dosages were finally adjusted to obtain the required fresh concrete behaviour using a rheometer and the slump flow test. The model developed for packing compels the usage of software which is not an open source (proprietary software). The calculation of rheological parameters is based on the BTRHEOM rheometer, which overestimates the values of the rheological parameters compared to other rheometers (Koehler and Fowler, 2007).

2.3.4 Excess Paste Theory

The excess paste theory was originally developed by Kennedy (1940) and was extended to SCC mix design by Oh *et al*. (1999). The basis of the theory lies in determination of excess paste volume, which is available after filling the voids between the aggregates. The thickness of the excess paste was calculated by dividing the excess paste volume by the surface area of the aggregates. The surface area of the aggregates was calculated based on a new approach. It was identified that no unique relationship exists between the thickness of excess paste and Bingham parameters for different paste composition. However, a relationship was found between the relative thickness of excess paste (ratio of thickness of excess paste to the projected diameter of the aggregate) and relative Bingham parameters (ratio of Bingham parameters of concrete to the Bingham parameters of paste). By determining the specific surface area of the aggregates and the rheology of paste, the rheology of concrete could be computed. The limitations are:

1. For the determination of surface area of aggregates, the approach proposed is computationally intensive, especially when fine aggregates are used.

2. When different rheometers are used for measuring the rheology of paste and concrete, it is not possible to link the concrete rheology to the paste rheology by using the excess paste theory (Hasholt *et al*., 2005).

3. Furthermore, the strength criterion is not discussed.

2.3.5 Gomes *et al*. Mixture Design Method

A simple four step experimental procedure for the mix design of high strength self-compacting concrete was developed by Gomes *et al*. (2001). The mix design assumes concrete as a two phase material containing paste and aggregates. The paste phase was optimised for superplasticiser dosage and filler dosage by using Marsh cone and Mini-slump tests respectively by keeping the w/c ratio (0.4) and the silica fume to cement ratio (0.1) constant. The aggregate skeleton, defined in terms of the fine/coarse aggregate ratio, was optimised for lowest void content (32.5 %) based on ASTM C 29 (2001) by calculating the dry density of aggregate mixtures experimentally without compaction. Based on the void content of the aggregates, the paste content (38 %) was optimised for adequate flowability without sacrificing the strength, durability and shrinkage resistance. Here, the method was designed specifically for high strength SCC. There are possibilities of error in the determination of the packing density of aggregates due to the subjectivities that may be encountered while performing the experiments on aggregates. The criteria proposed for optimisation of SP dosage in paste may not result in optimal workability in SCC.

2.3.6 Particle Matrix Model

Mortsell *et al*. (1996) developed the particle matrix model for conventionally placed concrete. Later, this model was applied to SCC by Smeplass and Mortsell (2001) with mixed success. The model assumes concrete to be a 2 phase material with matrix phase consisting of particles less than 0.125 mm such as powder, admixtures and water, and particle phase consisting of particles greater than 0.125 mm. The workability is governed by matrix rheology, matrix volume and the characteristics of the ingredients. In this model, the particle phase is characterised by air void modulus (approximately represents the volume that has to be occupied by the matrix material in order to obtain a "no-slump" concrete) and the matrix rheology was represented by flow resistance ratio (a representation of the difference in flow rate between the test material and an ideal fluid) which in turn was measured by FlowCyl (a modification of Marsh funnel test). A plot between the height of the matrix in the FlowCyl versus the flow rate for the tested material and for an ideal fluid was made. The difference between the 2 curves was defined as the loss curve. The flow resistance ratio was defined as the ratio of the area under the loss curve to the area under the ideal fluid curve. The flow resistance ratio for water is 0.1 and for SCC ranges from 0.6 to 0.8. The air void modulus was computed from the characteristics and volume fractions of the fine and coarse aggregates. After determining the matrix composition and aggregate blend, the workability was measured for various matrix volumes. A plot was made between the slump flow, yield stress or plastic viscosity and the matrix volume. Equations were also developed for multiple matrix flow resistance ratios and aggregate air void moduli. These equations help in predicting the effects of changes in mixture proportions and selection of optimum mixture proportions. The air void modulus is complicated, particularly in determining the aggregate parameters. The flow resistance ratio may not be a feasible choice to characterise matrix rheology as it does not address the effect of yield stress. Both flow resistance ratio and air void modulus have limited physical meaning.

2.3.7 Saak *et al*. Mixture Design Method

A theoretical model was developed by Saak *et al*. (2001) for SCC based on the segregation-controlled (static and dynamic) design methodology. The theory proposes that the rheology of cement paste matrix largely dictates the segregation resistance and workability of fresh concrete for a specified particle size distribution and volume fraction of aggregate. The concept of self-flow zone, defined in terms of a range of paste yield stress and apparent viscosity values necessary to achieve both self-flow and segregation resistance was introduced. The minimum paste volume was selected based on either solid phase (blocking of aggregates) or liquid phase (segregation, flowability and form surface finishability) criteria. The paste rheology was determined from empirical tests. The applicability of this theory was validated by systematically changing the rheology of cement paste matrix of fresh concrete. The theoretical model was developed for a single glass spherical particle suspended in infinite cementitious matrix, which is unrealistic in the case of concrete having continuous particle sizes. Limited guidance is available in this model for the selection of the average spacing between aggregates and paste rheology. Moreover, the strength criterion is not emphasized.

2.3.8 Su *et al*. Mixture Design Method

Su *et al*. (2001) proposed a mixture design method for SCC. The main principle of the proposed method is to fill the paste into the voids of aggregates which are piled loosely. This method introduces a new term called packing factor, which is the ratio of mass of the aggregate in a tightly packed state in SCC to that of the loosely packed state. It consists of six steps along with adjustment of water content and trial mixes. In the first step, coarse aggregate and fine aggregate contents were calculated from the packing factor and the unit volume of coarse and fine aggregates respectively. In the second step, the cement content was calculated based on the compressive strength by assuming 0.14 MPa / kg of cement. Step 3 involved the determination of mixing water content based on the w/c ratio and the cement content. The fly ash and slag contents were calculated based on the flow values of the cementitious paste in step 4. In step 5, the mixing water content required for fly ash and slag for SCC was determined. In step 6, the superplasticiser dosage was calculated based on flowability, self-compactability and segregation resistance of fresh SCC. This was followed by trial mixes until the mixture proportions ensured satisfactory performance. The packing factor and the proportions of fly ash and slag have to be decided based on previous experience. The assumption of compressive strength of 0.14 MPa/kg of cement does not have any scientific basis. The water content was selected for 3 different cementitious materials, but the combined effect on the strength and workability was not considered. No proper guidance was given for the optimisation of the superplasticiser dosage. The effect of VMA was not considered for the mixture proportions.

2.3.9 University of Rostock Method

A mixture design method for SCC was developed in University of Rostock in Germany by Marquardt *et al*. (2001). In the mixture proportioning process, based on the water requirement of individual solid components, the optimum water content for SCC was determined. Based on the void content of the aggregates, the paste volume was selected. Superplasticiser dosage required for sufficient fluidity was used. The concrete was assumed to be comprised of volume of aggregates, volume of paste required to fill the voids between the aggregates and the volume of excess paste. The first step includes the determination of aggregate grading with adequate amount of fine aggregate and high packing density. The aggregate content and the paste volume were determined in the second step. The paste volume was determined from the compacted volume of aggregate and the volume of voids between the aggregates for the selected grading. In the third step, the cement content was determined based on the strength requirements. The fourth step involved selection of the type of cementitious materials, type of HRWRA, the type of VMA and the air content. The water demand of all the ingredients was determined. The water requirements of aggregates were calculated from the surface area of aggregates and the water requirement of powders was determined by measuring the power consumption of a mixer when water was gradually added to the powder. As water is added, the power consumption increases due to agglomeration of powder particles and reaches a maximum value before decreasing. The water content corresponding to the maximum power consumption was considered as the water demand. This water demand was calculated separately for each powder. The volume of the additives such as fly ash was adjusted to achieve proper volume of concrete and finally trial mixtures were done to achieve required flowability by adjusting the dosage of HRWRA. Limited attention was given to the selection of aggregate blend. The water demand determination of aggregates and powders may not be feasible in practice.

2.3.10 Densified Mixture Design Algorithm

In Taiwan, the Densified Mixture Design Algorithm (DMDA) was applied for proportioning self-compacting concrete by Hwang and Chen (2002). This DMDA method aims to minimise the cement and the water content by maximising the volume of aggregates. In this method, fly ash was considered as a part of the aggregate. Initially, the blend of fly ash and fine aggregates giving maximum density was determined. This optimum blend of fly ash and fine aggregate was blended with different proportions of coarse aggregates to select the maximum packing density of all the three components. Then, the volume of paste was calculated by a factor considering the surface area of aggregates and thickness of paste around aggregates. The water - cementitious ratio was determined based on strength and durability requirements. The cement content, water content and superplasticiser dosage were determined based on the minimum w/c ratio of 0.42 (to prevent autogenous shrinkage) and maximum water content of 160 kg/m^3. This method was mainly developed for high strength concrete. As the fly ash was considered as aggregate for achieving minimum void content, it may not be optimal for workability. There is no clear information in the method about the ability of concrete to pass through the reinforcement, or its segregation resistance.

2.3.11 Statistical Mixture Design Methods

A few studies (Ghezal and Khayat, 2002; Patel *et al*., 2004; Sonebi, 2004) have used statistical design of experiments to investigate the influence of mixture proportions and their interactions on the properties of SCC with minimum number of trials. These methods assess the effects of different factors on the measured response. Researchers have commonly used the central composite design - response surface approach. The parameters generally considered were water powder ratio, powder content, powder composition, superplasticiser dosage and VMA dosage. The coarse aggregate content was held constant and fine aggregate was varied to achieve required volume in all the cases. The responses such as slump flow, V funnel time, L box height ratio, slump loss and compressive strength were obtained. The interaction between the parameters and the responses can be used for both mix optimisation and quality control. The limitation of statistical models is that, they are specific only to the materials used and the range of proportions considered. Moreover, some prior knowledge on the materials and SCC proportioning is essential to select the values of factors used in the experiments.

Nehdi *et al*. (2001) used artificial neural network technique for predicting the performance of SCC based on the mixture proportions. This model predicts values of slump flow, filling capacity, segregation resistance and 28 day compressive strength. In addition, a model was proposed for the acceptance/ rejection of SCC mixtures based on knowledge of the mixture proportions. The main drawback of the proposed neural network model is the limited open literature available to train the artificial neural network model on all aspects of the complex relationship between mixture proportioning and SCC performance.

2.3.12 University College London method

Schutter *et al*. (2008) proposed a simple mixture design method developed at University College London. The required mortar properties are obtained from the required concrete properties using predefined graphs. Initially, the coarse aggregate content is determined based on the specified concrete properties and it varies form 30 to 38 % by volume of concrete. The volume of fine aggregate is set to 45 % of the mortar volume. Based on the volume of the fine and coarse aggregates, the paste volume is determined. The paste composition i.e., w/p ratio and admixture dosage was determined by performing tests such as slump flow and V funnel on mortar phase. The mortar combinations are adjusted for the specified concrete properties recommended based on the experimental studies. Limited guidance is given for the selection of aggregates and the paste composition. The strength criterion is not considered in this method.

2.3.13 Guidelines

Apart from the mixture design procedures, a set of guidelines were proposed by European federation (EFNARC) and the Japanese Civil Engineering Society, by which one can assume the proportions from the guidelines to start with, and finalise based on trial and error using locally available materials.

The EFNARC guidelines and specifications for SCC were developed by a project group comprising of 5 European federations (EFNARC, 2005). The guidelines were drafted with an emphasis on Ready Mixed Concrete (RMC) and site mixed concrete in relation to the fresh and hardened concrete properties. It is assumed that in these guidelines the compressive strengths of SCC and traditional vibrated concrete are comparable. The fresh state SCC is classified based on flowability, viscosity, passing ability and segregation resistance into different classes (refer Table 2.2). The fluidity and the viscosity of the paste, which are essential for good filling ability, passing ability and resistance to segregation, are adjusted by controlling the w/p, SP dosage and VMA dosage (optional). The coarse aggregate to fine aggregate ratio in the mixture is reduced to decrease the interlock and bridging of coarse aggregates. A typical range of constituents in SCC are given Table 2.3. Guidelines were also provided for the mixing procedures, formwork design and placing procedure.

Similarly, recommendations for the mixture design of self-compacting concrete were provided by the Japan Society of Civil Engineers (JSCE, 1998). Manuals are provided for mixture proportioning along with test methods and placement of SCC. It classifies SCC into powder type, viscosity agent type and combination type constituting of powder and viscosity agent.

Table 2.2 Consistency classes of SCC as per EFNARC guidelines

Test Method	Measured Characteristics	Consistency class	Measured Value
Slump flow	Flowability	SF1- 550 to 650 mm	Total spread
		SF2 - 660 to 750 mm	
		SF3 - 760 to 850 mm	
V - funnel	Viscosity	VF1 - ≤ 8 s	Flow time
		VF2 - 9 to 25 s	
L - Box	Passing ability	PA1 ≥ 0.8 with 2 rebars	Passing ratio
		PA2 ≥ 0.8 with 3 rebars	
Sieve segregation	Segregation resistance	SR1≤ 20 %	Percent laitance
		SR2 ≤ 15 %	

Table 2.3 SCC mixture design guidelines

		EFNARC (2005)		JSCE (1998)	
		Minimum	Maximum	Minimum	Maximum
Powder	mass (kg)	380	600	300	600
	volume (litres)			95	190
Paste	volume (litres)	300	380		
Water	volume (litres)	150	210	155	175
Coarse Aggregate	mass (kg)	750	1000		
	volume (litres)	270	360	280	350
Fine Aggregate	(% by wt. of total aggregate)	48	55		
w/p	volume	0.85	1.1	0.85	1.15
w/p	weight			0.28	0.37
Max. Aggregate size	mm	20	25		
Slump flow	mm	550	850	500	750
V funnel time	s	-	25	7	20

2.3.14 Summary of Mixture Design Methods

From the available literature on mixture design of self-compacting concrete, it is observed that limited guidance is available for optimising the paste rheology. The criteria for selection of paste and aggregate content are not well defined. Mixture designs based on fundamental concepts (Rheology and Particle packing) are either application-specific or need a proprietary software. The strength criterion is not discussed properly in most of the methods. In the present study, the concepts of particle packing and rheology are used for evolving the mixture design of SCC. The following sections describe the concepts of particle packing and rheology in general and their relevance to self-compacting concrete.

2.4 PARTICLE PACKING

2.4.1 Introduction

The packing density of a multi-particle system is of basic importance in science and industry. Packing density is defined as the volume fraction of the system occupied by solids. Efficient packing in the making of ceramics has undoubtedly interested mankind for centuries. More recently, the concept of packing has proven useful to the concrete and nuclear power industries as well as in physics and soil mechanics. Efforts to understand and master efficient packing reflect the diversity of the interest in the subject (Stovall *et al.*, 1986). Particle packing involves the selection of appropriate sizes and proportions of particulate materials to get suitable combination for optimal packing.

2.4.2 Packing of Powder Combinations

The concept of particle packing has always been a key element in the mixture proportioning of concrete. Experiments have shown that the packing density of concrete mixtures and the flow properties of the corresponding fresh concrete are related. The optimal flow properties are obtained for mixture compositions close to the maximum packing density (Johansen and Andersen, 1991). The generally agreed theory is that the paste which is in excess after completely filling the voids of the aggregate will improve the flow properties of concrete. Therefore, a given workability can be achieved by lower paste content, or, for fixed paste content, a mixture with higher packing density leads to better workability. While particle packing has a significant influence on the properties of concrete, which contains different sizes of particulate inclusions, the paste properties are also affected by the interaction between the cementitious particles. Moreover, as the paste rheology has a major influence on the concrete rheology, it is important to understand the effect of packing of cementitious particles in paste. It has been shown that the improvement in the packing density of the cementitious materials by blending cement with fine materials plays a major role in enhancement of the properties of the mortar produced (Lange *et al.*, 1997). Jones *et al.* (2003) studied both theoretically and experimentally the effectiveness of different types of fillers in minimizing the voids content of cementitious materials. Their results revealed that the water demand was dependent on the presence of superplasticiser and the water demand measured with a superplasticiser generally agreed better with the theoretical packing model.

Experimentally, there are two different methods available for determining the packing densities of powder materials namely, dry method and wet method. According to BS 812 (1995), the dry packing density of the filler is measured under compacted condition. The problem with the dry packing is that with decreasing particle size (smaller than 100 μm), the Van der Waals' and electrostatic forces between the cementitious particles become predominant, causing agglomeration that results in increased void content (Yu *et al.*, 1997).

BS EN – 196 (2005) describes the procedure for measuring water demand by standard consistency test. In the standard consistency test, the Vicat apparatus is used and the consistency of the paste is determined by measuring the penetration depth of the plunger. The water content at which the penetration depth is equal to 34 ± 1 mm is arbitrarily taken as the water content for standard consistency. It is assumed that this water content for standard consistency is the same as the water demand of the cementitious materials. It is further assumed that there is no air entrapped in the paste. There is no solid proof that the water content corresponding to 34 ± 1 mm is sufficient enough to fill up the voids. Assumption of no air entrapment may lead to underestimation of voids content.

Another method, developed in Germany called the Puntke test (Puntke, 2002) falls under the category of wet method in measuring the packing density. The basic principle of the test is that the water which is added to the dry materials fills the voids in between the particles and acts as a lubricant to make the materials compact efficiently. The water, which is in excess after completely filling the voids, appears at the surface of the mix, indicating the saturation limit. From the volume of water added, the volume of voids is calculated; in turn the packing density is calculated from the void content.

Considering the limitations of the available test methods, it was decided to use Puntke test for the determination of packing density. A detailed explanation about the procedure for the test is given in Chapter 4. The reasons for choosing the Puntke test were its ease, simple apparatus, consumption of only small amount of material, and reliable results. The scope of the present study, however, does not include the determination of accurate numeric value of packing density of the powder combinations; rather, the emphasis was on the selection of combination of powders which gives maximum packing density.

2.4.3 Particle Packing of Aggregates

Aggregates give concrete its necessary property of volumetric stability, wear resistance, strength and stiffness (Alexander and Mindness, 2005). Legg (1974) insists that aggregates are not merely fillers to dilute the expensive cement. Apart from economic reasons, proper choice of aggregates has significant influences on the properties of concrete like workability of the fresh concrete and hardened properties like volume stability, strength and thermal properties. The proportioning of aggregates has been attempted using the concepts of particle packing to minimise the necessary amount of paste filling the voids between the aggregates. Research has shown that the packing density has significant influence on the fresh and hardened properties of concrete (Glavind and Pedersen, 1999). The use of the concept of particle packing of aggregates for concrete production incurred in 19^{th} century itself with the first work published on particle packing for concrete by Feret in 1892 (Joisel, 1952). Fuller and Thomson (1907) experimentally investigated the importance of the size distribution of the aggregates and the properties of the concrete on the basis of packing of constituent materials. Later, research studies were devoted for developing models for proportioning particles to attain densest packing by using the concept of particle packing. A review of particle packing theories can be found elsewhere (Senthilkumar and Santhanam, 2003).

The basic particle packing models were developed by Furnas (Furnas, 1931) and Andreassen (Andreasen and Andersen, 1930). Furnas considered a discrete approach by which the densest packing occurs when the finer particles exactly fill the void space within large particles without disturbing the packing of large particles; the shape of the particles was assumed to be spherical. This model is not valid when the diameter of the finer particles is nearer to the diameter of the coarser particles and for non spherical particles. In case of Andreassen model, continuous approach was considered by which the theoretically densest packing was achieved by assuming that the smaller particles are infinitely small. The limitation of Andreassen model is that in real size distributions, a minimal particle size is always present. Andreassen's model was modified by considering the minimum particle size in the distribution and incorporated in the Funk – Dinger equation (Dinger and Funk, 1992).

Despite the amount of research done in the past on this issue, contradictory results from many laboratories and manufacturing experiences results in questioning the efficiency of such methods. Oger *et al*. (1986) have shown that the predicted porosities by a statistical model are different from computer simulation and experimental results. This is attributed to the interaction effects and the local arching of coarse aggregates in real packing. The authors had also concluded that the fashion in which particles pack to form a structure depends on large number of factors, most of them being difficult to measure or sometimes even to define.

Many other theoretical models are also available for predicting the packing density of aggregates. However, those theoretical models are based on number of assumptions like: aggregates are perfect spheres, aggregates are mono sized, fine and coarse aggregates are of different size etc., which are conflicting with the practical combination of realistic aggregates (Goltermann *et al*., 1997). The porosity predicted from these models results in large variation with the experimentally measured porosities (Standish and Yu, 1987). Theoretical models are always desirable for providing a general platform for an alternative optimisation of aggregates; however, the development is extremely difficult. The applicability of the theoretical models is quite good for particles that are almost spherical, but the particles in engineering practice are usually not spherical (Romagnoli and Siligardi, 2004). The intention of the above conclusion should not be viewed as criticism of mathematical models, as better understanding of the structure and the porosity is possible only by using such models. Instead, the author's view is that the existing models are still being perfected and cannot expect to yield predictions of desired accuracy.

The applicability of particle packing models to both aggregate and powder phase was evaluated and it was found that the largest improvements in the void ratio were achieved with aggregate phase and only small improvements in voids ratio could be achieved with the powder phase (Jones *et al*., 2002). Moreover, proportioning concrete mixtures based on particle packing including the powder phase was found to produce harsh mixes. This present investigation involves three different sizes of aggregates. Therefore, it was decided to use a ternary packing system. Adequate number of studies are available on packing density for ternary systems (Joisel, 1952; Ridgway and Tarbuck, 1968; Standish and Yu, 1987). Generally, the packing density of the ternary packing mixtures is represented in a triangular diagram (refer Chapter 5, Fig 5.4). The range of proportions of aggregates for normal concrete compositions, when represented in the ternary packing diagram, is relatively small compared to the available combinations of aggregates in the diagram. Small variations within this range may have large effects on the rheological behaviour of concrete (Johansen and Andersen, 1991). This is applicable to SCC also. According to Johansen and Andersen (1991), the packing density of particles is influenced by particle size distribution, wall effect and method of compaction. Peronius and Sweeting (1985) suggest that the factors influencing the density of cohesionless materials are the distribution of particles, size and shape. However, accounting for shape and expressing particle size distribution comprehensively has proved to be a difficult task for determination of a successful correlation with porosity (or packing density). None of the correlations so far has yielded an empirical relationship which could be employed with confidence to a wide range of particle size distributions.

In the present investigation, an attempt was made to establish an empirical relationship between the particle size distribution and the packing density of aggregates. A detailed explanation about the empirical relationship is given in Chapter 5.

2.5 RHEOLOGY

2.5.1 Introduction

Rheology is the science of deformation and flow of matter. The word *rheology* is of Greek origin, referring to *panta rei*, meaning everything flows (Barnes, 1999). It investigates the relations between stress, strain and time. In general, rheological measurements are performed to understand the interactions between different ingredients of a product, to get an insight into the structure of the sample, and to control the quality of raw materials, processing conditions and final products (Wallevik, 1999). In engineering practice, materials vary in rheology from those having ideal model behaviour to those with much more complex rheological performance.

2.5.2 Rheology of Concrete

As far as concrete is concerned, the concept of rheology can be applied to both fresh concrete (related to concepts like consistency or workability) and hardened concrete (related to constitutive laws, creep and relaxation). Practically, it is possible to develop high performance concrete by completely neglecting the principles and tools of rheology; however, the difficulties that lead to delay in progress, lack of quality in the final construction and cost overruns necessitates the usage of rheology. Knowledge of the behaviour of fresh concrete provided by modern tools like rheometer allows the user to have a firm control over the quality and robustness of concrete, to speed up the casting process so that time and money can be saved and to have solid control over durability of concrete structures (de Larrard, 1999).

In fresh concrete, the changes occurring due to physico-chemical reactions influences the rheological characteristics in a non linear manner. The rate of change of the rheology depends on the composition of the mix and the environmental conditions (Schutter *et al.*, 2008). The rheological behaviour of the fresh concrete during placement into the formwork significantly influences the quality of concrete structures. With good rheological properties, a concrete should fill the formwork without excessive effort (Wallevik, 2005). Therefore, for highly flowable concrete like SCC, the application of rheology to understand the fresh concrete properties is essential. Wallevik (2003) states that rheology should be used right from selecting the ingredients of the concrete to the final development of SCC.

Fresh concrete can be considered as a suspension of aggregates of various sizes in a continuous paste phase. The rheological behaviour of concrete greatly depends on the paste phase. Therefore, a thorough understanding of the rheological behaviour of paste is required in predicting the influence of plasticisers, stabilizers and water reducers on concrete behaviour (Papo, 1988). The rheological properties of cement pastes have been the subject of study over the years due to the influence of their characterisation on concrete technology, despite the difficulties in extending the results of pastes to concrete (Schutter *et al.*, 2008). Moreover, formulation of models which satisfactorily describe the general behaviour of concrete has proved difficult (Erdogan *et al.*, 2008; Haist and Muller, 2006; Lu *et al.*, 2008; Papo, 1988). As a result, most research efforts reported in the literature are focussed on studying the rheology of pastes.

2.5.3 Rheological Models

There are several models available for describing the rheological behaviour of materials. The primary models used for cement based materials are described in this section.

2.5.3.1 Bingham model

The Bingham equation was used by Tattersall and Banfill (1983) for describing the behaviour of cement suspensions at low shear rates. The flow behaviour is described by two parameters – yield stress and plastic viscosity. The behaviour is shown in Fig. 2.2. The Bingham equation is written as:

$$\tau = \tau_o + \mu \dot{\gamma} \qquad (2.1)$$

where τ_o = yield stress, μ = plastic viscosity and $\dot{\gamma}$ = shear rate

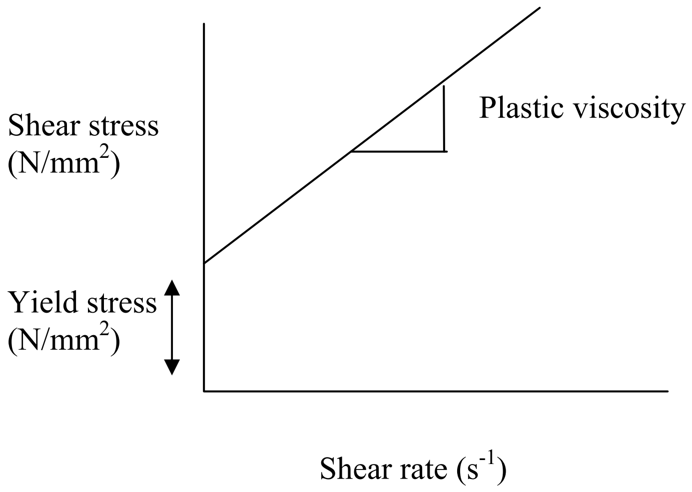


Fig. 2.2 Schematic representation of Bingham model

2.5.3.2 Herschel - Bulkley model

This model, which accounts for the non-linearity at low shear rates, involves 3 adjustable parameters, as shown in the equation below.

$$\tau = \tau_o + K \dot{\gamma}^n \qquad n < 1 \qquad (2.2)$$

where τ_o = yield stress (Pa), K = consistency, n = power index which represents the deviation from Newtonian behaviour; n is less than 1 for shear thinning systems. This model leads to a Newtonian behaviour ($\tau = \mu\dot{\gamma}$) for $\tau_o = 0$ and n = 1, to Bingham equation ($\tau = \tau_o + \mu\dot{\gamma}$) when $\tau_o \neq 0$ and n = 1, and to power law ($\tau = \mu\ \dot{\gamma}^n$) when $\tau_o = 0$ (Herschel and Bulkley, 1926).

2.5.3.3 Eyring model

The equation for this model is written as:

$$\tau = a \sinh^{-1} (b\dot{\gamma}) \qquad (2.3)$$

where a and b are constants

This model was previously applied to simple fluids and subsequently extended to suspensions. This model does not include the yield value term (Eyring, 1936). This model was modified by Atzeni *et al.* (1985) and successfully applied to cement pastes by involving a term linearly dependent on $\dot{\gamma}$ which made the above model effective in describing the behaviour at high shear rates.

2.5.3.4 Vom Berg model

According to this model, the shear stress and shear rate are related by the following equation:

$$\tau = \tau_o + b \sinh^{-1} (\dot{\gamma}/c) \qquad (2.4)$$

where b and c are constants.

This relationship was established for describing the flow behaviour of cement suspensions at shear rates up to 380 s^{-1}, where only shear thinning behaviour was observed, and for w/c ratios between 0.4 and 0.8 (Berg, 1979).

Among the models available, it should be noted that the cement based materials are most commonly viewed as having a Bingham behaviour, which is defined by 2 parameters - yield stress (minimum stress required for the flow) and plastic viscosity (that governs the flow after it is initiated) (Pedersen and Smeplass, 2003). As cement pastes are dispersed systems, coaxial cylinder viscometers must be preferred to avoid the friction phenomena occurring in cone and plate viscometer (Lapasin *et al*., 1983). The rheological results obtained from recent studies for measuring the flow parameters like yield stress and plastic viscosity help in understanding the compatability of cement – superplasticiser – viscosity modifying agent (VMA) system. Since rheometers and viscometers are expensive and widely differ in size of the sample, rotational geometries, calibrations and computational procedures, researchers have proposed simple test methods that are just extensions of available workability methods (Kantro, 1980; de Larrard *et al*., 1997). Sophisticated rheometers are best suited for research purpose for designing advanced concrete mixtures in laboratories. In the context of everyday quality control, simpler and cheaper tests are needed that allow the user to evaluate the fundamental rheological parameters (de Larrard, 1999). It is desirable and essential to establish correlations between empirical tests used for practical assessment of properties of fresh SCC and basic rheological characteristics obtained from rheometers. A study was conducted by Nielsson and Wallevik (2003) to relate the commonly used empirical test methods for fresh SCC to the true scientific values such as yield stress and plastic viscosity. The results indicated that yield value can be correlated to the slump flow of SCC. The advantages and the disadvantages of various fresh concrete tests were discussed in line with the rheological parameters. However, there is a need to clearly understand the link between rheological parameters (as determined from rheometer studies) and results of the laboratory based test methods (Walraven, 2003). Further, based on the requirements in specific applications of SCC, one should be able to decide the mixture proportions for achieving the desired properties (Ferraris *et al*., 2001). In other words, there is a distinct need to incorporate rheological concepts in designing SCC.

The above sections described the concepts of rheology and particle packing. In the present investigation, the particle packing concept is used for optimising the aggregate combination and the rheology for optimising the cementitious paste. The following section describes the role of mineral and chemical admixtures in achieving SCC and about optimisation of their dosages.

2.6 ADMIXTURES

ACI 116 R (2000) defines an admixture as 'a material other than water, aggregates, hydraulic cement and fibre reinforcement, used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing'. Mineral and chemical admixtures are almost always used to attain high deformability and adequate resistance to segregation in SCC. The commonly used mineral admixtures (Pozzolanic) are Fly ash, Blast furnace slag, Silica fume, Metakaolin, Rice husk ash, Volcanic ash. Apart from that, non-pozzolanic fillers (limestone and dolomite fines) also come under the category of mineral admixtures. These mineral admixtures act both chemically and physically to improve the properties of concrete, in addition to providing cost and energy savings (Erdogan, 1997). The following are the reasons for specifically using fly ash in this study

1. Pozzolanic nature
2. Replaces cement thereby reducing the potential for shrinkage and creep
3. In terms of rheology, fly ash reduces yield stress, but may increase or decrease plastic viscosity.
4. Reduces the cost of the concrete by replacing the cement

5. Availability (By 2000-01, the fly ash production was around 90 million ton per year and by 2020, fly ash production may reach 140 million ton per year in India) (Kalra *et al*., 1998; Vimal, 2003).

The chemical admixtures used for the production of SCC are superplasticiser (SP) and Viscosity Modifying Agent (VMA). High flowability is achieved by using SP, and to increase the stability of the paste, a high powder content or Viscosity Modifying Admixture (VMA) or a combination of both are used (Nanthagopalan and Santhanam, 2006).

Polycarboxylic ether based (PCE) superplasticiser is the most advanced cement dispersant having an excellent performance of water reduction and a superior workability retention ability compared to other superplasticizers like those based on sulphonated naphthalene or sulphonated melamine formaldehyde, lignosulphonates etc (Yamada and Hanehara, 2003). The dispersion mechanism of PCE based SP is in two stages. First, the molecules of the SP attach themselves to the cement particles and impart negative charge, thus causing electrostatic repulsion and deflocculation by releasing the entrapped water between the cement particles for increased mobility. Second type of dispersion is performed by the backbone of the SP molecule, having bulky side chains of varying length, which physically keeps the cement particles apart, thus allowing the water to surround more of their surface area, a mechanism called steric repulsion. In all superplasticizers based on graft chain copolymers (including PCE), the steric repulsion mechanism is dominant. Uchikawa *et al*. (1997) proved for the first time the existence of the steric repulsive force in addition to the electrostatic repulsive force. The combined effect of electrostatic repulsion and steric hindrance makes PCE perform excellently in dispersing the cement particles.

Studies were conducted to evaluate the effect VMA and SP on the thixotropy and the formwork pressure (Assaad *et al*., 2003). The results indicate that, irrespective of the VMA type and combination with HRWRA, incorporation of VMA at relatively low concentrations could result in lower formwork pressure compared to reference mixtures made without any VMA and those containing medium or high concentrations of VMA (Assaad and Khayat, 2006). A study was conducted by Nanthagopalan and Santhanam (2006) to investigate the interaction between high range water reducing agent (PCE) and viscosity modifying agent (microbial polysaccharide). The results reveal that the PCE based SP and VMA are compatible with each other with some evidence of thixotropy. For the present investigation a PCE based SP and a microbial polysaccharide based VMA was used.

2.6.1 Paste Studies – Optimisation of Superplasticiser Dosage

While extensive studies have been conducted to evaluate the effect of chemical admixtures and their compatibility issues in paste and concrete (Caszewski and Szwabowski, 2004; Chandra and Bjornstrom, 2002; Erdogdu, 2000; Hanehara and Yamada, 1999; Papo and Piani, 2004; Phan *et al*., 2006), only very few studies have been undertaken on the optimisation of superplasticiser (SP) dosage (Aitcin, 1998; Giaccia and Zerbino, 2002; Gomes *et al*., 2001; de Larrard, 1990; de Larrard *et al*., 1997). Apart from economic reasons, the dosage of SP beyond an optimum value will result in segregation of the mix. The Marsh cone test (de Larrard *et al*., 1997) is used to evaluate the characteristics of different types of pastes and for optimisation of SP dosage. In this test, the time taken for a certain volume of paste to flow through a cone with a definite sized aperture is measured. The Marsh cone flow time decreases with increase in SP dosage for a given w/c ratio until saturation point. The saturation point is defined as the SP dosage beyond which flow time does not decrease appreciably. Aitcin (1998) proposed a method for determining the optimum dosage of SP by using Marsh cone. In this method, for a given w/c ratio with different dosages of SP, the flow time has to be measured at 5 and 60 minutes. The dosage at which the two curves intersect corresponds to the optimised dosage. Gomes *et al.* (2001) proposed a criterion for the optimisation of SP dosage based on an experimental study. The dosage at which the log flow time vs. SP dosage curve exhibits an internal angle of 140º ± 10º was identified as the optimised dosage. There are some problems in using these criteria for optimisation of SP dosage. Sometimes, the flow time curve does not exhibit an internal angle of 140º ± 10º at any point, and there are possibilities for the 5 minute and 60 minute curve not to intersect at all (this happens mostly in case of incompatible combination of cement and SP).

Literature indicates that the superplasticiser has a significant influence on the yield stress to a greater extent in comparison with the viscosity of the paste or concrete (Wallevik, 2003). As discussed earlier, researchers use Marsh cone for determining the saturation dosage of SP. However, the author feels that the Marsh cone (device that measures the viscosity of the fluid) may not be a suitable apparatus for determining the saturation dosage of SP (which has more impact on the yield stress than viscosity), as the apparatus is not addressing the correct rheological parameter.

Based on these limitations, it was decided to use the Mini-slump test (Kantro, 1980) for optimization of SP dosage in the current study. The mini slump test is quick and can be conducted with a small sample size, so that many tests can be performed in a few hours by one person. The results of the mini-slump test on paste and slump test on concrete are generally correlated. The major effects observed in the mini-slump test correspond to the effects observed with slump of concrete (Perenchio *et al.*, 1978). A detailed description about the apparatus and the experimental procedure is given in Chapter 4.

2.6.2 Paste Studies – Optimisation of Viscosity Modifying Agent Dosage

VMAs are high molecular weight, water soluble organic polymers used to stabilise the rheological properties of SCC. There are two broad types of VMA: adsorptive and non-adsorptive. Adsorptive VMAs (cellulose based and acrylic based water soluble polymers) are adsorbed on to the surface of the cement particles forming a bridging structure between them. However, as the superplasticisers and the VMA compete for space on the cement particle surface, the effectiveness of any one chemical admixture may be reduced. Non-adsorptive VMAs (water soluble microbial polysaccharides) act on the water alone and increase the plastic viscosity by linking their own molecules. Therefore, they do not compete with superplasticiser for adsorption sites on the cement surface and hence, are preferably used for SCC (Yammamuro *et al.*, 1997). Most commonly used VMAs in cement based materials include organic materials such as polysaccharides from microbial sources, cellulose derivatives, acrylic based polymers and inorganic materials like colloidal silica, fine carbonate fillers etc. In the present study, a non-adsorptive type microbial polysaccharide (Diutan gum - powder) was used as the Viscosity Modifying Agent. Diutan gum is a second generation viscosity modifying agent possessing pseudo plastic behaviour.

The mode of action of a VMA depends on the type and concentration of the polymer. Diutan gum and cellulose derivatives are believed to increase the viscosity of mixing water since long chain polymer molecules adhere to the periphery of water molecules, thus adsorbing and fixing a part of the mixing water. Molecules in adjacent polymer chains can also intertwine and develop attractive forces, thus further blocking the motion of free water and causing the formation of three dimensional gel, contributing to the control of rheology of the mix by increasing the plastic viscosity and improving the distribution and suspension of the aggregates, thereby reducing the bleeding and segregation of the concrete (Khayat and Yahia, 1997).

Generally, VMAs are used to reduce the segregation in highly flowable concrete, to reduce the washout in underwater concrete, to reduce the friction and pressure in pumped concrete, to reduce formwork pressure by thixotropic effect, to compensate for poor aggregate grading - especially a lack of fines in the sand, to reduce the powder content in SCC, to reduce bleeding and to make the concrete more robust to the changes in moisture content of aggregates. The purpose of using VMA instead of higher powder content is to have a firm control over the stability of the mix as well as to achieve SCC at the same powder content as normal concrete. As a result, the potential for creep and shrinkage of SCC is also reduced. Literature indicates that SCC produced with low powder content and VMA has similar fresh concrete properties as SCC with high powder contents without VMA (Lachemi *et al*., 2003).

The overdosing of VMA may result in loss of workability, retardation, increase of coarse air bubbles, difficulty in cleaning the equipment and slow placing rate. On the other hand, under-dosing can result in too much wash out in under water applications, continued problems with bleed and segregation and low viscosity.

It is well understood that the properties of concrete are highly sensitive to the VMA dosage (EFNARC, 2006). Most studies on VMA focus only on the influence of different types and dosages of VMA on the rheological properties and the compatibility issues between superplasticiser and VMA (EFNARC, 2006; Khayat, 1998; Khayat and Guizani, 1997; Lachemi *et al*., 2004a; Lachemi *et al*., 2004b; Leemann and Winnefeld, 2007; Rols *et al*., 1999; Sonebi, 2006). However, the optimisation of VMA dosage is not addressed. Hence, there is a need to optimise the dosage of VMA in order to obtain controlled rheological properties as well as to reduce the cost of the concrete. In general, the optimum dosage of VMA can be considered as the minimum dosage which results in a paste capable of suspending the aggregates without segregation, in both static and dynamic conditions.

In the present study, a new empirical method for determining the optimal VMA dosage was developed, with an emphasis on the static conditions. The detailed description and procedure about the developed method is given in Chapter 4.

2.7 FRESH CONCRETE PROPERTIES

The essential properties of SCC are flowability, passing ability and segregation resistance. For assessing these properties, fresh concrete tests are used, such as slump flow test (flowability), V funnel test (viscosity), L box and J ring test (passing ability) and sieve segregation resistance test for segregation resistance of concrete (EFNARC, 2005; Schutter *et al*., 2008). Some of test methods are depicted in Fig. 2.3.

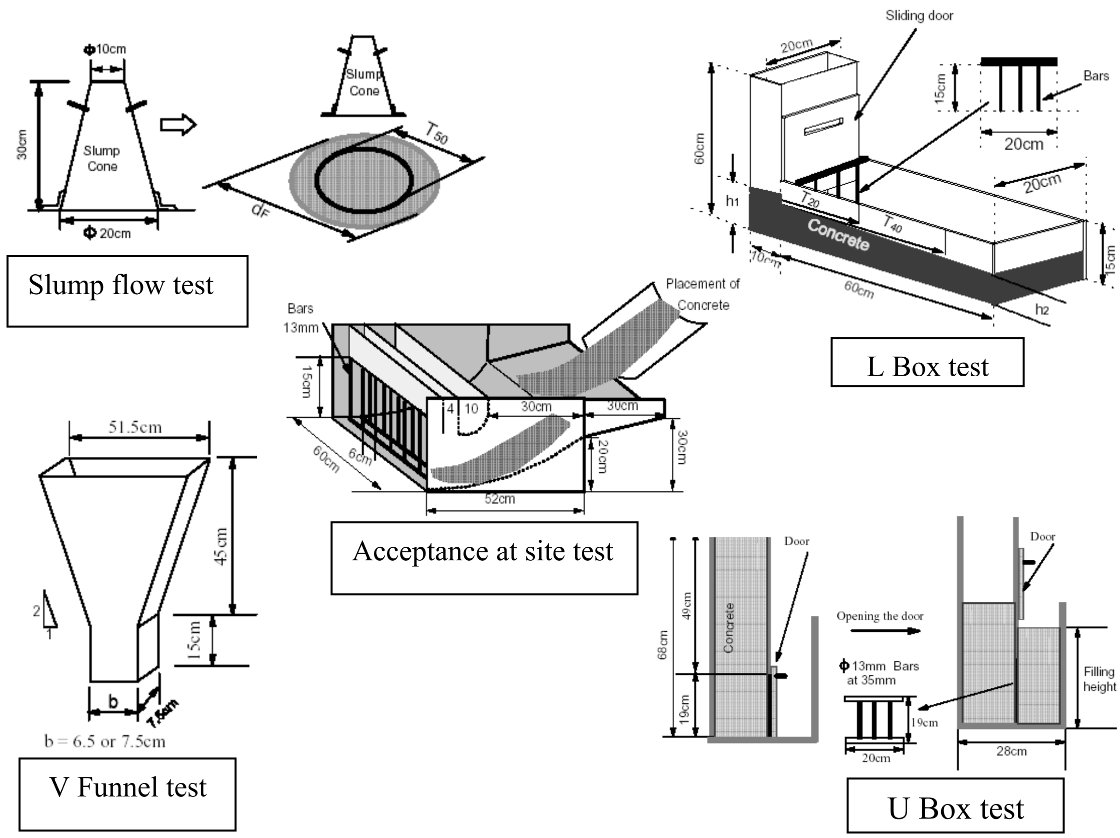


Fig. 2.3 Fresh concrete test apparatus for SCC

2.8 HARDENED CONCRETE PROPERTIES

Extensive literature is available about the mechanical properties of SCC. A review of hardened properties of SCC was given by Domone (2007). Approximately 70 different SCC mixtures from different research studies were analysed for their hardened mechanical properties. The studies showed significant scatter with different studies, due to difference in materials, mix designs and test procedures used. However, a number of clear conclusions were obtained about the behaviour of SCC in relation to Normal Vibrated Concrete (NVC). Compressive strength of SCC was comparable with NVC. The ratio of tensile to compressive strength for SCC was also similar to that for NVC. The elastic modulus of SCC was found to be up to 40 % lower than of NVC at low compressive strengths (~ 20 MPa), but the difference reduced to less than 5 % at high strengths (90 –100 MPa). SCC had similar or lower toughness to NVC, but structural performance tests on reinforced concrete elements indicated greater ductility, particularly with columns. The bond of SCC to embedded reinforcing and prestressing steel was similar to the equivalent NVC. For SCC, the mix design was suggested as the most important factor for obtaining good performance, whereas with NVC, site practice was deemed more critical. Reinforced or prestressed structural elements cast with SCC with similar load capacities showed slightly higher deflections than the equivalent NVC.

CHAPTER 3

MATERIALS USED FOR THE STUDY

3.1 INTRODUCTION

This chapter presents the details of physical and chemical properties of the raw materials used in the experimental investigation. The raw materials used for the present investigation include cement, fly ash (class F), fine aggregate (River sand), two sizes of coarse aggregate (crushed granite), water, superplasticiser (SP) and a viscosity modifying agent (VMA).

3.2 CEMENT

In the present investigation, a commercially available Ordinary Portland Cement (OPC) - 53 grade conforming to IS 12269-2004 (ASTM C 150, 2002) was used. The physical properties and the chemical composition of the cement are presented in Tables 3.1 and 3.2 respectively. The particle size distribution curve of the cement (determined by Laser diffraction method) is presented in Fig 3.1.

3.3 FLY ASH

Class F Fly ash conforming to IS 3812-1999 (ASTM C 618, 2003) was used as a mineral admixture for partial replacement of cement. The class F fly ash was obtained from the North Chennai Thermal Power Station, Chennai. The physical properties and chemical composition (IS 1727-1999) are reported in Tables 3.1 and 3.2 respectively. The particle size distribution (determined by Laser diffraction method) is given in Fig. 3.1.

3.4 AGGREGATES

River sand conforming to IS 383 – 1997 was used in the present investigation. The physical properties of the river sand are given in Table 3.3. Two different sizes of coarse aggregates (12.5 mm maximum size and 20 mm maximum size) conforming to IS 383 - 1997 were used for the study. The physical properties of the coarse aggregates are shown in Table 3.3. The particle size distribution of the aggregates (IS 2386 Part 1 - 2002) used is presented in Fig. 3.1 and in Table 3.4.

3.5 WATER

Potable water conforming to IS 456 - 2005 was used for all the paste and concrete studies.

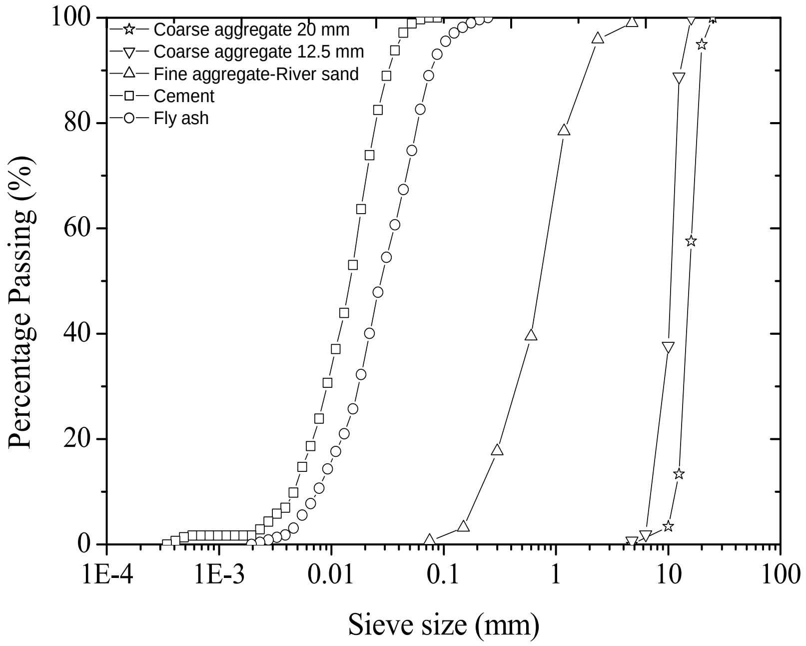


Fig. 3.1 Particle size distribution of ingredients used in the study

Table 3.1 Physical properties of cement and fly ash

Properties	Cement	Fly ash
Specific gravity IS 4031 Part 11 - 2005 (ASTM C 188, 1995)	3.15	2.00
Mean diameter (µm)	16.74	38.16
Blaine Fineness (m^2/kg) IS 4031 Part 2 - 2004 (ASTM C 204, 2000)	355	151
Consistency (%) IS 4031 Part 4 - 2005 (ASTM C 187, 1998)	31	-
Initial setting time (minutes) IS 4031 Part 5 - 2005 (ASTM C 191, 2001)	106	-
Final setting time (minutes) IS 4031 Part 5 - 2005 (ASTM C 191, 2001)	190	-

Table 3.2 Chemical composition of cement and fly ash

<table>
<tr><td rowspan="2">Chemical composition</td><td colspan="3">Cement (% by mass)</td><td colspan="4">Fly ash - Class F (% by mass)</td></tr>
<tr><td>Test result (%)</td><td>IS 12269 (2004)</td><td>ASTM C 150 (2002)</td><td>Test result (%)</td><td>IS 3812 (1999)</td><td colspan="2">ASTM C 618 (2003)</td></tr>
<tr><td>CaO</td><td>61.18</td><td></td><td></td><td>1.41</td><td></td><td colspan="2"></td></tr>
<tr><td>SiO_2</td><td>20.01</td><td></td><td>>20</td><td>60.56</td><td>> 35</td><td rowspan="3">> 70</td><td rowspan="3">> 70</td></tr>
<tr><td>Al_2O_3</td><td>4.98</td><td></td><td><6</td><td>32.67</td><td></td></tr>
<tr><td>Fe_2O_3</td><td>4.88</td><td></td><td><6</td><td>4.44</td><td></td></tr>
<tr><td>MgO</td><td>1.78</td><td>< 6</td><td>< 6</td><td>0.23</td><td>< 5</td><td colspan="2"></td></tr>
<tr><td>SO_3</td><td>2.36</td><td>< 3</td><td><3</td><td>0.02</td><td>< 2.75</td><td colspan="2">< 5</td></tr>
<tr><td>Loss on Ignition</td><td>2.18</td><td>< 4</td><td><3</td><td>0.21</td><td><12</td><td colspan="2">< 6</td></tr>
<tr><td>Total Chloride content</td><td>0.03</td><td>< 0.1</td><td></td><td>0.01</td><td></td><td colspan="2"></td></tr>
<tr><td>Na_2O</td><td>0.20</td><td></td><td></td><td>0.02</td><td></td><td colspan="2"></td></tr>
<tr><td>K_2O</td><td>0.60</td><td></td><td></td><td>0.03</td><td></td><td colspan="2"></td></tr>
<tr><td>Insoluble residue</td><td>1.23</td><td>< 2</td><td>< 0.75</td><td>0.46</td><td></td><td colspan="2"></td></tr>
<tr><td colspan="8">Bogue compound composition of cement</td></tr>
<tr><td colspan="4">Compound</td><td colspan="4">% by mass</td></tr>
<tr><td colspan="4">C_3S</td><td colspan="4">49.82</td></tr>
<tr><td colspan="4">C_2S</td><td colspan="4">19.78</td></tr>
<tr><td colspan="4">C_3A</td><td colspan="4">4.94</td></tr>
<tr><td colspan="4">C_4AF</td><td colspan="4">14.84</td></tr>
</table>

Table 3.3 Physical properties of aggregates

Properties	River Sand	12.5 mm	20 mm
Specific gravity IS 2386 Part 3 - 2002 (ASTM C 128 - 2001, ASTM C 127- 2001)	2.57	2.80	2.78
Bulk density (kg/m^3) IS 2386 Part 3 – 2002 (ASTM C 29 - 2003)	1678	1528	1644
Void content (%) IS 2386 Part 3 – 2002 (ASTM C 29 - 2003)	34.80	45.45	40.86
Water absorption (%) IS 2386 Part 3–2002 (ASTM C127-2001, ASTM C 128-2001)	0.50	0.24	0.20
% passing through 125 micron sieve IS 383-1997	1.9	-	-

Table 3.4 Particle size distribution of aggregates

Sieve Size (mm)	River sand (% passing)	12.5 mm max. size (% passing)	20 mm max. size (% passing)
25	100	100	100.00
20	100	100	94.89
16	100	100	57.57
12.5	100	88.73	13.37
10	100	37.23	3.41
6.3	100	1.16	0.00
4.75	99.00	0.00	0
2.36	95.90	0	0
1.18	78.40	0	0
0.6	39.50	0	0
0.3	17.70	0	0
0.15	3.20	0	0
0.075	0.70	0	0

3.6 SUPERPLASTICISER (SP)

Commercially available third generation polycarboxylic ether (PCE) based superplasticiser was used for the present study. The properties of the superplasticiser conforming to IS 9103-2004 (ASTM C 494 – 99) are given in Table 3.5.

Table 3.5 Properties of superplasticiser

Density (kg/m^3)	1100 (at 30 ºC)
Solid content (%)	33
pH	7.4 (at 30 ºC)

3.7 VISCOSITY MODIFYING AGENT (VMA)

A commercially available non adsorptive type microbial polysaccharide (powder form) was used for the present investigation. This is a second generation viscosity modifying agent possessing pseudo-plastic behaviour. It is a high molecular weight, microbial polysaccharide produced by controlled aerobic fermentation. The repeating unit comprises of six sugar units (see Fig. 3.2). The molecular weight of this VMA is about 2.88 to 5.18 million Daltons (1 Dalton = 1.66×10^{-24} grams) (Sakata *et al.*, 2001).

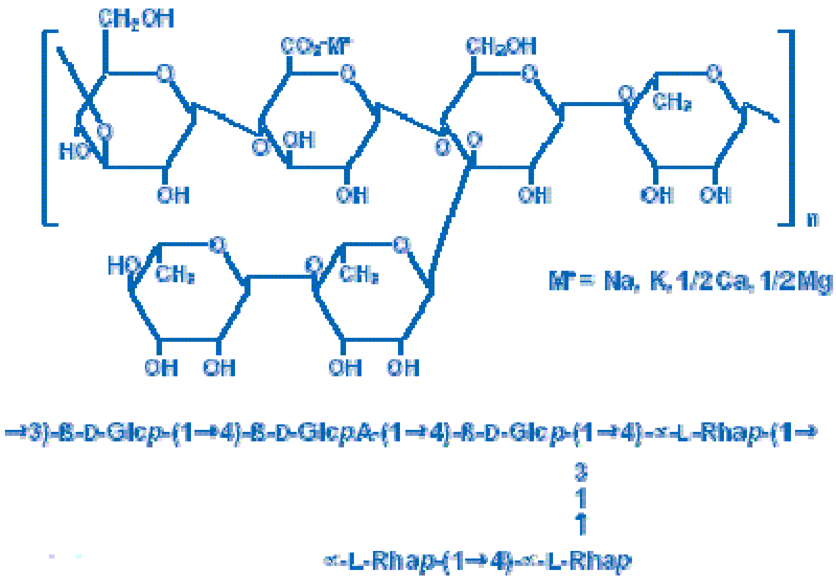


Fig. 3.2 Molecular structure of Diutan gum (CPKelco, 2006)

CHAPTER 4

OPTIMISATION OF MINERAL AND CHEMICAL ADMIXTURES FOR SCC

4.1 INTRODUCTION

This chapter is presented in two sections. The first section describes the method for the optimisation of powder (cement and fly ash) combinations based on the concept of packing density. The second section details the optimisation of the dosage of chemical admixtures (superplasticiser and viscosity modifying agent) for different w/p ratio. This is followed by a discussion of the viscometric studies conducted to evaluate the effect of the chemical admixtures on the rheological properties of the cementitious paste.

4.2 OPTIMISATION OF POWDER COMBINATIONS

4.2.1 Introduction

Flow is a distinct aspect for self-compacting concrete. Nanthagopalan *et al.*, (2008) identified that the flow of paste is significantly influenced by the packing density of cementitious materials. Therefore, the concept of packing density was used for optimising the powder (Cement and Fly ash) combinations. For the determination of the packing density of powders, the Puntke test (Puntke, 2002) was used. Initially, the packing density of different powder (cement and fly ash) combinations was determined. This was followed by studies on the flow of cementitious paste for different combinations having different packing densities. The results are discussed in the following sections.

4.2.2 Puntke Test - Principle

The basic principle of the Puntke test is that the water which is added to the dry materials fills the voids in between the particles and acts as a lubricant to make the materials compact efficiently. The water, which is in excess after completely filling the voids, appears at the surface of the mixture, indicating the saturation limit. One advantage of the technique is that the tests for the cementitious materials are performed in wet condition, which closely resembles the real situation of cementitious materials in paste.

4.2.3 Puntke Test - Procedure

The apparatus required for conducting the test is shown in Fig. 4.1. The mass equivalent of 20 cm^3 of cementitious materials (cement and fly ash) was placed in a plastic beaker. The cementitious materials were mixed thoroughly for homogenisation. Potable water was then added gradually, working the mixture with a stirrer until it acquired a closed structure after repeated tapping (number of taps each time should be consistent - in this case 25 times) of the beaker. Water was added drop by drop, mixing carefully, until the saturation point was reached. Care should be taken to add the water, as transition from a humid soil (see Fig 4.2 a) to a thick paste may need very few drops of water. At this point, the surface smoothes itself after repeated tapping of the beaker and appears glossy (see Fig. 4.2 b). The total time taken for each experiment was 10 minutes. The experiment was repeated 3 times to get the least water required to achieve saturation. From the volume of water used, the packing density was determined by using the following equation:

$$\text{Packing density } \Phi_p = 1 - V_w / (V_w + V_p) \qquad (4.1)$$

where V_w = Volume of water (cm^3)

V_p = Volume of solid particles = 20 cm^3

Fig. 4.1 Puntke test apparatus

Fig. 4.2 (a) Humid cement particles

Fig. 4.2 (b) Thick cementitious paste at saturation point

4.2.4 Results and Discussions

Partial replacement was done on a volume basis instead of mass basis due to different specific gravities of cement and fly ash. The relationship between packing density (as measured from Puntke test) and different powder combinations is shown in Fig. 4.3. The fly ash percentage was varied between 0 to 100 % by volume of cement. The packing density of 100 % cement (0.602) was marginally higher than the packing density of 100 % fly ash (0.595) due to the coarse nature of fly ash. Initially, the packing density increased with increase in percentage replacement of fly ash up to 40 % by volume. Though the fly ash is coarser in nature, the reason for the increase in packing density could be attributed partly to the spherical shape of the fly ash and partly due to wetting of powder which made it to compact efficiently. The maximum packing density obtained by using water was 0.617 for a combination of 60:40 ratio of cement: fly ash by volume. Above 40 % replacement of fly ash, the packing density reduced due to the loosening effect imparted by the addition of fly ash to the packing structure of the cement particles.

Initially, experiments were done only with water. As the paste contains superplasticiser, it was decided to investigate the effect of superplasticiser along with water on the packing of powders. The experiments were carried out by adding superplasticiser dosage of 0.33 % by weight of water. Irrespective of the powder combinations, the SP dosage was maintained constant. As the SP disperses the cementitious particles and reduces agglomeration, the powder compacts effectively. From the results (see Fig. 4.3), it was observed that for different powder combinations with water and SP, the packing density was higher than with water alone due to enhanced dispersion of cementitious particles. The maximum packing density obtained was 0.627. However, the powder combination (cement: Fly ash - 60:40 by volume) that gave the maximum packing density remained the same in both the cases. This proves that water alone can be used with confidence to determine the packing density. However, to avoid any influence of hydration of cement particles on packing density within the time span of 10 minutes, Puntke test was also conducted by using kerosene. The test results with kerosene also confirm that the cement: fly ash - 60:40 combination yields the maximum packing density. From Fig. 4.3, it is clear that though the numeric value of packing density differs, the powder combination which yields maximum packing density remains the same. From the results of the experiments, it was decided to use cement: fly ash combination at 60:40 by volume for further investigations on paste and concrete.

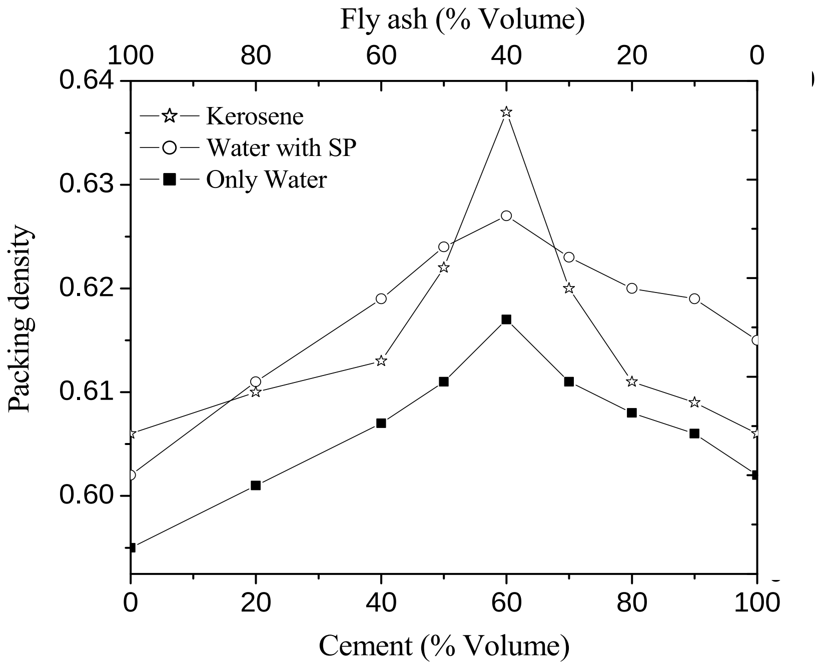


Fig. 4.3 Results of Puntke test for various combinations of cement and fly ash

To confirm whether the powder combination giving maximum packing density resulted in the best flow properties, the mini-slump spread of different powder combinations was determined with constant w/p ratio (1.0 by volume) and SP dosage (0.1 % bwoc). The results are shown in Table 4.1. From the results, it is observed that with increase in packing density, the spread of the cementitious paste increases and reaches a maximum (160 mm) for the combination (cement: fly ash = 60:40 by volume) giving maximum packing density. When the packing density decreases after reaching the maximum, correspondingly the spread also decreases, further resulting in bleeding. These results provide solid proof to select the powder combination giving maximum packing density for further investigations on the cementitious paste.

Table 4.1 Mini-slump spread for different combinations of cement and fly ash

Cement (volume)	Fly ash (volume)	SP (% bwoc)	Mini-slump (mm)	Remarks
100	0	0.1	138	No bleeding
80	20	0.1	140	No bleeding
70	30	0.1	155	No bleeding
60	40	0.1	160	No bleeding
50	50	0.1	156	No bleeding
40	60	0.1	-	Bleeding

4.3 OPTIMISATION OF SUPERPLASTICISER DOSAGE

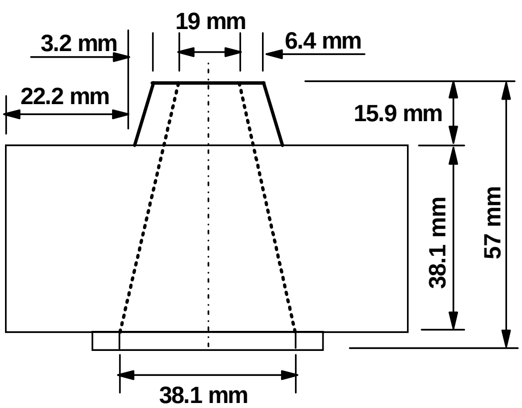
For the present study, a polycarboxylic ether based superplasticiser (SP) was used. The SP dosage was optimised by using the mini-slump test for different w/p ratio and the optimised dosage of SP was validated in SCC.

4.3.1 Cement Paste Preparation

The cement and fly ash combination of 60:40 by volume was selected for studies on the paste. The cementitious paste was prepared by using a planetary motion high shear (Hobart) mixer (ASTM C 305, 1999). Initially, the cement and fly ash were mixed in dry condition for homogenisation. After dry mixing, 80 % of the total water was mixed for 60 seconds at low speed (paddle - 140 ± 5 rpm, planetary motion - 62 ± 5 rpm) to make the powders wet so that the superplasticiser performed effectively. Then, the remaining water was added along with the superplasticiser and mixed for 60 seconds at low speed. Finally, the cementitious paste was mixed for 120 seconds at high speed (paddle - 285 ± 10 rpm, planetary motion – 125 ± 10 rpm). The total volume of paste prepared was 1 litre. The ambient temperature was 28 ± 1˚C. First, mini-slump test was performed after completion of mixing. Following that, the Marsh cone test and viscometric tests were done. All these tests were completed within 15 minutes of preparation of the paste.

4.3.2 Mini - Slump Test

For the optimisation of the SP dosage, mini-slump cone was used. The dimensions of the mini-slump cone are shown in Fig 4.4 a. A paste volume of 40 ml was taken and poured into the cone. The excess paste was removed by levelling the paste to the height of the cone and it was collected on the wide flange. Slight tapping was given on the flanges to release the entrapped air (if any). The mini-slump cone was lifted with a motion rapid enough without obstructing the flowing paste, but slow enough to avoid disturbing the paste. Subsequently, the spread of the paste was measured after 2 minutes (See Fig. 4.4 b). Paste tests with mini-slump cone were conducted for 5 different w/p ratios (0.8 to 1.2 by volume) by varying the dosages of SP. The dosage corresponding to a spread in the range 170 ± 10 mm, without bleeding (separation of water from the paste - see Fig. 4.5), was identified as the optimum dosage of the superplasticiser.



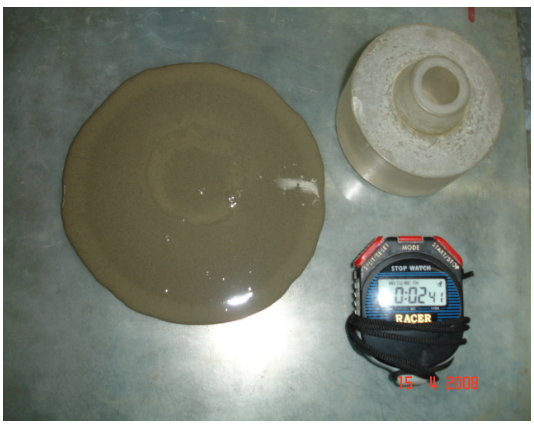


Fig. 4.4 (a) Mini-slump apparatus (b) Mini-slump spread (without bleeding)

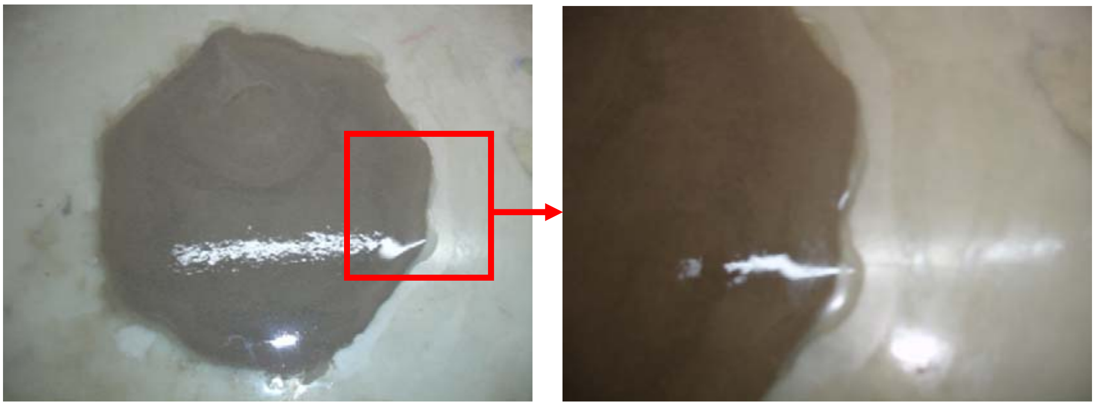


Fig. 4.5 Cementitious paste sample showing bleeding

4.3.3 Marsh Cone Test

The Marsh cone (Marsh, 1931) is an apparatus basically developed for measuring the viscosity of a liquid (see Fig. 4.6). The viscosity of the liquid is measured indirectly by measuring the flow time for certain amount of material flowing out of the cone. The procedure of Marsh cone test for the present study is as follows.

1. 800 ml of the cementitious paste was poured in the cone by closing the bottom nozzle (diameter 8 mm).
2. The paste was allowed to stabilise for 15 seconds
3. Then, the orifice was opened and the stop watch was started.
4. The time taken for 400 ml of the paste to fill the cylinder kept under the cone was noted down.

Longer the flow time, higher is the viscosity. Though the Marsh cone test was not used for optimising the SP dosage, experiments were conducted along with the viscometric studies to investigate the relationship with the rheological parameter (plastic viscosity). The results are discussed in detail in section 4.5.

Fig. 4.6 Marsh cone apparatus

4.3.4 Results and Discussions

The results shown in Fig. 4.7 indicate that for a given w/p ratio, fluidity increases with increase in SP dosage, and for a given SP dosage the paste fluidity increases with an increase in w/p ratio. This trend was observed until the optimum dosage. Beyond optimum dosage, no significant change in the flow was observed. Dosages above the optimum resulted in bleeding of the paste. The results of the optimum dosage for different w/p ratio (by volume) are shown in Table 4.2. The optimum dosage of the SP ranges from 0.12 to 0.21 % by weight of cementitious materials. It decreases with increase in w/p ratio from 0.8 to 1.2, as shown in Table 4.2.

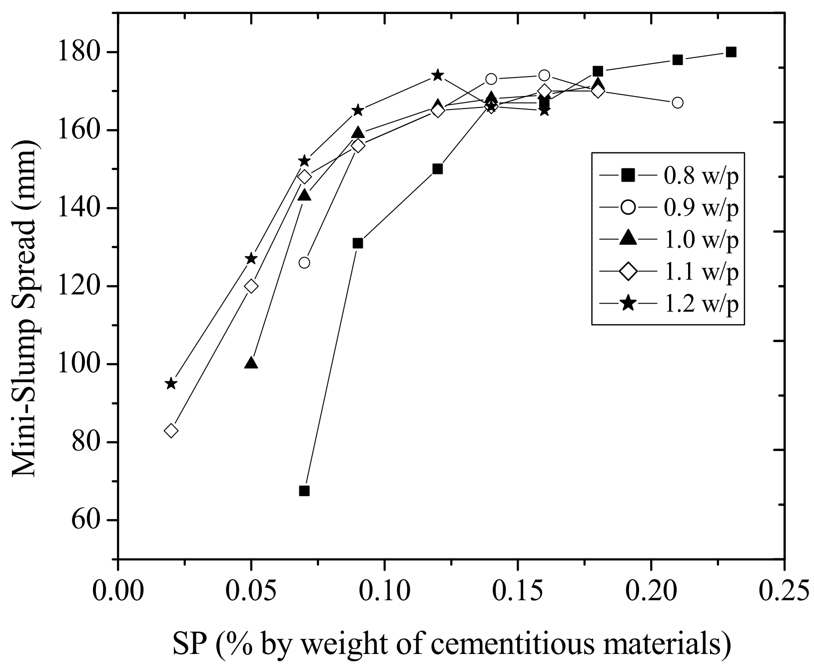


Fig. 4.7 Variation of mini-slump spread with SP dosage

Table 4.2 Optimum dosage of Superplasticiser

w/p ratio (volume)	Mini-Slump spread (mm)	Optimum dosage (% by weight of cementitious material)
0.8	178	0.21
0.9	170	0.18
1.0	169	0.16
1.1	166	0.14
1.2	174	0.12

4.3.5 Viscometric Studies

Viscometric studies were conducted to determine the rheological parameters of the cementitious paste, using a Brookfield HA DV II Pro Viscometer (Coaxial Cylinder type-smooth walled) (see Fig. 4.8a). The diameters of inner and outer cylinder are 11.76 mm and 19.05 mm respectively (see Fig. 4.8b). The effective length of the inner cylinder is 39.29 mm and the depth of the outer cylinder is 86.24 mm. The volume of the sample taken was 10.4 ml. In this study, the effect of wall slip was not considered.

Fig. 4.8 (a) Photograph of Viscometer (Coaxial Cylinder) (b) Photograph of inner and outer cylinder

It was decided to use the shear rate experienced by paste in the concrete. The maximum shear rates experienced in typical concrete processes like hauling, placing and casting are most likely between 1 and 100 s^{-1} (Saak *et al.*, 2001). Based on the above facts and considering the limitations of the viscometer, a shear profile was prepared as follows:

1. Preshearing from 0 – 30 s^{-1} in 60 s to erase the previous shear history of the paste due to mixing
2. 30 seconds pause to make the paste to stabilise
3. Ramping up shear rate from 0 to 60 s^{-1} in 105 seconds (data recording for every 15 seconds)
4. Ramping down from 60 to 0 s^{-1} in 90 seconds (data recording for every 15 seconds)

The schematic representation of the shear profile is given in Fig. 4.9.

The ramp down curve data was taken for the plot between shear stress and shear rate to determine yield stress (minimum stress required for flow) and plastic viscosity (governs the flow after it is initiated) of the cementitious paste by using Bingham model. The reason for considering the down curve is that in these flow conditions the thixotropic structure is entirely broken, which allows simpler and more reproducible results (Papo, 1988).

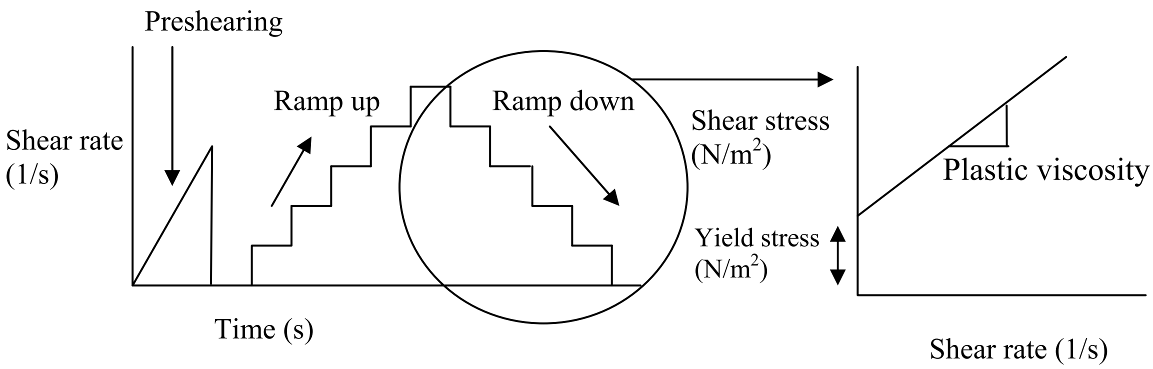


Fig. 4.9 Schematic representation of the shear profile of viscometric studies

Viscometric studies were conducted for pastes with optimum dosage of superplasticiser for different w/p ratio. The results are shown in Fig. 4.10.

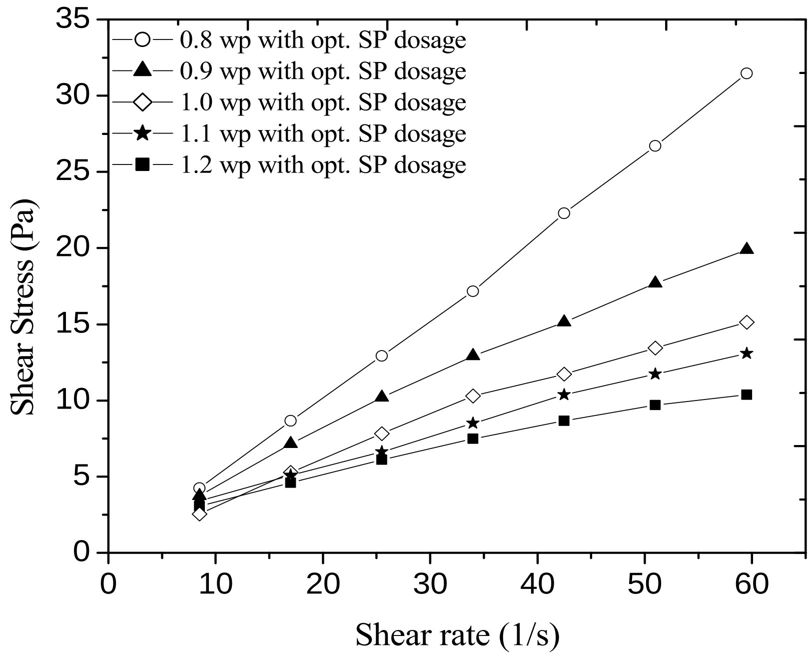


Fig. 4.10 Relationship between shear rate and shear stress for optimum SP dosage

As the w/p ratio (at the optimum dosage of SP) increases, the slope of the curve decreases, indicating significant decrease in the plastic viscosity from 533 mPa s (milli Pascal second) to 146 mPa s. This is attributed to the effect of increase in water content with increase in w/p. There was no significant effect on the yield stress (0 to 2.19 Pa) of the pastes with different w/p ratio. The rheological parameters for the various pastes are presented in Table 4.3.

Table 4.3 Rheological parameters for pastes with different w/p ratio

w/p ratio	Yield stress (Pa)	Plastic viscosity (m Pa s)
0.8	0	533
0.9	1.75	313
1.0	1.18	244
1.1	1.82	194
1.2	2.19	146

4.3.6 Validation of the Optimum Dosage of Superplasticiser in SCC

The optimum cement – fly ash combination, as well as optimum dosages of the SP for different w/p ratios determined in paste studies were validated in concrete. The aggregate and paste contents (388 litres/m^3- includes 20 litres of air) were maintained constant so that any change in the concrete would be a direct contribution of the composition of cementitious paste. The tests were done for different water powder ratios (0.8, 0.9, 1.0, 1.1, and 1.2 by volume). Fresh concrete tests such as slump flow and T_{500} were conducted for each w/p ratio, along with visual observation.

Table 4.4 Fresh concrete properties of SCC

w/p ratio (volume)	Powder content (kg/m^3)	Paste content (litres/m^3)	Slump flow (mm)	T_{500} (s)
0.8	550	388	555	6.0
0.9	521	388	600	5.0
1.0	495	388	600	4.0
1.1	472	388	590	1.9
1.2	450	388	580	1.0

From the results shown in Table 4.4, it is observed that the optimum dosage of the superplasticiser resulted in a slump flow range of 550 to 600 mm without segregation and time taken for 500 mm spread (T_{500}) ranged from 1 to 6 seconds for all the concretes. As per the consistency classification of the European guidelines (EFNARC, 2005), the fresh concrete conforms to the slump flow class SF1 and viscosity classes VS1 and VS2.

4.4 OPTIMISATION OF VISCOSITY MODIFYING AGENT DOSAGE

In the present study, a microbial polysaccharide based viscosity modifying agent was optimised. As explained in the previous section, the SP dosage was optimised by using mini-slump cone. For pastes with optimum SP dosage, the VMA dosage was optimised by using a new empirical method called “MARBLE TEST”.

4.4.1 Mixing Procedure

The cementitious paste was prepared by using a planetary motion (Hobart) high shear mixer. The mixing procedure is given in Table 4.5. The total volume of the paste prepared was 1 litre. The ambient temperature was 28 ±1˚C. After mixing the paste, the newly developed Marble test was performed. Subsequently, the viscometric tests were conducted. All these tests were completed within 15 minutes of mixing.

Table 4.5 Mixing procedure of cementitious paste

Step	Activity	Duration (seconds)	Speed*
1	Dry mixing of cement and fly ash for homogenisation	120	1
2	Add 80 % total water	60	1
3	Clean the side walls	15	
4	Add 20 % water + SP	60	1
5	Clean side walls	15	
6	Add VMA (sprinkle evenly)	15	
7	Mixing	60	1
8	Clean side walls	15	
9	Final mixing	120	2

*Speed 1 – paddle = 140 ± 5 rpm and planetary motion = 62 ± 5 rpm

Speed 2 – paddle = 285 ± 10 rpm and planetary motion = 125 ± 10 rpm

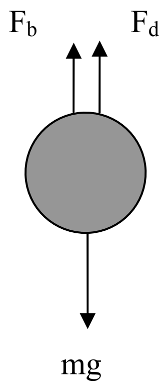
4.4.2 Marble Test - Principle

For the optimisation of VMA dosage, a new empirical test method called marble test was developed. When a spherical body is suspended in a fluid medium, three forces act on it (see Fig. 4.11 a). The first two forces arise from the buoyancy effect of the displacing paste and from the viscous drag of the paste on the sphere. Both the forces act upwards – Buoyancy (F_b) tending to float the sphere and the drag force (F_d) resisting the acceleration due to gravity (Daugherty *et al.*, 1985). The only force acting downwards is the force resulting from the gravitational attraction (mg, where m = mass of the sphere and g = acceleration due to gravity). For equilibrium:

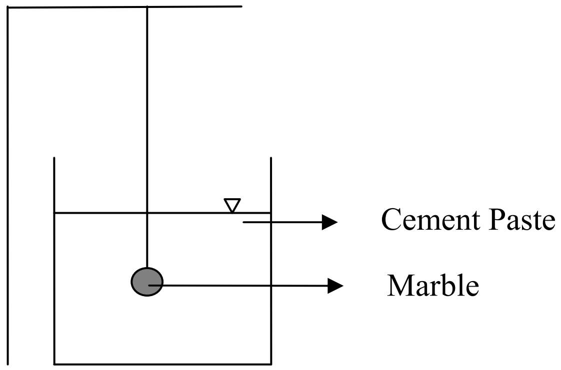
$$F_b + F_d = mg \tag{4.2}$$

Among these forces, the buoyancy force and the force due to gravitational attraction remain constant. Therefore, the variation in viscous force alone is responsible for the movement of the marble in the cementitious paste. The VMA influences the viscosity of the cementitious paste. From this, it is evident that the change in viscosity of the paste due to change in VMA dosage can be determined by the marble test. This is done by measuring the depth of penetration of the marble.

Initially at low dosages of VMA, the marble will settle down due to low viscosity of the paste. As the percentage of VMA increases, the viscosity of the paste increases. As a result, the cement paste will have the capability of lifting and holding the glass marble without settling down. The new method developed is simple, effective and easy to handle in laboratories and construction sites.



(a)



(b)

(c)

Fig. 4.11 (a) Free body diagram of a sphere suspended in a liquid medium
(b) Schematic representation of the marble test set up
(c) Photograph of the marble test set up

Marbles were chosen instead of aggregates due to their simple shape, and similar specific gravity. Aggregates pose complications owing to their irregular shape and orientation; furthermore, there is the experimental difficulty of reusing the same aggregates for all experiments. It was decided to use glass marbles of size closest to the maximum size of the aggregates for the studies (18 mm diameter).

4.4.3 Marble Test - Procedure

The apparatus consists of a beaker (1000 ml capacity), glass marble (Specific gravity - 2.51, diameter - 18 mm) tied with nylon wire and a stand to hold the nylon wire (See Fig. 4.11 b and 4.11 c). The size of the glass marble should be equal to or close to the maximum size of the aggregate used. The beaker is filled with about 800 ml of cement paste. The surface of the glass marble is wiped with a wet cloth each time before doing the experiment. Then by careful means, the nylon wire is held and the glass marble is placed just over the paste and released. Depending upon the viscosity of the paste, the glass marble will move down in the paste. After a time lapse of 4 minutes (when the downward movement is almost imperceptible) the height of immersion of the marble is measured. The height of immersion of the marble is obtained by measuring the height of the paste adhering to the nylon thread up to the bottom of the marble. The experiment is repeated by varying the dosage of the VMA. The optimum dosage of VMA for different w/p ratio is determined from the plot between the penetration depth and the VMA dosage. The optimum dosage is the dosage above which the cementitious paste starts to resist the downward movement of the marble.

4.4.4 Results and Discussions

The marble test was done for the different w/p ratios with optimum SP dosage by varying the VMA dosage. The optimum dosage of VMA for different w/p ratio was determined from the plot between the penetration depth and the VMA dosage (see Fig. 4.12). The optimum dosages are encircled in Fig 4.12. It should be noted that using the current set up, the fully stretched nylon wire with the glass marble corresponds to a depth of penetration of 82 mm. The results of the optimum dosage of

VMA are shown in Table 4.6. As expected, more VMA was required for stabilisation at higher w/p ratios.

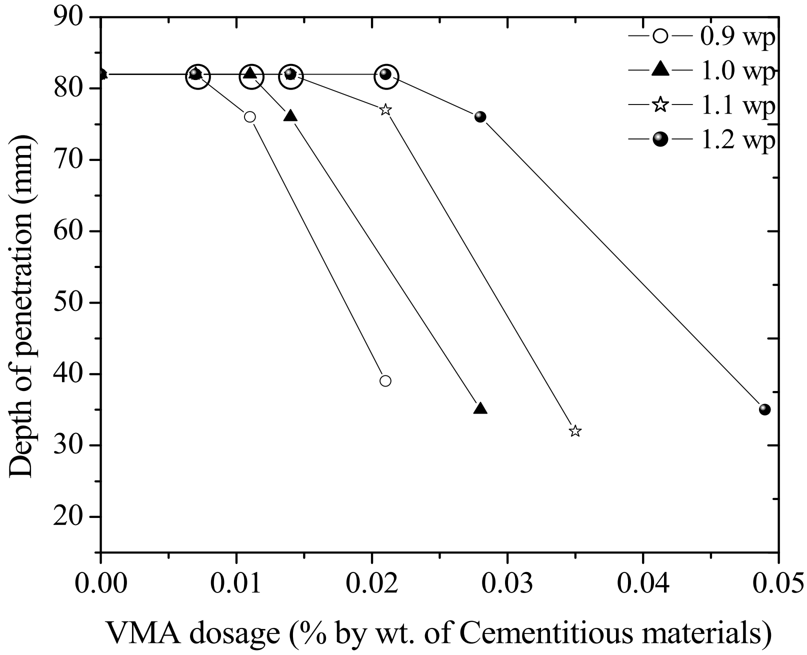


Fig. 4.12 Depth of penetration of the marble (Diameter -18 mm) for different w/p ratio (Note: the optimum dosages are encircled)

Table 4.6 Optimum dosage of VMA

w/p ratio (volume)	Opt. SP dosage (% bwoc)	Opt. VMA dosage (% bwoc)
0.9	0.14	0.007
1.0	0.16	0.011
1.1	0.18	0.014
1.2	0.21	0.021

4.4.5 Viscometric Studies

Viscometric studies were conducted to explore the rheological changes due the addition of VMA, which has a direct influence on the viscosity of the paste. A detailed description about the viscometer and the shear profile is given in section 4.3.5. Viscometric studies were conducted for pastes with optimum dosage of superplasticiser by varying VMA dosage for each w/p ratio. For each paste, the rheological parameters – yield stress and plastic viscosity were determined. Fig. 4.13 shows the relationship between the shear stress and shear rate for the pastes with optimum dosage of VMA.

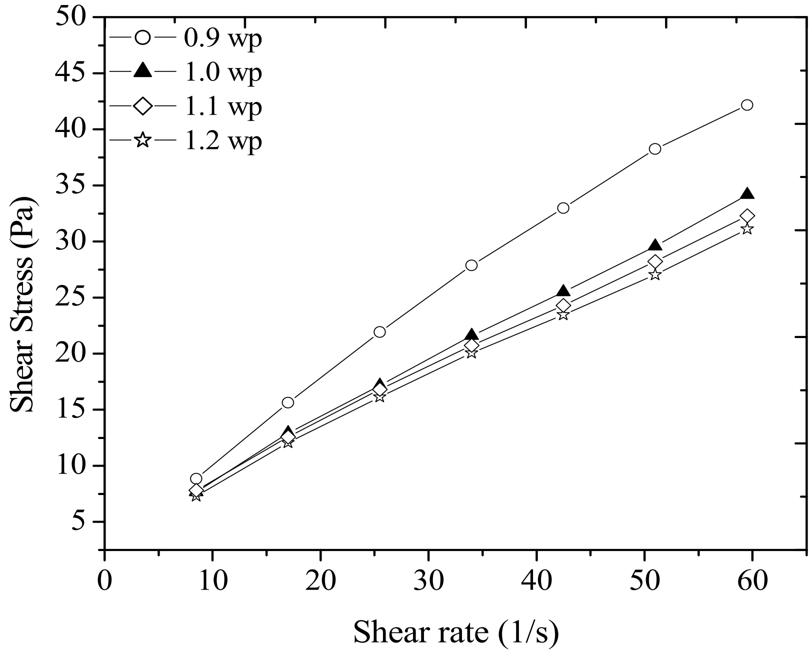


Fig. 4.13 Relationship between shear stress and shear rate for optimum VMA dosage

As the w/p ratio increases, the slope of the curve decreases indicating a decrease in the plastic viscosity of the paste. However, there was no significant effect of w/p ratio on the yield stress of the pastes. The rheological parameters (yield stress and plastic viscosity) for the cementitious pastes containing optimum dosage of VMA are given in Table 4.7.

Table 4.7 Rheological parameters of the optimised cementitious paste

w/p ratio (volume)	Optimum VMA dosage (% by weight of cementitious materials)	Yield stress (Pa)	Plastic Viscosity (mPa s)
0.9	0.007	4.493	656
1.0	0.011	3.910	510
1.1	0.014	4.371	471
1.2	0.021	4.080	456

Figure 4.14 depicts the relationship between the yield stress and VMA dosage. It is observed that the yield stress increases with increase in VMA dosage for a given w/p ratio. For a given VMA dosage, the relation between yield stress and w/p ratio is not clear, specifically at lower dosages of VMA. Figure 4.15 shows the relation between plastic viscosity and VMA dosage. It is clear that with increase in VMA dosage, the plastic viscosity increases for given w/p ratio. This could be attributed to the fact that the VMA increases the viscosity of the water, in turn increasing the viscosity of the paste. For a given VMA dosage, the viscosity increases with decrease in w/p ratio. In general, the yield stress varied from 2 Pa to 12 Pa and the plastic viscosity varied from 250 mPa s to 1500 mPa s with increase in the VMA dosage.

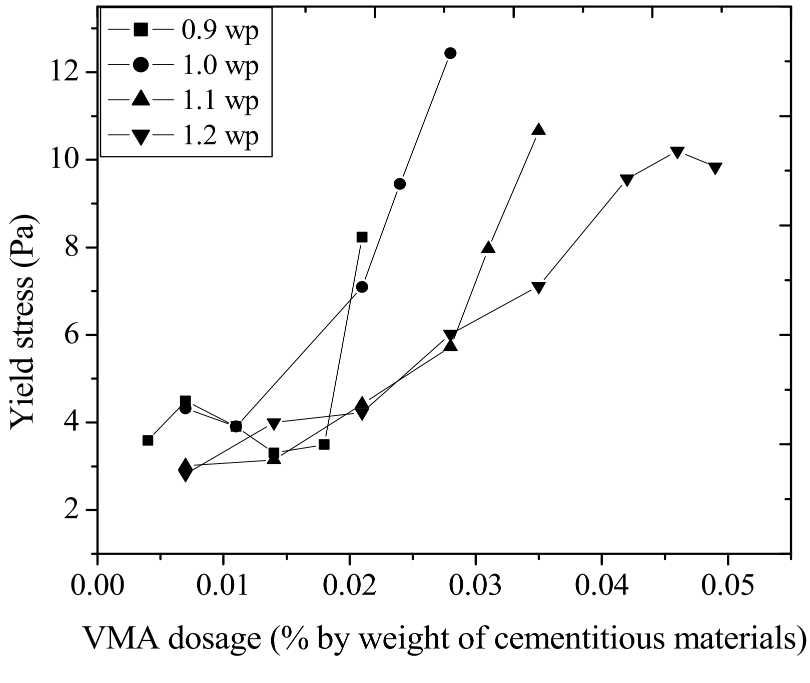


Fig. 4.14 Effect of VMA dosage on yield stress of cementitious paste for different w/p ratio

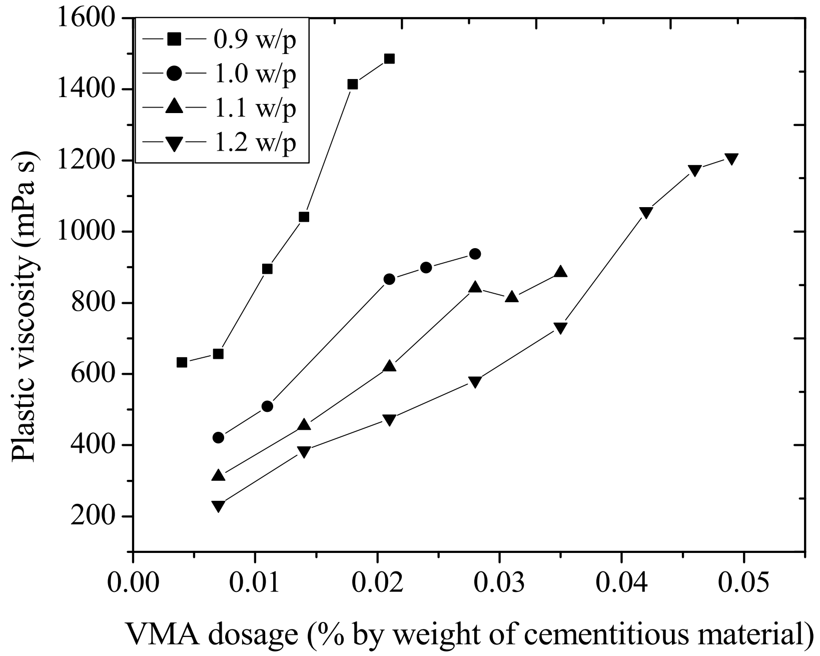


Fig. 4.15 Effect of VMA dosage on plastic viscosity of cementitious paste for different w/p ratio

Fig. 4.16 plots the rheological parameters for all the pastes. The plastic viscosity of the pastes with optimum dosage of VMA at different w/p ratios is in the range of 456 to 656 mPa s.

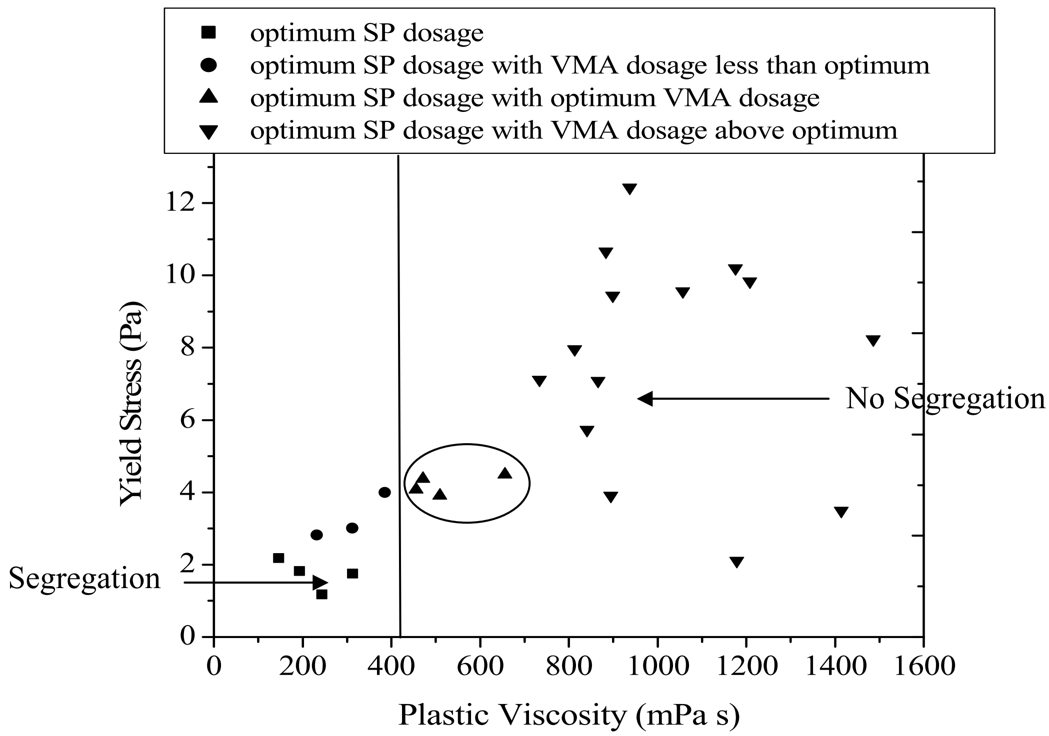


Fig. 4.16 Rheological parameters for all pastes

4.4.6 Validation of the Optimum Dosage of VMA in SCC

The optimum dosage of the VMA determined from the cementitious pastes was validated by conducting experiments on self-compacting concrete. For validation of the optimum dosage of VMA, 4 mixes with different water powder ratios (0.9, 1.0, 1.1, and 1.2 by volume) that segregated were selected. Generally, segregation of SCC mixtures depends on the water content (approximately ≥ 220 litres) and proportion of fine aggregate (approximately less than 40 % by volume of the total aggregate content). The proportions for the selected SCC mixtures are presented in Table 4.8. The slump flow, T_{500} and sieve segregation tests were conducted for each mixture. For validation, the sieve segregation test was performed according to European guidelines (EFNARC, 2005).

The sieve segregation test consists of 4.75 mm sieve with a pan and a weighing machine. The fresh SCC (10 ± 0.5 litres) was allowed to stand for 15 minutes in a bucket with lid without any disturbance and any separation of water was noted down. Approximately 5 kg of concrete was poured at the centre on the top of the 4.75 mm sieve with a pan underneath to receive the concrete passing through the sieve and allowed it to stand for 2 minutes. The segregation resistance was measured by ratio of weight of the concrete in the pan to the weight of the concrete poured on the sieve. The set up of the test is shown in Fig. 4.17. From the results, it was observed that, with optimum VMA dosage for all the w/p ratios (the data points are encircled in Fig. 4.16), the measured segregation is less than 20 %, indicating that the SCC conforms to class SR1 of EFNARC guidelines. Dosages lower than the optimum were not sufficient enough to control the segregation in concrete (the corresponding rheological parameters of the paste are in the left part of Figure 4.16). On the other hand, higher dosages (right part of Figure 4.16 for the corresponding rheological parameters of the paste) resulted in reduced slump flow of concrete. The fresh concrete test results are presented in Table 4.8.

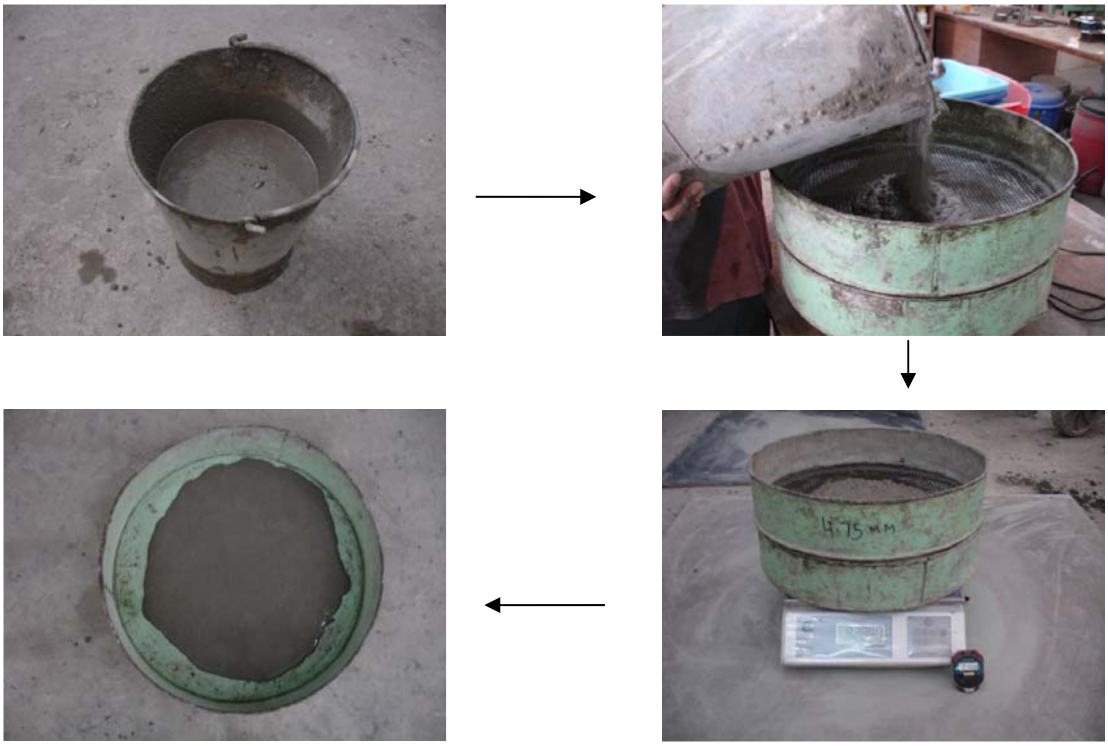


Fig. 4.17 Sieve segregation test

Table 4.8 Mixture proportions of the selected SCCs

Ingredients	0.9 w/p	1.0 w/p	1.1 w/p	1.2 w/p
Cement (kg/m^3)	457	386	386	387
Fly ash (kg/m^3)	193	163	163	164
Water (kg/m^3)	217	204	225	245
Paste volume (litres/m^3)	479	429	449	470
River sand (kg/m^3)	669	441	708	681
Coarse aggregate- max. size 12.5 mm (kg/m^3)	292	641	309	297
Coarse aggregate- max. size 20 mm (kg/m^3)	435	477	460	442
SP dosage (% bwoc)	0.18	0.16	0.14	0.12
VMA dosage (% bwoc)	0.007	0.011	0.014	0.021
Sieve Segregation (%)	19.97	19.80	19.87	19.68
Slump flow (mm)	790	740	690	680
T_{500} (s)	2.09	1.97	1.56	0.44
V Funnel (s)	26.91	14.94	10.60	6.44

4.5 CORRELATION BETWEEN RHEOLOGICAL AND EMPIRICAL PARAMETERS

Rheological parameters (yield stress and plastic viscosity) are determined by using rheometers and viscometers which are expensive and widely differ in size of the sample, rotational geometries, calibrations and computational procedures. As a result, simple test methods that are just extensions of available workability methods were proposed by the researchers (Kantro, 1980; de Larrard *et al.*, 1997). While the sophisticated rheometers are well suited for research purposes for designing advanced concrete mixtures in laboratories (Wallevik, 2006), for everyday quality control, simple tests are needed that allow the user to indirectly evaluate the fundamental rheological parameters (de Larrard 1999). No single empirical method or a combination of methods has achieved universal approval (Mahesh and Santhanam, 2004). Hence, there is a need to understand the link between rheological parameters (as determined from rheometer studies) and results of the laboratory based test methods (Walraven 2003).

In the present investigation, experiments were conducted to determine both rheological and empirical parameters for cementitious pastes with different w/p ratios. The rheological parameters of the paste were measured using a viscometer (Section 4.3.5 and 4.4.5) and the empirical parameters – spread and flow time – were measured using Mini-slump cone and Marsh cone (Section 4.3.2 and 4.3.3) respectively. To understand the link between the rheological and empirical parameters, various graphs were plotted. From Fig. 4.18, it is observed that as the mini-slump spread increases, the yield stress decreases. Therefore, it is evident that there exists a good correlation between yield stress and spread. This is in agreement with the trends observed in the literature (Roussel *et al.*, 2005a; Saak *et al.*, 2004). However, there is no clear relationship between the yield stress and flow time (see Fig. 4.19) Fig. 4.20 indicates that as the spread increases, plastic viscosity decreases, and from Fig. 4.21, it is clear that as the flow time increases, the plastic viscosity increases. From this, it is evident that both spread and flow time have a good correlation with the plastic viscosity. The graphs (Fig. 4.18 to Fig. 4.21) were plotted to understand the relationship between the empirical parameters and the rheological parameters which will help in better understanding of the behaviour of the cementitious paste for variation in the dosages of the chemical admixtures. From the results, it is evident that these empirical apparatus can be used with confidence as they are well correlated with rheological measures. However, the relationships (best fit equations) obtained from the experiments cannot be generalised (as they are specific to the materials used).

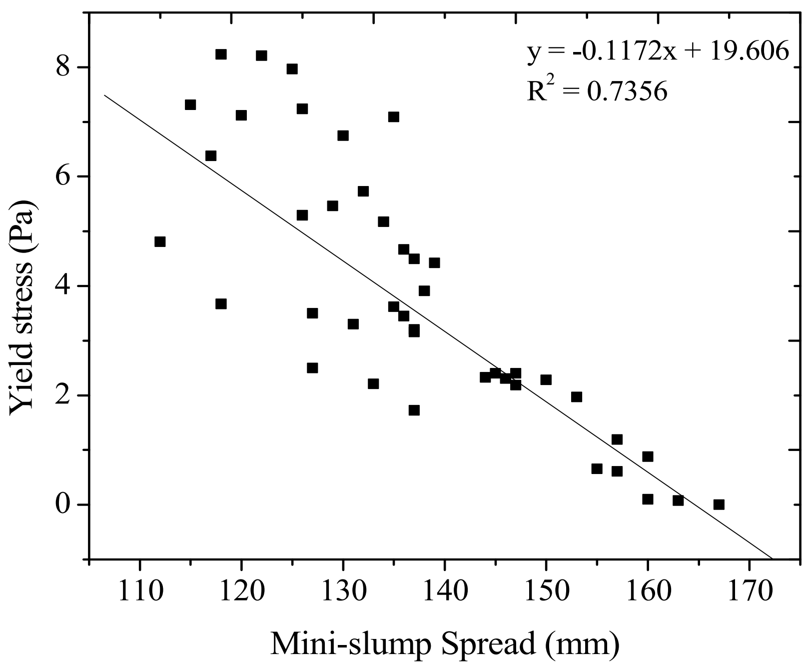


Fig. 4.18 Relationship between yield stress and mini-slump spread

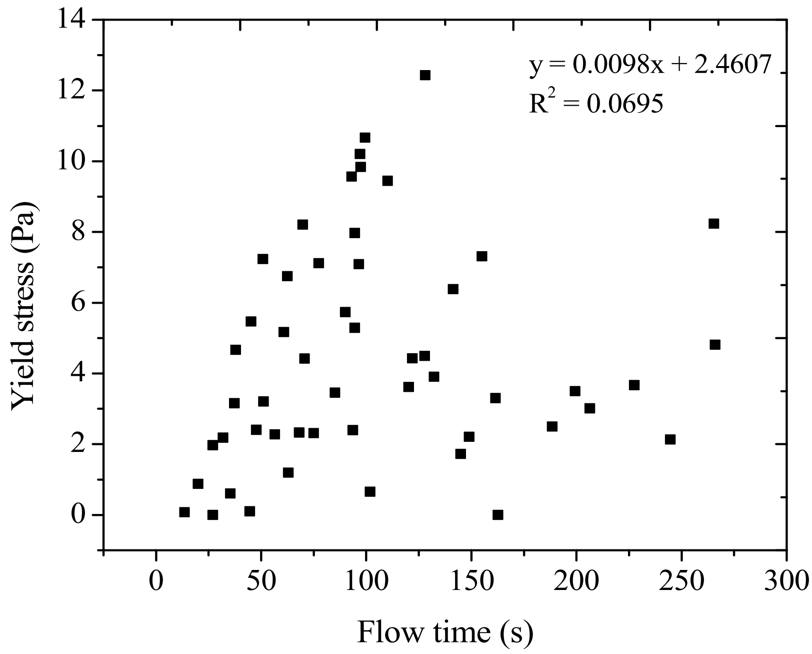


Fig. 4.19 Relationship between yield stress and flow time

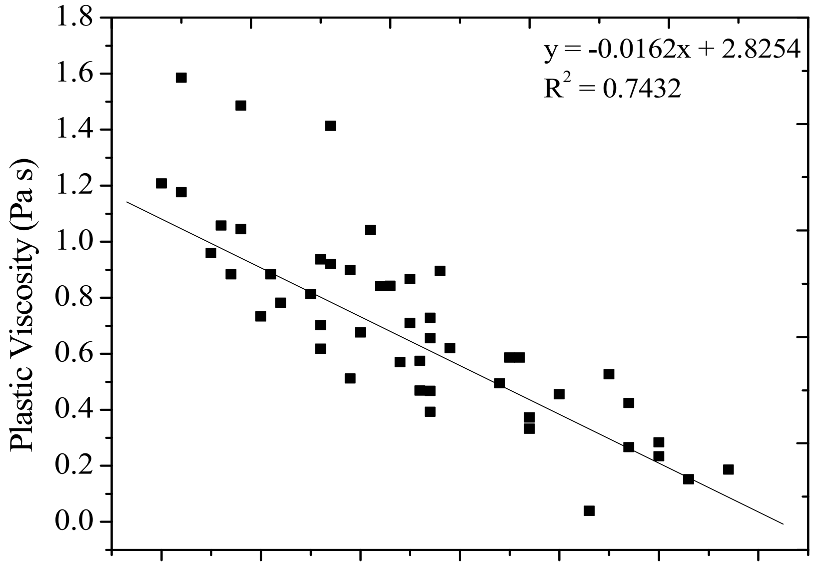


Fig. 4.20 Relationship between plastic viscosity and mini-slump spread

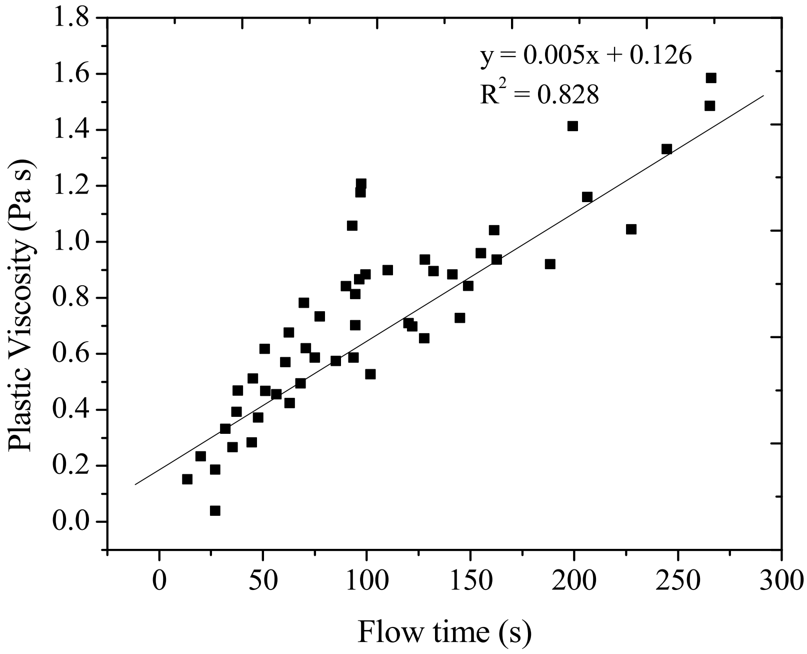


Fig. 4.21 Relationship between plastic viscosity and flow time

4.6 SUMMARY

The first part of the chapter describes the method for the optimisation of powder (cement and fly ash) combinations based on the concept of packing density. Puntke test was used for the calculation of the packing density of powders. The powder combination of 60:40 (cement: fly ash) results in a maximum packing density. This combination was selected for further investigations in the cementitious paste.

With the optimised combination of powders, the optimisation of the dosage of chemical admixtures (superplasticiser (SP) and viscosity modifying agent (VMA)) for different w/p ratio was carried out. Polycarboxylic ether was used as SP and mini-slump cone was used for the optimisation of the SP dosage for different water powder ratio. The proposed criterion for the optimisation of SP dosage was that the paste should have a spread of 170 ± 10 mm without bleeding. The optimum dosage of the SP for different w/p was validated in SCC. The paste volume (388 litres/m^3) and aggregate combinations were kept constant. As per the consistency classification of the European guidelines (EFNARC), the fresh concrete conformed to the slump flow class SF1 and viscosity classes VS1 and VS2.

A microbial polysaccharide was used as VMA. The VMA dosage is optimised by using the Marble test. Experiments were conducted for different VMA dosage. The dosage above which the cementitious paste starts to resist the downward movement of the marble was identified as the optimum dosage. The optimum dosage of VMA was validated in SCC by sieve segregation test. With optimum VMA dosage for all the w/p ratios, the measured segregation was less than 20 %, indicating that the SCC conformed to class SR1 of EFNARC guidelines. Dosages lower than the optimum were not sufficient enough to control the segregation in concrete. On the other hand, higher dosages resulted in reduced slump flow of concrete.

This was followed by a discussion of the viscometric studies conducted to evaluate the effect of the chemical admixtures on the rheological properties of the cementitious paste. As stated earlier, the rheometers and viscometers are well suited for laboratories; however, in practical construction sites simple apparatus are used. Therefore, it is essential to understand the link between the empirical parameters (spread and flow time) and the rheological parameters (yield stress and plastic viscosity). The last part of the chapter explains the relationship between the empirical and the rheological parameters. From the results, it can be concluded that the empirical measures can be used with confidence in the absence of rheological measurement.

CHAPTER 5

OPTIMISATION OF AGGREGATE COMBINATIONS BASED ON PACKING DENSITY AND ITS INFLUENCE ON THE SCC PROPERTIES

5.1 INTRODUCTION

As stated in Chapter 2 (Section 2.4.3), the packing of aggregates has a significant influence on fresh and hardened concrete properties. The first part of the chapter describes experiments that were conducted to measure the packing density for different combinations of aggregates precisely. Additionally, the relationship between packing density and particle size distribution is also addressed. This is followed by the investigations on the influence of packing density of the aggregates on the fresh and hardened concrete properties of self-compacting concrete.

5.2 TERNARY PACKING DIAGRAM

5.2.1 Materials Used

In the present investigation, two different sizes of coarse aggregates (Crushed Granite – maximum sizes 12.5 mm and 20 mm) and a fine aggregate (River sand) were used. The physical properties and the particle size distribution of the aggregates are given in Chapter 3 (Table 3.3 and 3.4).

5.2.2 Test Set up for the Determination of Packing Density of Aggregates

The packing density of the aggregates was determined experimentally, using a modified version of the test procedure described in ASTM C 29 (2001). Generally, when aggregates are mixed and poured into a container by using scoop or shovel, two types of subjectivity are encountered during the measurement of packing density. The height from which the aggregates are poured and the method of pouring may lead to error in the measurement of the packing density. The error due to the subjectivity in measuring the packing density is completely eliminated by using the method developed in this study.

Fig. 5.1 shows the test set up for determining the packing density of aggregates. It consists of a steel bucket with a top diameter of 340 mm, bottom diameter of 140 mm, and height of 310 mm. A tightly fitting hinged trap door is provided at the bottom of the bucket with a quick release catch to guide the falling of aggregates. The bucket rests on a stand. A cylindrical container of diameter 270 mm (maximum size of the aggregate was 20 mm) with a capacity of 10 litres was used for receiving the aggregates falling from the steel bucket. The dimensions of this container were selected to avoid wall effects and related variations (literature suggests that the cylinder diameter should be more than 10 times the maximum size of aggregates) (Johansen and Andersen 1991). The distance from the bottom of the steel bucket to the top of the cylindrical container was 200 mm.

Fig. 5.1 Test set up for determining the packing density of aggregates

5.2.3 Test Procedure for the Determination of the Packing Density of Aggregates

The experimental procedure for the determination of the packing density of aggregates is as follows.

Step 1: A mass equivalent of 12 litres of coarse aggregates (12.5 mm max. size and 20 mm max. size) and river sand was taken according to the corresponding volume proportions in separate plastic trays (see Fig. 5.2 a)

Step 2: The three type of aggregates were mixed manually for obtaining a proper blend (see Fig. 5.2 b)

Step 3: The mixed aggregates were poured into the steel bucket without any compaction. The bottom door of the steel bucket was then opened to make the aggregates fall instantaneously into the bottom container.

Step 4: The excess aggregates remaining above the top level of the bottom cylinder were struck off. From the portion of aggregates removed, the mass of each aggregate type was calculated based on the proportions taken. This mass was deducted from the original mass of corresponding aggregate type taken to determine the exact quantity of individual aggregates filled in the bottom container.

Knowing the mass of the individual aggregate type added and the volume of the container, the void content was calculated. The packing density of the aggregates was calculated from the void content. The equations for calculating the void content and packing density are as follows:

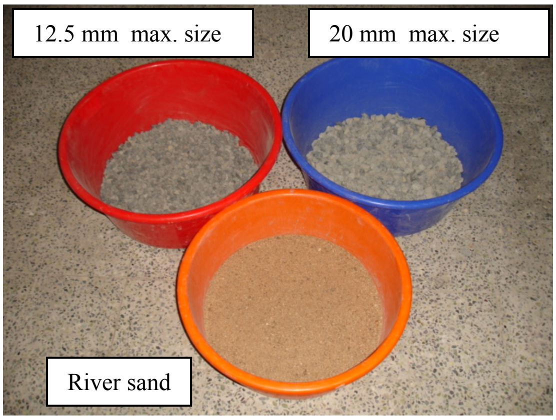
$$\text{Void content} = (V_c - ((M_1 / S_1) + (M_2 / S_2) + (M_3 / S_3))) / V_c \quad (5.1)$$

where V_c = Volume of the container

M_1, M_2, M_3 = Mass of each aggregate type

S_1, S_2, S_3 = Specific gravity of corresponding aggregate type

$$\text{Packing density} = 1 - \text{void content} \quad (5.2)$$



(a)


(b)

Fig. 5.2 (a) Photograph of coarse and fine aggregates separately

(b) Photograph of coarse and fine aggregates after proper blending

5.2.4 Development of Ternary Packing Diagram (TPD)

Experiments were conducted for different proportions (by volume) of aggregates. 24 different combinations of aggregates were selected in order to cover a wide range of ternary proportions (see Fig. 5.3). Based on equations 1 and 2, the packing density of the aggregates was determined; the packing densities are reported in Table 5.1.

As 24 data points are inadequate for developing a ternary packing diagram, interpolation was performed to generate additional data points, using radial basis function, and in particular, the norm function (Wenland, 2005).

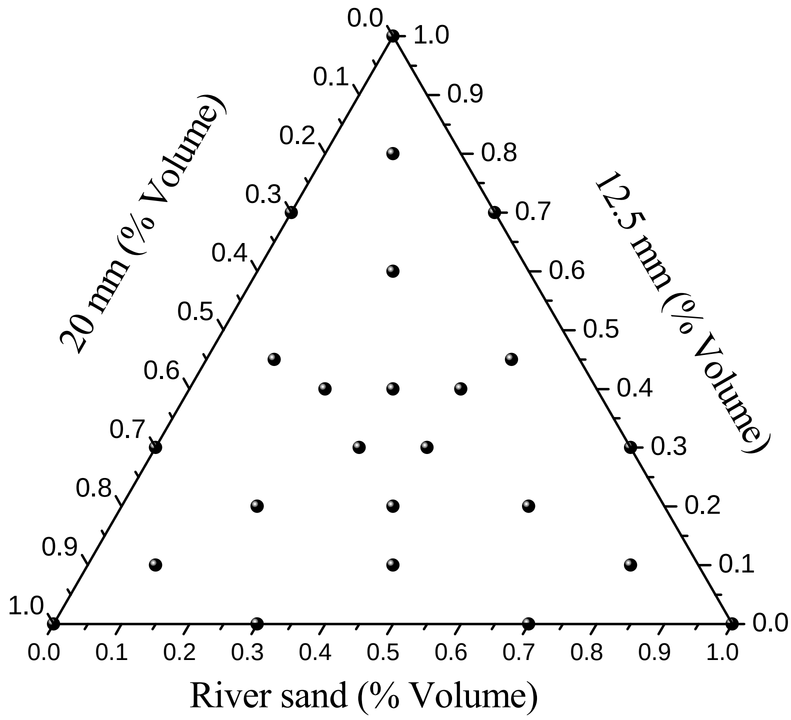


Fig. 5.3 Experimental points for packing density determination

Each experimental coordinate was represented as a vector in three dimension space, i.e.,

$$X = (x_1, x_2, x_3) \tag{5.3}$$

where x_1 = proportion of fine aggregate by volume

x_2 = proportion of 12.5 mm coarse aggregate by volume

x_3 = proportion of 20 mm coarse aggregate by volume

The norm function is represented by

$$\|X\| = \|(x_1, x_2, x_3)\| = (\sqrt{(x_1^2 + x_2^2 + x_3^2)})^r \tag{5.4}$$

where r = constant

The interpolation matrix A was formulated from

$$A_{ij} = \|(X_i - X_j)\|^r, 1 \leq I \leq 24, 1 \leq j \leq 24 \tag{5.5}$$

where X_i represents the i^{th} experiment.

The interpolating coefficients c_j were determined by solving the equation

$$C = (c_1, c_2 \ldots c_{24}) = A^{-1}B \tag{5.6}$$

where $B = (b_1, b_2, b_3 \dots b_{24})$

b_i represents the packing density of corresponding experimental coordinate X_i, $1 \le i \le 24$.

The packing density of the required combination of aggregates $Z = (z_1, z_2, z_3)$ can be determined by the following equation:

$$\text{Packing density of the required combination} = \sum_{j=1}^{24} c_j \left\| z - x_j \right\|^r \qquad (5.7)$$

Table 5.1 Proportions of aggregates with corresponding packing density

Fine aggregate (% volume)	12.5 mm max. size (% volume)	20 mm max. size (% volume)	Packing Density
100.00	0.00	0.00	0.61
70.00	0.00	30.00	0.67
30.00	0.00	70.00	0.67
0.00	0.00	100.00	0.54
0.00	30.00	70.00	0.55
0.00	70.00	30.00	0.58
0.00	100.00	0.00	0.52
30.00	70.00	0.00	0.63
70.00	30.00	0.00	0.65
80.00	10.00	10.00	0.65
60.00	20.00	20.00	0.68
45.00	45.00	10.00	0.67
45.00	10.00	45.00	0.68
40.00	40.00	20.00	0.65
40.00	30.00	30.00	0.66
40.00	20.00	40.00	0.68
30.00	40.00	30.00	0.64
30.00	30.00	40.00	0.67
20.00	60.00	20.00	0.61
20.00	40.00	40.00	0.62
20.00	20.00	60.00	0.62
10.00	80.00	10.00	0.56
10.00	45.00	45.00	0.56
10.00	10.00	80.00	0.61

In this case, the value of n = 3 (River sand, 12.5 mm aggregate, 20 mm aggregate) and r = 1.99. This norm function was used in a MATLAB program (Refer Appendix A), for determining the packing density of several other combinations to get adequate data for developing the ternary packing diagram. The final ternary packing diagram is presented in Fig. 5.4

The maximum packing density obtained was 0.68 and the minimum packing density was 0.54. From Fig. 5.4, it is clear that the higher packing density contours are localised in the portion where the 12.5 mm maximum size aggregates are lower in quantity. In other words, 20 mm maximum size aggregates and the fine aggregates play a dominant role in determining the packing density of aggregates. This is in agreement with available literature (McGeary, 1961).

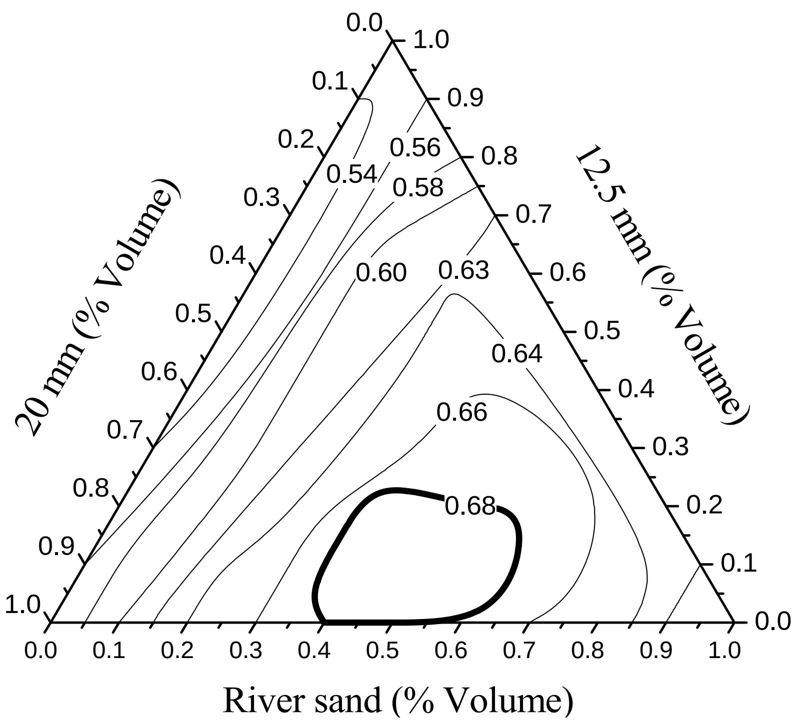


Fig. 5.4 Ternary packing diagram of the aggregates

For validation of the interpolated data, different combinations were chosen randomly and experiments were conducted. The precision for interpolated packing density is approximately ± 2 %. This means that for a correct value of 0.63, an interval of 0.62 to 0.64 can be expected.

5.3 MAPPING PARTICLE SIZE DISTRIBUTION TO THE PACKING DENSITY OF AGGREGATES

5.3.1 Empirical Relationship for Packing Density of Aggregates

The developed Ternary Packing Diagram (TPD) shown in Fig. 5.4 is suitable for Ready Mixed Concrete (RMC) plants and large scale construction sites having batching plants. However, for an individual user, developing TPD is not a viable solution. Therefore, an attempt was made to establish an empirical relationship between the packing density of aggregates and the particle size distribution (PSD) of the aggregates. Among the parameters which influence the packing density, particle size distribution is significant. A well known parameter in the field of soil mechanics, called the coefficient of uniformity (C_u), was chosen as the parameter for expressing the particle size distribution of the aggregates. C_u expresses the gradation of the particle sizes qualitatively. In other words, it indicates how well the particles are graded. Larger the C_u value, wider the range of particles (Arora 2004). As the range of particle sizes dictates the packing density of the particles, it was decided to use C_u for further investigations. C_u is calculated by using the following formula:

$$C_u = D_{60}/D_{10} \quad (5.8)$$

where D_{60} implies 60 % of the particles are finer than this size

D_{10} implies 10 % of the particles are finer than this size

From the particle size distribution of individual aggregates, the PSD for different combined proportions of aggregates was calculated. For each PSD, the D_{60} and D_{10}

were determined to calculate the C_u value. The corresponding packing density was determined from the ternary packing diagram shown in Fig. 5.4.

From the plot between C_u and packing density of aggregates (Fig. 5.5), it is observed that there exists a good correlation between these two parameters. As the C_u value increases, the packing density of the aggregates increases. This could be attributed to the fact that as the C_u value increases the range of particles sizes increases and helps in better packing of aggregates.

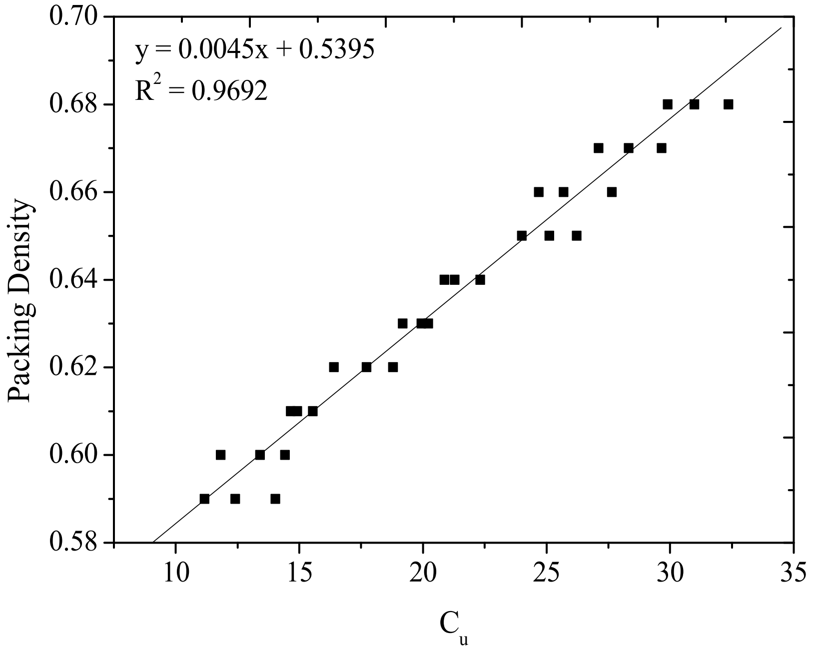


Fig. 5.5 Relationship between C_u and packing density of aggregates

The following empirical relationship is proposed based on the results obtained (see Fig. 5.5):

$$\text{Packing density} = 0.0045\ C_u + 0.5395 \qquad (5.9)$$

5.3.2 Procedure for Calculation of Packing Density of Aggregates Using the Proposed Relationship

From the experimentally determined PSD of individual aggregates, the PSD of any number of aggregate combinations can be calculated mathematically. For each of these combinations, the corresponding C_u value can be obtained by using equation 5.8. The proportion of aggregates having maximum C_u value can be selected for mixture design; the corresponding packing density can be calculated using equation 5.9. The packing density gives an idea of the voids content, which indicates the minimum amount of paste required to complete the volume of concrete. Beyond this stage, the user would only have to determine the paste composition (w/c, cement replacement by mineral admixture etc.). The paste content in excess of the voids content can be decided based on the desired level of workability – trials can be conducted to ascertain this aspect.

5.3.3 Effect of Different Proportions of Aggregates Having Same Packing Density (0.68) on C_u

The studies were further extended to investigate the influence of C_u on the aggregate proportions having same packing density. Nine sets of proportions giving a maximum packing density of 0.68 were selected from the ternary packing diagram (see Fig. 5.4). The combinations having fine aggregate content greater than or equal to 60 % (by volume), and less than 35 %, were discarded for analysis, as they are unrealistic for concrete (ACI 211, 2002; EFNARC, 2005, IS 10262, 2004). Fig. 5.6 shows the C_u values determined for different aggregate combinations with the same packing density of 0.68. It is evident that there is no significant variation in the C_u for different aggregate proportions having same packing density.

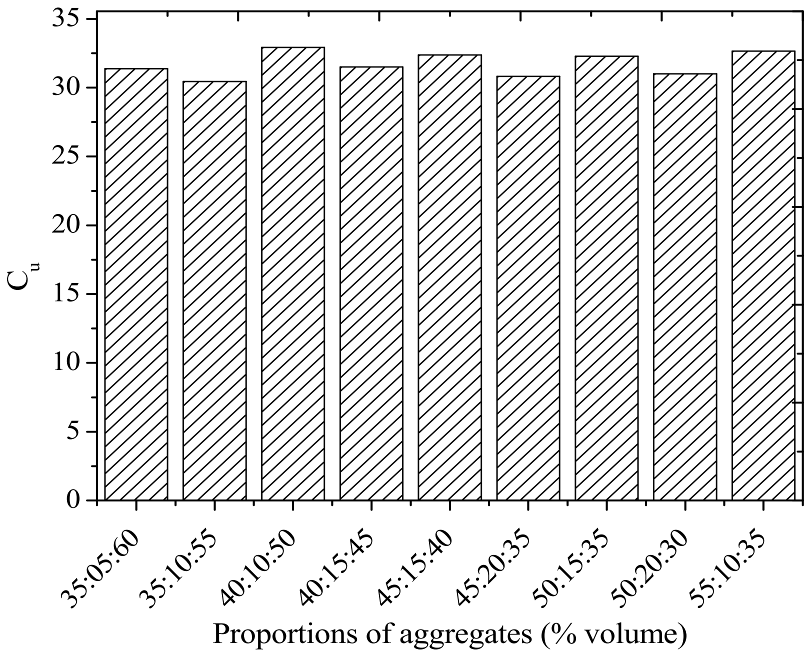


Fig. 5.6 Relationship between C_u and different proportions of aggregates (FA: CA12.5 mm: CA 20 mm) having same packing density (0.68)

5.4 INFLUENCE OF PACKING DENSITY ON THE PROPERTIES OF SCC

5.4.1 Fresh Properties of SCC

The method adopted for the determination of packing density of aggregates is explained in Section 5.2. A ternary packing diagram (TPD) was developed based on experimental and interpolated data (see Fig 5.4). Based on the ternary diagram, three different packing densities (0.64, 0.66 and 0.68) of aggregates were selected for the present investigation. The influence of packing density on fresh concrete properties of SCC was determined by conducting fresh concrete tests such as slump flow test, T_{500} and J ring test on SCC. The fine aggregate proportion (40 % by volume) was kept constant and only the coarse aggregate proportion was changed (10 to 50 % by volume) for obtaining the three different packing densities. The paste composition (1.0 w/p) and the paste volume (388 litres) were kept constant for all the mixtures so that any change in the fresh concrete properties would be a result of the change in the packing density of the aggregates. The mixture design details and the results of fresh concrete tests such as slump flow, T_{500} and J ring are shown in Table 5.2.

From the results, it can be observed that as the packing density increases from 0.64 to 0.68, the slump flow increases from 420 mm to 615 mm. The reason could be attributed to the fact that with an increase in packing density the void content decreases, and so the amount of paste required to fill the voids decreases. Therefore, the excess paste available after filling the voids is used for the enhanced flow of SCC. The passing ability of the concrete (blocking assessment) was also checked by conducting the J ring test (ASTM C 1621, 2006). The results indicate that when the packing density increased, the J ring flow increased as the excess paste available after filling the voids is sufficient enough to make the aggregates pass through the reinforcement. From the test results, it is evident that the flow of SCC is significantly influenced by the packing density of the aggregates.

Table 5.2 Mixture proportions and fresh concrete properties of SCC for different packing densities

Ingredients	Packing density		
	0.64	0.66	0.68
Cement (kg/m^3)	348	348	348
Fly ash (kg/m^3)	147	147	147
Water (kg/m^3)	184	184	184
Fine aggregate (River sand) (kg/m^3)	629	629	629
Coarse aggregate - Max. size 12.5 mm (kg/m^3)	857	514	171
Coarse aggregate - Max. size 20 mm (kg/m^3)	170	510	851
SP dosage (% bwoc)	0.16	0.16	0.16
VMA dosage (% bwoc)	0.011	0.011	0.011
Fresh properties of SCC			
Slump flow (mm)	420	500	615
T_{500} (s)	-	9.72	3.84
J ring flow (mm)	380	465	600

5.4.2 Compressive strength of SCC

The influence of packing density on the compressive strength of self-compacting concrete was also investigated. Cubes were cast for 3 different packing densities (0.64, 0.66 and 0.68) with same paste composition (1.0 w/p ratio) and paste volume (388 lit/m^3). Therefore, any change in the compressive strength would be a direct influence of the packing density of the aggregates. For each packing density value, 3 cubes were cast. The average of the 3 cubes was taken as the compressive strength. From Table 5.3, it is observed that when the packing density was increased from 0.64 to 0.68, the compressive strength increased from 40.5 MPa to 45.6 MPa. This could be attributed to the fact that with increase in packing density, the void content decreases resulting in higher strength. Moreover, with increase in packing density, the paste in excess will help in better compactability leading to higher strength. Therefore, the packing density has a significant influence on the compressive strength of concrete.

Table 5.3 Influence of packing density on compressive strength

Packing density	Proportions of aggregates River sand: CA 12.5 mm: CA 20 mm (% volume)	Compressive strength (N/mm^2) 28 days	Standard deviation (N/mm^2)
0.64	40:50:10	40.5	0.67
0.66	40:30:30	42.7	0.44
0.68	40:10:50	45.6	0.56

5.4.3 Influence of Different Proportions of Aggregates Having the Same Packing Density (0.68) on the Properties of SCC

In the previous section, the influence of packing density on the fresh and hardened concrete properties of SCC was investigated. Further, the investigations were extended to identify the influence of different proportions of aggregates having same packing density on the performance of SCC. Ten different proportions having the maximum packing density of 0.68 were selected for the present study. The details of the aggregate proportions are given in Table 5.4.

Table 5.4 Proportion ID of different proportions of aggregates

Proportion ID	Fine Aggregate River sand (% by volume)	Coarse Aggregate 12.5 mm max. size (% by volume)	Coarse Aggregate 20 mm max. size (% by volume)
1	40	10	50
2	45	10	45
3	45	15	40
4	50	10	40
5	50	20	30
6	55	5	40
7	55	15	30
8	60	10	30
9	60	20	20
10	65	5	30

Experiments were conducted for the determination of fresh and hardened concrete properties of SCC by keeping the paste composition (1.0 w/p) and the paste volume (388 litres) constant along with the packing density for all the mixtures. The mixture proportions are given in Table 5.5. For each proportion of aggregates, 3 cubes were cast. The average of the 3 cubes was taken as the compressive strength. From the results, given in Table 5.5, it is clear that there is significant change in the fresh properties (the slump flow varies from 720 mm to 445 mm) of SCC when the aggregate proportions are changed; however, there is not much difference in compressive strength for different proportions of aggregates. The pronounced variation in the slump flow could be attributed to the fact that with increase in fine aggregate content, the surface area increases, demanding higher amount of paste to wet the surface of aggregates, resulting in reduced slump flow. On the other hand, the mixtures with higher coarse aggregate contents result either in segregation or blocking of aggregates. The T_{500} and the J ring tests were also conducted for the corresponding

SCC mixtures. The results indicate that as the proportion of the fine aggregate increases, the requirement of the paste to wet the aggregate surface increased and so the cohesion of the SCC mixtures increased. As a result, the time taken for T_{500} increased (from 1.5 s to 5.2 s) with increase in fine aggregate fractions. In the J ring test, the J ring flow decreases from 710 mm to 380 mm with increase in fine aggregate proportion. In addition, the difference between slump flow and J-ring flow also increases, indicating increased risk of blocking. This is due to insufficiency of the paste available to wet the surface of the fine aggregate, at large fine aggregate contents.

From the previous sections (5.4.1 and 5.4.2), it is evident that the packing density of the aggregates plays a crucial role in improving the fresh and hardened concrete properties of SCC. The results of this section (5.4.3) reveal that selection of maximum packing density of aggregates alone should not be a criterion for the improved performance of the SCC; in addition, selection of aggregate combinations should also be considered as a criterion for obtaining the improved fresh concrete performance of the SCC.

From the results, it was observed that the combinations having higher proportion of coarse aggregates resulted either in segregation or aggregates blocking. On the other hand, combinations with higher fine aggregate proportions resulted in reduced slump flow due to the requirement of higher paste content for wetting the surface of the fine aggregates. A combination of aggregates resulting in maximum packing density coupled with optimum flow and without segregation has to be selected. Therefore, it was decided to use 50:20:30 (fine aggregate: 12.5 mm: 20 mm) combinations for further investigations on the SCC.

Table 5.5 Mixture proportion details of the SCC with fresh and hardened concrete properties

Proportion ID	1	2	3	4	5	6	7	8	9	10
Cement (kg/m^3)	348	348	348	348	348	348	348	348	348	348
Fly ash (kg/m^3)	147	147	147	147	147	147	147	147	147	147
Water (kg/m^3)	184	184	184	184	184	184	184	184	184	184
Fine aggregate (River sand) (kg/m^3)	629	708	708	786	786	865	865	944	944	1022
Coarse aggregate- Max. size 12.5 mm (kg/m^3)	171	171	257	171	343	86	257	171	343	86
Coarse aggregate- Max. size 20 mm(kg/m^3)	851	766	681	681	510	681	510	510	340	510
SP dosage (% bwoc)	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Slump flow (mm)	720	690	700	660	635	570	555	530	480	445
T_{500} (s)	1.50	2.20	2.06	3.12	3.04	4	5	5.2	-	-
J ring flow (mm)	710	670	670	635	615	520	505	495	415	380
Compressive strength (N/mm^2)	44.9	44.7	44.3	43.6	44.8	44.6	44.2	43.9	44.2	43.8
Remarks	Segregation and aggregate stayed in centre	Aggregate stayed in centre	Aggregate stayed in centre	NS*	NS	NS	NS	NS	NS	NS

* NS = No segregation

5. 5 SUMMARY

It is observed from the literature that the packing density of aggregates has a significant influence on the fresh and hardened concrete properties. Therefore, it is essential to select the combination of aggregates resulting in maximum packing density. For the selection of aggregates resulting in maximum packing density, a precise experimental method was developed using a modification of the test procedure of ASTM C 29. A ternary packing diagram (TPD) was developed based on experimental and interpolated data. The developed TPD is suitable specifically for RMC plants; however, for an individual user, TPD is not a viable solution. Therefore, an empirical relationship was proposed between the packing density of aggregates and their combined particle size distribution (using coefficient of uniformity C_u). Results indicated that a good correlation existed between the C_u values and the packing density of aggregates. Studies were also extended to investigate the variation in C_u values when different proportions of aggregates having same packing density were used. Results showed that there was no significant change in the values of C_u for the same packing density. From these results, it is clear that the C_u can be considered as a valuable parameter and confidently used for estimating the optimal combination of aggregates giving maximum packing density. The numerical value of C_u may vary for aggregates from different locations; however, for a given source of aggregates, the maximum packing density will be obtained for proportions yielding higher C_u value. In mixture proportioning of concrete, for designing the proportions of aggregates, this proposed relationship can be used for any gradation or any shape, as it depends on the combined particle size distribution of the particles alone without any predefined assumptions.

Experiments were conducted to evaluate the influence of packing density of aggregates on the properties of SCC. Three different packing densities (0.64, 0.66 and 0.68) were considered for the investigation. The results indicated that for a constant paste volume (388 litres) and paste composition, when packing density was increased from 0.64 to 0.68, the slump flow increased from 420 mm to 615 mm and the J ring flow increased from 380 mm to 600 mm. This could be attributed to the fact that with increase in packing density the void content decreases, demanding lesser paste to fill the voids, so that the excess paste improves the flow properties of SCC. Positive influence of packing density was also observed on the hardened properties, with an increase in compressive strength from 40.5 N/mm^2 to 45.6 N/mm^2. These results establish a solid proof for the utilisation of packing density concept for the mixture design of concrete, specifically SCC. An attempt was also made to evaluate the influence of 10 different proportions of aggregates having the same packing density (0.68), with constant paste volume (388 litres) and paste composition, on the properties of SCC. The results indicated that the fresh concrete properties were significantly influenced by aggregate proportions, with little or no influence on the hardened properties. From this result, it is evident that along with maximum packing density, selection of aggregate combinations should also be considered for improved fresh properties of SCC.

CHAPTER 6

EVOLUTION OF MIXTURE DESIGN PROCEDURE FOR SELF-COMPACTING CONCRETE

6.1 INTRODUCTION

The first part of the chapter deals with the investigation on the influence of various parameters on the fresh and hardened concrete properties of SCC for the selected combination of aggregates (refer Chapter 5, Section 5.6). The second part of the chapter describes the process of developing the mixture design procedure.

6.2 INFLUENCE OF PASTE VOLUME AND W/P RATIO ON THE PROPERTIES OF SCC

Experiments were carried out using different powder contents (350 to 650 kg/m^3) and w/p ratios (0.7 to 1.7 by volume) with corresponding variation in the paste volume (which includes 20 litres of air) to investigate the influence on properties of SCC. The aggregate combination of 50:20:30 resulting in maximum packing density (0.68) or minimum void content (0.32, or 320 litres in terms of concrete volume) was used. Table 6.1 lists the results of fresh concrete tests such as slump flow, T_{500}, J ring and V funnel.

From Fig. 6.1, it is observed that for a given powder content, with increase in w/p ratio, the slump flow increased and for a given w/p ratio, the slump flow increased with increase in powder content. The reason for the above observation is attributed to the fact that the paste volume increased when the w/p ratio or the powder content increased. This is clearly brought out in Fig. 6.2, which shows that the slump flow increases with increase in paste volume and (approximately) a minimum of 380 litres of paste is essential for achieving slump flow of 550 mm, the minimum for SCC. Mixtures with slump flow more than 900 mm resulted in segregation. Further, investigations were extended to estimate the required paste volume in excess of void content to achieve SCC.

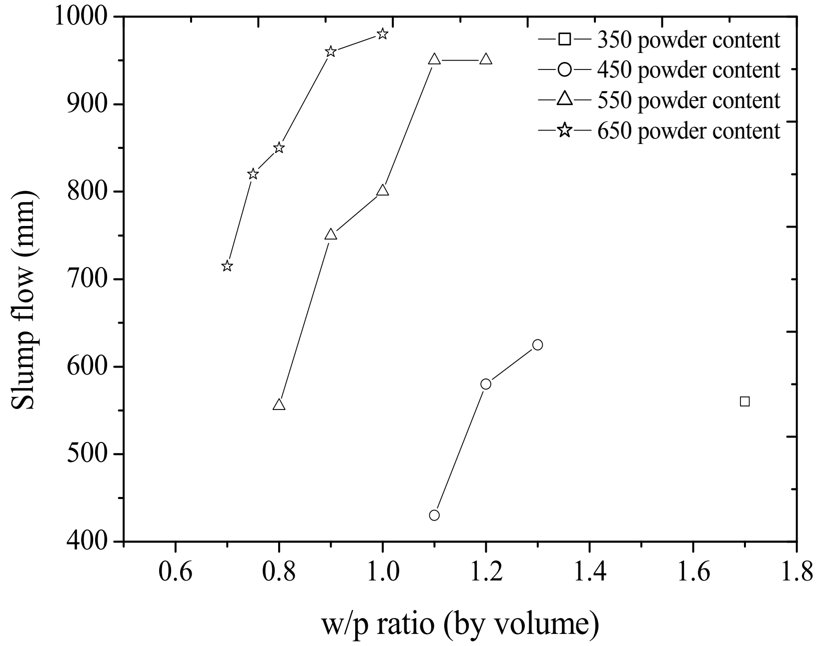


Fig. 6.1 Relationship between the slump flow and w/p ratio (by volume)

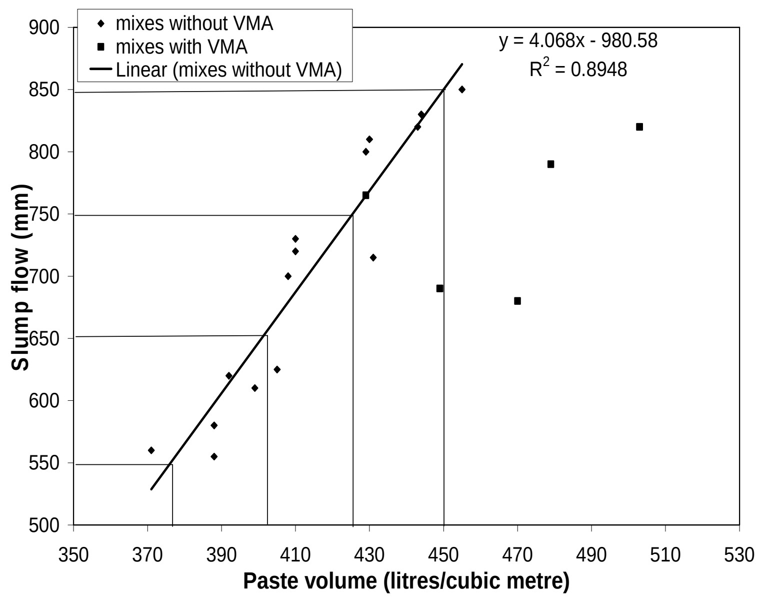


Fig. 6.2 Relationship between the slump flow and paste volume

Table 6.1 Fresh concrete properties of SCC

slump flow range (mm)	w/p	Powder (kg/m^3)	Water (lit./ m^3)	Paste (lit./ m^3)	Excess paste volume (litres)	Slump flow (mm) A	T_{500} (s)	J ring flow (mm) B	V funnel time (s)	Blocking Assessment, A – B (mm)
550 - 650	0.8	550	164	388	68	555	6.07	510	135.84	45.00
	1.7	350	221	371	51	560	1.85	510	2.07	50.00
	1.2	450	201	388	68	580	1.31	530	15.34	50.00
	0.7	600	156	399	79	610	35.8	570	blocked	40.00
	1	500	186	392	72	620	1.28	580	31.16	40.00
	1.3	450	218	405	85	625	1.03	570	5.25	45.00
650 - 750	0.7	650	169	431	111	715	8.28	670	41.53	45.00
	0.9	550	184	408	88	700	1.72	670	60	30.00
	1	525	195	410	90	720	1.6	680	15.6	40.00
	1.1	500	204	410	90	730	1.5	700	10	30.00
750 - 850	1	550	205	429	109	800	1.12	790	4.07	10.00
	0.75	650	181	443	123	820	2.62	755	30.12	50.00
	0.8	650	193	455	135	850	1.43	840	55	10.00
	1.1	525	215	430	110	810	1.5	790	9.5	20.00
	0.9	600	201	444	124	830	2.2	810	12.5	20.00
with opt. VMA dosage										
650 - 750	1.1	550	225	449	129	690	1.56	680	10.6	10
	1.2	550	245	470	150	680	0.44	670	6.44	10
750 - 850	0.9	650	217	479	159	790	2.09	780	26.91	10
	1	650	242	503	183	820	0.63	765	11.13	20

From Fig. 6.3, it is observed that a minimum of 50 to 70 litres of excess paste volume, over and above the paste volume corresponding to the void content, is required for achieving the minimum slump flow of 550 mm. Fig. 6.3 includes the experimental points as well as data from the literature (Rajayogan *et al*., 2003; Kumar, 2004; Bui *et al*., 2002b). An empirical relation was proposed based on the regression analysis of the data.

$$\text{Paste volume} = \text{Void volume} + (\text{Slump flow} - 321)/4.068 \quad (6.1)$$

This empirical relationship was used in the mixture design for calculating the paste volume for any given slump flow.

Apart from slump flow test, experiments were conducted to determine the V funnel time and J ring flow. Fig. 6.4 shows the relationship between the V funnel time and paste volume.

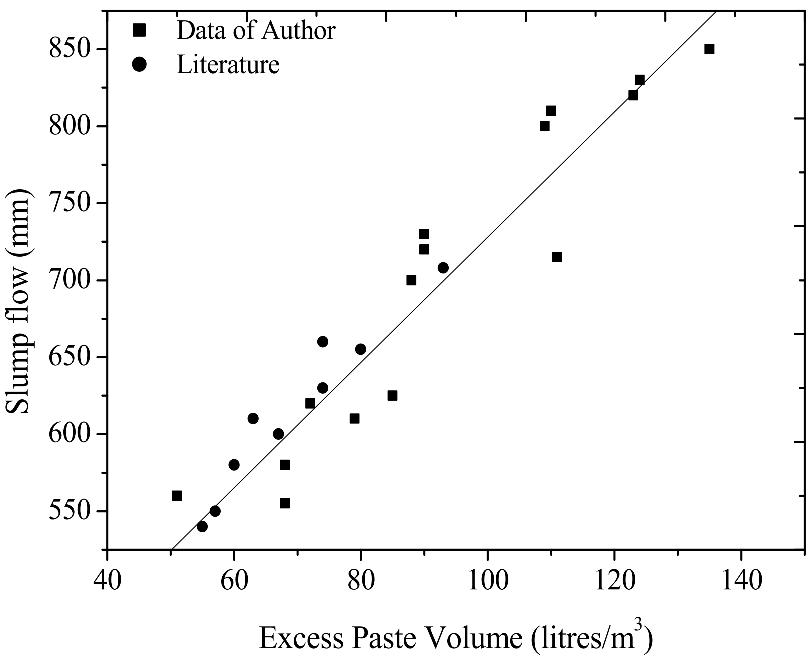


Fig. 6.3 Relationship between excess paste volume and the slump flow

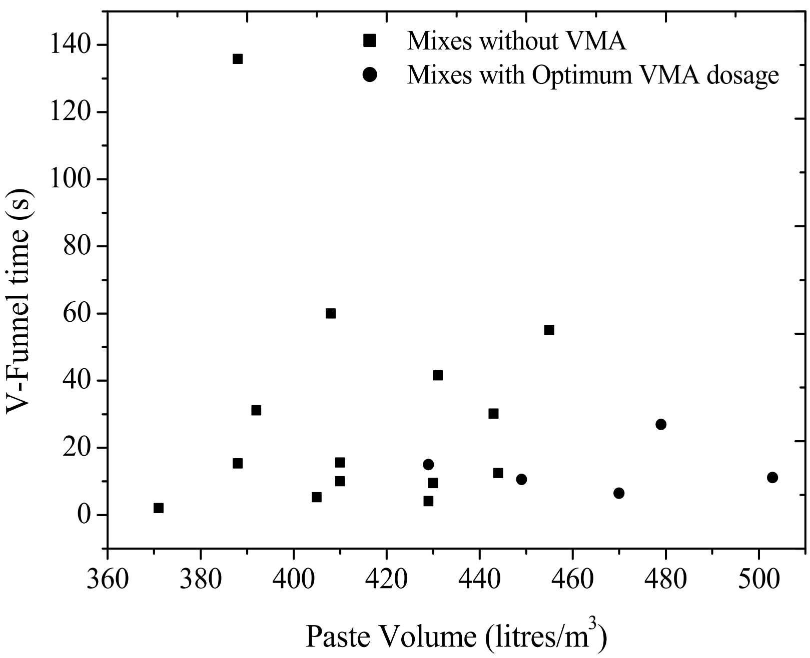


Fig. 6.4 Relationship between the V funnel time and paste volume

From Fig. 6.4, it is observed that the effect of paste volume on the V funnel time is not clear. This could be attributed to the local arching effect of the coarse aggregates nearer to the opening of the V funnel. Therefore, these results are not used for the development of the mixture design procedure of SCC. For assessing the passing ability of SCC, J ring test was conducted for all the mixtures according to ASTM C 1621 (2006). The criterion for passing ability was set as difference between the slump flow and J ring flow being less than 50 mm. The J ring criterion was used in the mixture design procedure for assessing the passing ability. All the SCC mixtures passed the criterion. The fresh concrete results of SCC are given in Table 6.1. The results include the SCC mixtures without VMA and SCC mixtures with optimum dosage of VMA.

From Fig. 6.5, it is observed that there is a good correlation between the compressive strength and w/p ratio. The compressive strength ranges from 20 MPa to 70 MPa. This graph was used an input parameter for the mixture design.

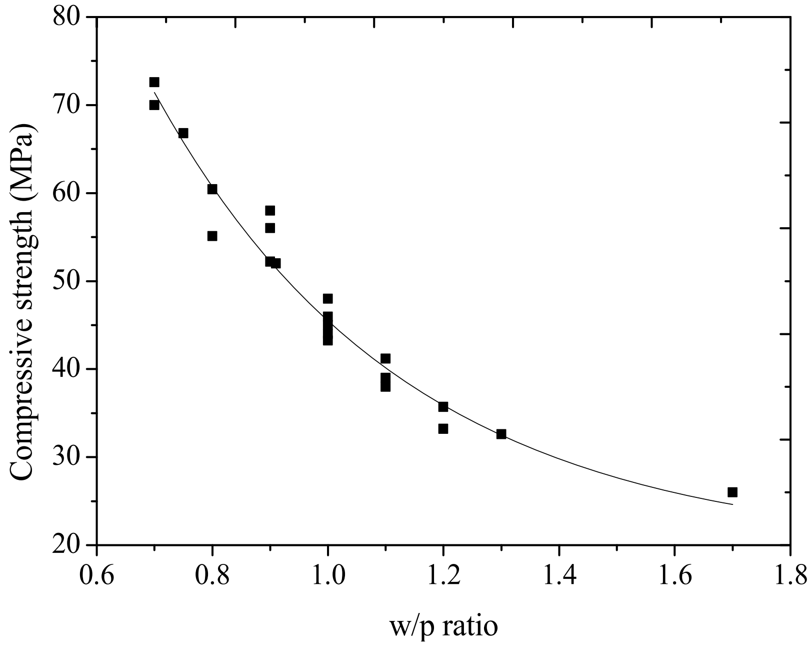


Fig. 6.5 Relationship between the compressive strength and the w/p ratio

The results of slump flow and compressive strength obtained for all mixtures in the study are collectively presented in Table 6.2. These results are classified according to the range of slump flow and compressive strength obtained. The numbers presented in each cell are (in order): the specific compressive strength, water to powder ratio (by volume), powder content (kg/m^3), water content (kg/m^3), and paste volume ($litres/m^3$). The shaded cells represent mixtures with optimum dosage of VMA. The results indicate that it was possible to achieve SCC with a slump flow of 560 mm for powder content as low as 350 kg/m^3. From Table 6.2, it is possible to select the paste composition for a required combination of slump flow and compressive strength (the aggregates are blended to achieve optimal packing).

Table 6.2 Matrix of Strength and Slump flow obtained in the study

	Compressive strength (MPa)					
	Range	20 - 30	30 – 40	40 - 50	50 - 60	60 - 75
Slump flow (mm)	550- 650	26 - 1.7 (350,221,371)	33.2 - 1.2 (450,201, 388)	44 - 1 (500,186,392)	55.1 - 0.8 (550,164,388)	70 - 0.7 (600, 156, 399)
			32.6 - 1.3 (450,218,405)			
	650-750		38 - 1.1 (500, 204, 410)	45 - 1.0 (525,195,410)	52.2 - 0.9 (550,184,408)	72.6 - 0.7 (650,169,431)
			35.7 - 1.2 (550,245,470)	41.2 - 1.1 (550,225,449)		
	750-850		39 - 1.1 (525, 215, 430)	45.9 - 1 (550,205,429)	56 - 0.9 (600,201,444)	60.4 - 0.8 (650,193,455)
				48 - 1 (650,242,503)	58 - 0.9 (650,217,479)	66.8 - 0.75 (650,181,443)

6.3 MIXTURE DESIGN PROCEDURE FOR SCC

Based on the experimental results, a simple and systematic mixture design method was proposed. This is presented as a flowchart in Fig. 6.6. The mixture design procedure is described as follows:

The input parameters for the mixture design procedure are the compressive strength, slump flow, and particle size distributions of the individual aggregates.

Step 1: Calculation of the void content of the combined aggregates, either from a ternary packing diagram (for RMC plants), or from the proposed relationship between C_u and packing density (for Individual user - Refer equation 5.9).

Step 2: Calculation of paste volume from the proposed relationship between the excess paste volume and the slump flow (Refer Equation 6.1).

Step 3: Determination of the w/p ratio for the corresponding compressive strength from the proposed graph (Refer Fig. 6.5).

Step 4: Calculation of the volume of powder and the volume of water from the paste volume and the w/p ratio.

$$\text{Volume of paste} = \text{Volume of powder} + \text{Volume of water} + \text{Volume of air (20 litres)} \quad (6.2)$$

Step 5: Determination of the powder combination by using the Puntke test. The powder combination resulting in maximum packing density of the powder has to be selected. For the selected combination of powder and w/p, the SP dosage is optimised by using the mini-slump test.

Step 6: Trial mixtures are then evaluated for segregation and blocking. In case of segregation, use of VMA is recommended. The dosage of VMA for subsequent trials is optimised by using Marble test. In case of blocking, the user needs to make adjustments in the paste volume and aggregate combinations (at, or close to, the maximum packing density), and perform new trials. Final casting can be performed once all the criteria are satisfied.

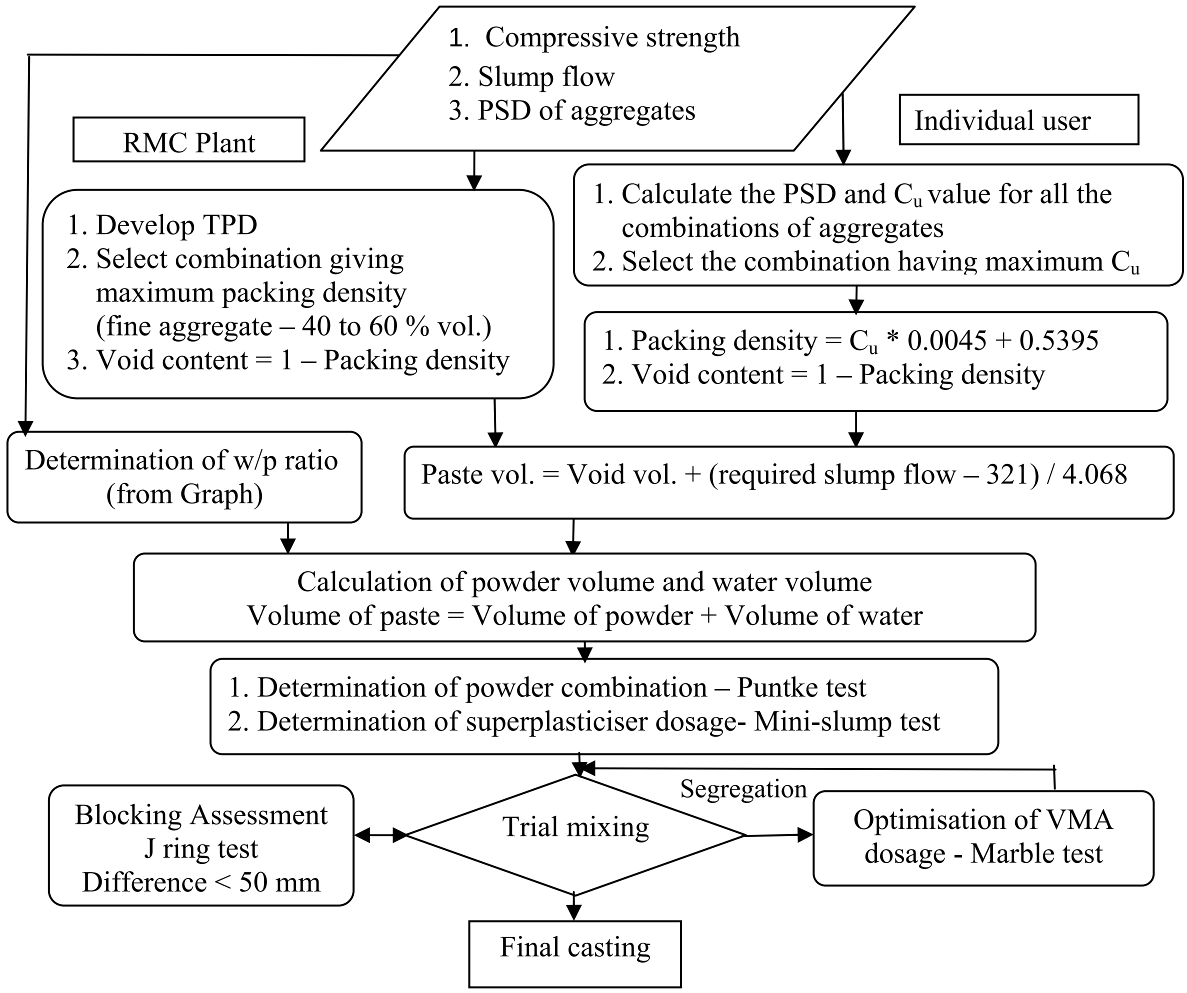


Fig. 6.6 Flow chart of Mixture Design Procedure for SCC

6.4 SUMMARY

This chapter focuses on the development of a mixture design procedure for SCC. The influence of the paste volume and w/p ratio on the fresh and hardened concrete properties of SCC was discussed initially. These experimental results were analysed for utilising in the process of the development of mixture design of SCC. Experimental results revealed that paste volume had a predominant effect on the fresh concrete properties in comparison with the water or the powder content. An empirical relationship was established for the determination of the excess paste volume for the required slump flow in addition to the void content of aggregates. A minimum of 50 to 70 litres of excess paste was found essential for achieving SCC with a slump flow of 550 mm. The effect of paste volume on the V funnel flow time was not clear due to the blocking of aggregates nearer to the V funnel opening. For assessing the passing ability, the J ring test was conducted. As expected, the w/p ratio had a good correlation with the compressive strength of SCC. The compressive strength of mixes developed in this study ranged from 20 to 70 MPa. A matrix combination of strength and the slump flow was established based on the experimental results from which one can select the combination of desired slump flow and the compressive strength. Based on the results obtained, a simple and systematic mixture design procedure was proposed for SCC.

CHAPTER 7

GENERAL DISCUSSIONS

7.1 INTRODUCTION

The primary contribution of this research study is the development of a simple and systematic mixture design method for SCC based on the concepts of rheology and particle packing. Apart from that, an experimental set up for precisely measuring the packing density of aggregates, and a simple empirical method (Marble test) for the optimisation of VMA dosage were developed and an empirical equation was proposed for the determination of packing density of aggregates using the combined particle size distribution.

The proposed mixture design method provides a well defined methodology for optimising the paste composition which includes optimisation of powder combinations, SP dosage and VMA dosage. The mixture design utilises a precise method for the determination of the packing density of aggregates from the particle size distribution of the combined aggregates without any unrealistic assumptions. The paste volume is calculated empirically by using the relationship between excess paste volume and slump flow, along with the void content of aggregates. Proper attention was given to selecting the experimental methods and criteria for optimisation of the ingredients so that, for the user, it should be easy to perform in laboratory and construction sites. The mathematical calculations for the determination of void content and paste volume were also made as simple as possible with appropriate scientific basis.

The purpose of this chapter is to provide comprehensive understanding of the test methods used, the results obtained in various sections and to explain the usage of the concepts of rheology and particle packing in the development of the mixture design of SCC.

7.2 OPTIMISATION – WHY/HOW?

The type of test methods and the criteria adopted for the selection of the proportions of materials plays a vital role in the mixture design process and for deciding the quality and economy of the product. In selecting an experimental method for the optimisation, it is essential to identify how far the measurement can be related to field performance. Flow properties can be characterized in terms of empirical or rheological parameters. Empirical test methods should simulate the relevant field placement condition. Hence, in the present study, it was decided to use simple and appropriate test methods for the optimisation of the different phases. This includes already available test methods as well as newly developed ones.

7.2.1 Powder Combinations

The basic principle and the procedure of the Puntke test was discussed in Chapter 4. Sufficient description was given in Chapter 2 for selecting the Puntke test among the available test methods. However, some more discussion on the test is essential in terms of its practical use. Experiments were conducted by using different liquids such as water, water with superplasticiser, and kerosene, to assess the applicability and reliability of the test method. From the results (Refer Fig. 4.3), it is evident that though the numeric value of the packing density for different powder combinations differs, the combination resulting in maximum packing density remains the same irrespective of the liquid used. Moreover, the scope of the present study does not include the determination of accurate numeric value of packing density of the powder combinations; rather, the emphasis was on the selection of combination of powders which gives maximum packing density. Apart from this, Puntke test is easy, uses simple apparatus and consumes only small amount of material. Therefore, Puntke test can be used with confidence in optimising the powder combinations.

7.2.2 Superplasticiser Dosage

From literature (Wallevik, 2003), it is observed that the superplasticiser has a significant influence on the yield stress with negligible effect on the viscosity of the paste or concrete. In Chapter 2 (Section 2.6.1), it was mentioned that researchers commonly use Marsh cone (sample volume – minimum 800 ml of paste) for determining the saturation dosage of SP. However, the author feels that the Marsh cone (device that measures the viscosity of the fluid (Marsh, 1931)) may not be a suitable apparatus for determining the saturation dosage of SP, as the apparatus is not addressing the correct rheological parameter. Apart from that, Roussel and Roy (2005b) stated that there are two limitations for using Marsh cone. First, the flow time is not a meaningful measurement from a rheological point of view, when it is less than 12 s (for EN445 (1996) cone geometry). Secondly, when a fluid has higher yield stress than the pressure gradient created by the fluid weight above the nozzle, the flow will not occur and the Marsh cone becomes useless. Even if there is no flow in the Marsh cone, there may be spread in mini-slump. Moreover, from the results obtained in the present study (Chapter 4, Fig. 4.18), there was no clear relationship between the yield stress and flow time measured by Marsh cone. Apart from that, even if Marsh cone is used, the criteria proposed for the optimisation of SP in the cementitious paste (Gomes *et al*., 2001; de Larrard, 1990) may yield a high slump concrete, but not SCC. In the present study, based on the criteria proposed by using Marsh cone, a slump flow range between 300 mm and 450 mm was observed in concrete for different w/p ratio. On the other hand, the mini slump test (Kantro, 1980) is quick and can be conducted with a small sample size (40 ml), so that many tests can be performed in a few hours by one person. The results of the mini-slump test on paste and slump flow test on concrete are generally correlated. The major effects observed in the mini-slump test correspond to the effects observed with slump of concrete (Perenchio *et al.*, 1978). From the results obtained in the present study (Chapter 4, Fig. 4.18), it was observed that a good correlation existed between the yield stress and the spread measured by mini-slump cone and this result supports the use of mini-slump cone rheologically. Hence, it was decided to use the mini-slump cone (used for the determination of spread) for the optimisation of the superplasticiser dosage instead of Marsh cone. The dosage corresponding to a spread in the range 170 ± 10 mm, without bleeding was identified as the optimum dosage of the superplasticiser. This value was arrived at by checking if the spread was enough to yield a slump flow greater than 550 mm in concrete.

7.2.3 Viscosity Modifying Agent Dosage

For the optimisation of VMA dosage, a new empirical test (Marble test) was developed, with an emphasis on the static conditions. The detailed description and procedure for the developed method are given in Chapter 4, Section 4.4. The VMA used in this study acts on the water in paste and increases the viscosity of the paste. It was decided to develop a method that addressed this issue completely. The developed empirical method is based on Stokes' law. When a spherical body is dropped into liquid medium, three forces act on it: the buoyancy force (F_b), drag force (F_d) (upward forces) and the acceleration due to gravity (mg) (downward force).

For equilibrium:

$$F_b + F_d = mg \tag{7.1}$$

The buoyant force is given as:

$$F_b = \frac{4}{3}\pi r^3 \rho g \tag{7.2}$$

The drag force is expressed as:

$$F_d = 6\ \pi\mu V d \tag{7.3}$$

Where r = Radius of the sphere

d = Diameter of the sphere

V = Terminal velocity of the sphere

μ = Viscosity of the liquid

ρ_{liquid} = Density of the liquid (in this case - 2000 kg/m^3)

Substituting equations 7.2 and 7.3 in 7.1, the following relationship is obtained

$$V = 2r^2 (\rho_{sphere} - \rho_{liquid})\ g / 9\mu \tag{7.4}$$

By using equation 7.4, the velocity of marble movement in the cementitious paste was numerically calculated and the results are shown in Fig. 7.1.

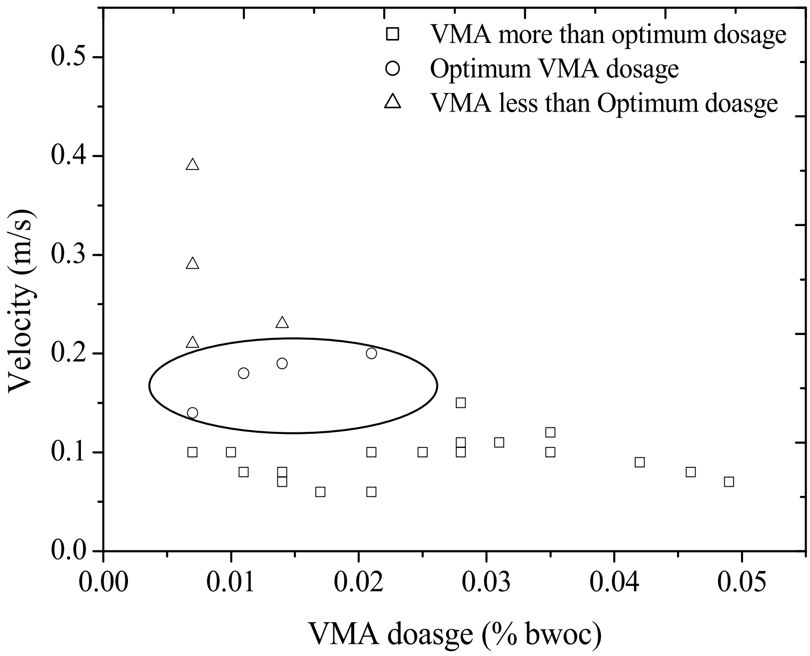


Fig. 7.1 Relationship between the velocity and the VMA dosage

From the results, it is observed that the velocity of the marble in paste with optimum dosage of VMA lies between 0.14 and 0.20 m/s (encircled in Fig. 7.1), while for pastes with dosages above the optimum dosage, it is less than 0.14 m/s, and for pastes with dosage below the optimum, it is more than 0.20 m/s.

Initially, as the glass marble is dropped into the cementitious paste, the marble moves down till the sum of viscous and buoyancy forces equal the weight of the ball. The depth of penetration of the marble indicates the resistance offered by the paste to the downward movement of the marble. The viscosity of the paste increases with increase in the VMA dosage, which is reflected in reduction in the depth of penetration.

7.2.4 Viscometric studies

Viscometric studies were conducted on the cementitious paste with optimum SP dosage for different w/p ratio. The results indicated that there was no significant variation in the values of the yield stress at the optimum dosage of SP (Refer Table 7.1). From these results, it is evident that at optimum dosage of SP in cementitious paste, the yield stress is minimal (almost zero). This is reflected in paste with a closer range of mini-slump spread for different w/p ratio. The experiments on concrete with optimum SP dosage in SCC for different w/p ratios, with a minimum paste volume of 380 litres resulted in a range of slump flow of 550 to 600 mm (Refer Table 7.1). Thus, these results provide a strong rheological support for the SP dosage optimised empirically by using mini-slump cone test.

Table 7.1 Paste and concrete properties of SCC at optimum SP dosage

w/p ratio	Cementitious paste			Concrete properties (Paste volume - 388 litres)	
	Optimum dosage (% bwoc)	Yield stress (Pa)	Mini-Slump spread (mm)	Slump flow (mm)	T_{500} (s)
0.8	0.21	0	178	555	6.0
0.9	0.18	1.75	170	600	5.0
1.0	0.16	1.18	169	600	4.0
1.1	0.14	1.82	166	590	1.9
1.2	0.12	2.19	174	580	1.0

Viscometric experiments were also conducted for cementitious pastes with different dosages of VMA dosage for different w/p ratio. The results revealed that the VMA has a significant effect both on the yield stress and plastic viscosity (Fig. 4.14 and Fig. 4.15). The yield stress varied from 2 Pa to 12 Pa and the plastic viscosity varied from 250 mPa s to 1500 mPa s with increase in the dosage of VMA. Specifically, for the optimum dosage of VMA (Refer Table 7.2), it was observed that there is no significant variation in the yield stress; however, the plastic viscosity varied from 456 mPa s to 656 mPa s. The result based on the yield stress in cementitious paste was clearly reflected in SCC in terms of slump flow. The range of plastic viscosity obtained in cementitious paste resulted in SCC without compromising on slump flow; however, some more studies are required to propose a general viscosity range for cementitious paste essential to achieve SCC without segregation.

Table 7.2 Paste and concrete properties of SCC at optimum VMA dosage

w/p ratio	Cementitious paste				Concrete properties	
	Opt. SP dosage (% bwoc)	Opt. VMA dosage (% bwoc)	Yield stress (Pa)	Plastic Viscosity (Pa s)	Sieve Segregation (%)	Slump flow (mm)
0.9	0.18	0.007	4.493	656	19.97	790
1.0	0.16	0.011	3.910	510	19.80	740
1.1	0.14	0.014	4.371	471	19.87	690
1.2	0.12	0.021	4.080	456	19.68	680

7.2.5 Aggregate Blend

Generally, for the determination of packing density of a ternary blend of aggregates (Fine aggregate, Coarse aggregates of 2 different sizes), experiments are performed initially with the two coarse aggregates. The combination of coarse aggregates resulting in maximum packing density is then selected for experiments with fine aggregate for determining the packing density. The effect of fine aggregate (wall effect/ loosening effect) on the packing of aggregates is not accounted for in these experiments. Moreover, in the concrete mixture, the aggregates are mixed simultaneously. For these reasons, in the present study, the experiments were conducted for determining the packing density by mixing all the three aggregates simultaneously.

Apart from that, proper attention was given for precise determination of packing density by elimination of subjectivities encountered during the measurement by fabricating a simple apparatus. In this test set up (Refer Fig. 5.1), the height of falling of aggregates and the method of falling was constant. Irrespective of the person doing the experiment, the results will be consistent as the subjectivity was eliminated. Apart from that, the bottom container receiving the falling aggregates was selected to eliminate the wall effect by selecting a diameter 10 times more than the maximum size of aggregates.

The ternary packing diagram (TPD) can be developed by commercially available software which are expensive in nature. Hence, it is essential to develop a feasible method for developing the TPD without compromising on the accuracy of the results. For the present investigation, with 24 experimental data points, an interpolation was performed to get adequate data for drawing the ternary packing diagram by using available graphing software. The precision for interpolated packing density is approximately ± 2 %. Therefore, developing TPD becomes easy without spending any money by adopting this method.

Many theoretical models are available for predicting the packing density of aggregates. However, those theoretical models are based on number of unrealistic assumptions which are conflicting with the combination of realistic aggregates used for engineering practice (Goltermann *et al.,* 1997). The porosity predicted from these models results in large variation with the experimentally measured porosities (Standish and Yu, 1987). Theoretical models are always desirable for providing a general platform for an alternative optimisation of aggregates; however, the development is extremely difficult. The intention of the above conclusion should not be viewed as criticism of mathematical models, as better understanding of the structure and the porosity is possible only by using such models. Instead, the author's view is that the existing models are still being perfected and cannot expect to yield predictions of desired accuracy. Therefore, in the present investigation for the calculation of the packing density an attempt was made to establish a simple empirical relationship based on the particle size distribution by conducting experiments.

An equation is proposed for the calculation of packing density by using C_u based on regression (Refer Fig. 5.5). Though the proposed equation is material specific, it gives the user approximate estimate of the packing density of the aggregates. From this, the user can calculate the void content, and in turn the required paste volume for achieving SCC. Experiments were also extended to investigate the influence of C_u on the aggregate proportions having same packing density. It is evident from the results (Refer Fig. 6.6), that there is no significant variation in the C_u for different aggregate proportions having same packing density. Therefore, C_u can be considered as a valuable parameter and confidently used for estimating the optimal combination of aggregates giving maximum packing density. The numerical value of C_u may vary for aggregates from different locations; however, for a given source of aggregates, the maximum packing density will be obtained for proportions yielding higher C_u value. Moreover, the calculation of packing density by using this method is simple. In mixture proportioning of concrete, for designing the proportions of aggregates, this proposed relationship can be used for any gradation or any shape, as it depends on the combined particle size distribution of the particles alone without any predefined assumptions.

7.2.6 Concrete phase

Experiments were conducted on SCC for different powder content and w/p ratio. The results reveal that selection of maximum packing density of aggregates alone should not be a criterion for the improved performance of the SCC; in addition, selection of aggregate combinations should also be considered as a criterion for obtaining the improved fresh concrete performance of the SCC. Based on the results, a particular combination of aggregates (50:20:30) was selected for investigations of different powder content (350 to 650 kg/m^3) and w/p ratio (0.7 to 1.7 by volume) with corresponding variation in the paste. The slump flow increased with increase in paste volume; however, the water content did not show any clear relationship with the slump flow. Approximately 160 litres of water is essential for producing SCC irrespective of the paste volume. A minimum of 380 litres of paste is essential for achieving slump flow of 550 mm, the minimum for SCC. Investigations were also extended to estimate the required paste volume in excess of void content to achieve SCC. It is observed (Refer Fig. 6.2) that a minimum of 50 to 70 litres of paste volume is required for achieving the minimum slump flow of 550 mm. An empirical relation was proposed based on the regression analysis of the data. This empirical relationship was used in the mixture design procedure for calculating the excess paste volume for any given slump flow. In the present study, apart from slump flow, J ring and V funnel tests were also conducted. The V funnel test results are not clear (Refer Fig. 6.4).

As far as fresh concrete tests are concerned, a lot of devices such as U box, L box, V funnel have been proposed in the literature to test the fresh concrete properties (Ozawa *et al*. 1995). However, they are either cumbersome to perform (large samples are required and very limited practical application) or more research is required to make them representative of the real confinement of structures in the case of very dense reinforcements (Sedran *et al*., 1996). Therefore, the V funnel time was not used in the mixture design developed. The results obtained from the slump flow and J ring tests were used for the development of the mixture design procedure.

For SCC, achieving high strengths is not a difficult task, due to the presence of high powder content. However, achieving low and medium strength SCC with adequate flow is a challenge. Therefore, in this investigation, the main focus was to achieve low and medium strength SCC. From the results (Fig. 6.5), it is seen that compressive strength of the designed mixes ranges from 20 to 70 MPa. From the matrix of combinations of slump flow and compressive strength (Table 6.2), it is possible to select the paste composition and paste volume for a specific strength and flow.

The SCC mixtures that segregated either had water content more than 215 litres or fine aggregate fraction less than 40 % of the total aggregate. This information is included in the proposed mixture design for the selection of aggregate combinations. With regard to the present study, the segregation phenomenon is reduced by maximising the packing density; the choice of high packing density increases the range of aggregate particles, which reduces segregation by the lattice effect. At high water contents, using optimum dosages of VMA, it is possible to obtain SCC without segregation and without compromising on the slump flow. Hence, it is suggested that VMA can be used to have a firm control over the stability and robustness of the mix as well as to achieve SCC at the same powder content as normal concrete. As a result, the potential for creep and shrinkage of SCC can also be reduced.

7.3 MIXTURE DESIGN PROCEDURE

Limited guidance is available for optimising the paste rheology from the available literature. The criteria for selection of paste and aggregate content are not well defined. Some mixture design method based on concepts (Rheology and Particle packing) are either application specific or need proprietary software.

Considering the limitations observed from the literature and based on the experimental results, a simple and systematic mixture design procedure was proposed. The proposed mixture design method includes optimisation of three phases namely, paste phase, aggregate phase and the concrete phase based on the concepts of rheology and the packing density. This is a six step process. Simple new methods and criteria were proposed for precisely optimising the phases which will eliminate the confusion for the user to follow the procedure. The optimisation of different phases was clearly defined.

The economic aspects are not considered in this process of mixture design; however, the following will reduce the cost of SCC produced by using this method:

1. Use of mineral admixtures
2. Minimising the paste volume by maximising the packing density
3. Low powder (350 kg/m^3) SCC

Apart from that, instead of looking at the production cost of SCC, it would be better to look in terms of cost benefit ratio.

7.4 RHEOLOGY AND PARTICLE PACKING

Mixture design is an optimisation process which involves determination of appropriate proportions of materials used for a specific requirement. For precise optimisation of proportions of materials for mixture design, specific tools are essential. Different types of High Performance Concrete like Fibre Reinforced Concrete, Light Weight Concrete and High Strength Concrete are designed basically by using different tools for the specific requirement. In the present study, rheology and particle packing are used as tools for the mixture design of SCC.

Fresh concrete is a concentrated suspension of aggregates and cementitious materials in water. SCC, unlike conventional concrete, is a highly flowable concrete in fresh state, with minimum slump flow of 550 mm. Flow is a distinct phenomenon of SCC. Rheology is a science which deals with deformation and flow. Hence, it is appropriate to use this tool for characterising the SCC for the development of mixture design. The main aim of using rheology is to provide a consistent, repeatable and scientific description of concrete flow properties. It is possible to specify concrete mixtures in terms of rheology; however, this may not be appropriate to all relevant aspects of workability. For example, passing ability depends mainly on aggregate characteristics and paste volume and cannot be predicted completely from rheological parameters. One can argue that it is also possible to design SCC by completely neglecting the principles of rheology; however, the risks involved can lead to delay in construction, lack of quality in the final construction and cost overruns. On the other hand, adequate knowledge of the rheological behaviour of fresh concrete will provide the user a rapid and successful placement of high quality concrete, saving money and time without compromising on the service life expectancy. Though extensive studies have been conducted related to rheological aspects of paste and concrete, there is a belief that the usage of the viscometers or rheometers for the real time construction is impractical due to the expensive nature of the instruments. This led to the development of simple apparatus (Marsh Cone and Mini-Slump) for the characterisation of fresh pastes. In the present study, viscometric studies were conducted to evaluate how well the empirical apparatus and the methods used for characterising the pastes are addressed with the help of rheology. In rheological terms, the paste should have minimal yield stress to get maximum flow with sufficient plastic viscosity for avoiding the segregation. The SP dosages optimised by using the empirical test (mini – slump test) resulted in minimal yield stress and VMA dosage optimised by using marble test resulted in a plastic viscosity between 456 mPa s and 656 mPa s. The optimum dosages of SP and VMA were validated in concrete. From these results, it is evident that the empirical tests used for the optimisation of paste composition have sound rheological basis.

Compressive strength is a primary parameter in the mixture design process. The strength mainly depends on w/c ratio, and marginally on other factors such as cement content. Apart from that, packing density also plays a major role in influencing the strength for a given composition of materials. The packing density provides an indication of the void content of the aggregates which is related to the paste volume. Thus, the fresh concrete properties can also be improved by using the concept of particle packing. The concept of particle packing was used for powders and aggregates separately. For powders, the combination (Cement and Fly ash) resulting in maximum packing density was selected for the paste studies. The results showed that the combination of powders with maximum packing density resulted in maximum flow without segregation. As far as aggregates are concerned, the packing density has a positive influence on both the fresh and hardened concrete properties of SCC for a given paste volume. Thus, it was identified that particle packing and rheology played a vital role in improving the performance of the SCC. The proposed mixture design method involves different experimental methods and empirical relationships implicitly addressing the rheology and particle packing concepts.

CHAPTER 8

CONCLUSIONS

8.1 INTRODUCTION

The first part of the chapter outlines the specific conclusions of different phases of the research work. Recommendations for further research are provided in the second part.

8.2 CONCLUSIONS

The salient conclusions drawn from the research study are presented in the sections below, separately for individual phases.

8.2.1 Paste Phase

- For optimising the powder combination, the concept of particle packing was used. From the experimental results, it was observed that the combination resulting in maximum packing density leads to maximum spread of the cementitious pastes. The cement: fly ash combination of 60:40 (by volume) resulted in maximum packing density in the Puntke test.

- The Puntke test was conducted with different liquids (water, water with superplasticiser, kerosene). While the numeric value of packing density differed for different liquids, the combination of powder resulting in maximum packing density remained the same.

- The optimum combination of powder was used for optimising the superplasticiser (SP) dosage for different w/p ratios (0.8 to 1.2 by volume) using Mini-slump cone test. The dosage corresponding to a spread in the range 170 ± 10 mm, without bleeding, was identified as the optimum dosage of the superplasticiser. The optimum dosage of SP decreased from 0.21 to 0.12 (% by weight of cementitious material) when the water powder ratio increased from 0.8 to 1.2 (by volume).

- The results of the viscometric studies revealed that there was no significant influence of w/p ratio (at the optimum SP dosage) on the yield stress. On the other hand, the plastic viscosity varied from 533 mPa S to 146 mPa S when the w/p ratio increased from 0.8 to 1.2.

- The optimum dosage of SP in cementitious paste was validated in SCC by keeping the paste composition and paste volume (388 litres) constant. The optimum dosage of SP for different w/p ratios (0.8 to 1.2) resulted in a slump flow between 550 and 600 mm, and T_{500} between 1 to 6 seconds in SCC.

- The VMA dosage was optimised in the cementitious paste with optimum SP dosage by using a new method called "Marble test". The optimum dosage was defined as the dosage above which the cementitious paste starts to resist the downward movement of the marble. The optimum dosage of the VMA increased from 0.007 to 0.021 (% by weight of cementitious material) when the w/p ratio increased from 0.9 to 1.2 (by volume).

- The results of viscometric studies on cement pastes with optimum SP dosage indicated that the yield stress varied from 2 Pa to 12 Pa and the plastic viscosity varied from 250 mPa s to 1500 mPa s with increase in VMA dosage for different w/p ratio. At the optimum dosage of VMA, the variation in the yield stress was negligible for different w/p ratios. On the other hand, the plastic viscosity varied from 456 mPa s to 656 mPa s when the w/p ratio decreased from 1.2 to 0.9.

- For validating the optimum dosage of VMA in SCC, sieve segregation test was performed for the segregated mixtures. For optimum dosage of VMA, a segregation value less than 20 % was obtained and these results conform to class SR1 of EFNARC guidelines. Dosages less than optimum resulted in segregation and the dosages above optimum resulted in reduced slump flow.

- Overall, the paste results indicated that there existed a good correlation between the rheological parameters (yield stress and plastic viscosity) and the empirical parameters (spread and flow time).

8.2.2 Aggregate Phase

- A precise and practicable method was developed for the determination of packing density of a combination of aggregates. The maximum packing density obtained was 0.68 and the minimum packing density was 0.54, for the available aggregates. A Ternary Packing Diagram (TPD) was developed based on the experimental and interpolated data for packing density. Using this diagram, the packing density for any combination of 20 and 12.5 mm coarse aggregates and sand can be determined.

- In order to facilitate the determination of packing density, studies were conducted to determine correlations between packing density and particle size distribution. An empirical relationship was proposed between the packing density and the coefficient of uniformity C_u:

$$\text{Packing density} = 0.0045\, C_u + 0.5395 \qquad (8.1)$$

  Further studies also indicated that there was negligible variation in the C_u for different aggregate proportions having same packing density.

- In order to study the effect of packing density of aggregates on properties of SCC, experiments were conducted by keeping the paste composition and the paste volume (388 litres) constant. When the packing density was increased from 0.64 to 0.68, the slump flow was increased from 420 mm to 615 mm and compressive strength was increased from 40.5 MPa to 45.6 MPa.

- Experiments were extended with same paste composition and paste volume to identify the influence of different proportions of aggregates having same packing density on the performance of SCC. The results revealed that there was significant change in the fresh properties (the slump flow varied from 720 mm to 445 mm) of SCC when the aggregate proportions were changed; however, negligible variation in compressive strength for concrete with different proportions of aggregates (giving same packing density) was observed.

- For the present study, a combination of 50 : 20 : 30 (river sand : 12.5 mm coarse aggregate : 20 mm coarse aggregate) that gave the maximum packing density of 0.68, was chosen for the trials on SCC in the concrete phase.

8.2.3 Concrete Phase

- From the SCC trials with optimum cementitious paste composition and aggregate combination with maximum packing density, it was observed that for a given powder content, with increase in w/p ratio, the slump flow increased and for a given w/p ratio, the slump flow increased with increase in powder content. In other words, the slump flow increased with increase in paste volume.

- A paste volume of 50 to 70 litres, in excess of the void content determined from aggregate packing calculations, was essential for achieving a minimum slump flow of 550 mm. An empirical relationship was proposed for the estimation of paste volume for the required slump flow.

$$\text{Paste volume} = \text{Void volume} + (\text{Slump flow} - 321) / 4.068 \quad (8.2)$$

- The results of the J ring test indicated that, apart from the influence of nominal maximum size of aggregates on the passing ability of SCC, excess paste volume plays a crucial role.

- It was possible to achieve SCC with a slump flow of 560 mm for powder contents as low as 350 kg/m^3. A compressive strength range of 20 to 70 MPa was achieved from the experiments conducted in this study.

- Based on the results of the study, a new methodology for mixture design based on particle packing and rheology was proposed.

8.3 RECOMMENDATIONS FOR FURTHER RESEARCH

A simple and systematic mixture design procedure for SCC proposed based on scientific concepts was the primary contribution of this study. However, the results and discussions at various stages of the present study have opened doors for various other aspects that can be studied further. The following recommendations are suggested for enhancing the proposed mixture design for SCC.

- It is clear from results that the test methods adopted and proposed criteria for optimising the paste composition were suitable for specific mineral (Class F Fly ash) and chemical admixtures (PCE based superplasticiser and microbial polysaccharide based VMA). The suitability of these methods and criteria for different mineral (Silica fume, Metakaoline, Slag, limestone powder) and chemical admixtures (lignosulphonate, melamine and Napthalene based superplasticisers) needs to be validated. In addition, microstructural studies can also be conducted on the hardened cementitious paste to understand the influence of packing density on the microstructure.

- The rheology of paste and its volume control the rheology of concrete. As a result, the rheological studies were focused only on paste. However, establishing connection between the rheology of paste and concrete rheology is difficult. One of the reasons is that rheological measurement of paste and concrete are performed in different rheometers or viscometers having different rotational geometries, calibrations and computational procedures. It is therefore desirable to perform rheological tests of pastes and concrete in the same rheometer or viscometer to obtain experimental data, so that it could be possible to develop a precise model for predicting the rheological behavior of concrete from the rheological behaviour of paste.

- The formula proposed for the calculation of paste volume required for the desired slump flow was based on the void content and the excess paste volume (obtained from experimental studies). There are chances for variation in the paste volume requirement for aggregates having different surface area (such as when rounded aggregate is used, or when manufactured sand is used). Hence, a model incorporating the void content and surface area of aggregates (complexity in calculation should be avoided) accounting shape and overall gradation of the aggregates would result in a more generalized approach for mixture design.

- There are many tests for assessing the fresh properties of SCC. It is desirable to develop an All-in-One apparatus which should address filling ability, passing ability and segregation resistance. It should also be simple and practically useful at the construction site. This may reduce the complexity involved in the calculation of the paste volume and other related factors in the mixture design process.

- The paste volume for SCC mixtures used in the present study ranged between 370 litres/m^3 and 503 litres/m^3. With such high paste volumes there are possibilities for the SCC to be affected by shrinkage and creep, which are detrimental to the performance of structures in the long term. Therefore, it is necessary to conduct investigations on the shrinkage and creep of SCC.

- Mixture design methods are proposed based on blocking criteria (Petersson *et al*., 1996) and segregation resistance (Saak *et al*., 2001). The present mixture design addresses both the segregation and the passing ability issues. However, a comprehensive model incorporating passing ability and segregation resistance would be desirable for precisely designing the SCC.

- The results of the present study indicated that it is possible to achieve SCC with powder content as low as 350 kg/m^3 (with 221 litres of water) with slump flow of 560 mm. However, some more investigations are essential on low powder SCC with lesser water content.

- The mixture design method can be made generic by conducting round robin tests in different laboratories across the country. Further, with the observations and the results obtained from the laboratories, the mixture design process can be refined.

APPENDICES

APPENDIX A: MATLAB PROGRAM

```
%r=input('enter the shape parameter ');
r=1.99
%n=input('enter the dimension of the vector ');
n=3;
%m=input('enter the number of vectors ');
m=24;
A=zeros(m,m);
b=zeros(m,1);
c=zeros(m,1);
x=zeros(n,m);
% for i=1:1:m
%    x(:,i)=input('enter the vectors ');
%    b(i,1)=input('enter functionl value ');
% end
x(:,1)=[100;0;0];
x(:,2)=[70;0;30];
x(:,3)=[30;0;70];
x(:,4)=[0;0;100];
x(:,5)=[0;30;70];
x(:,6)=[0;70;30];
x(:,7)=[0;100;0];
x(:,8)=[30;70;0];
x(:,9)=[70;30;0];
x(:,10)=[80;10;10];
x(:,11)=[60;20;20];
x(:,12)=[45;45;10];
x(:,13)=[45;10;45];
x(:,14)=[40;40;20];
x(:,15)=[40;30;30];
x(:,16)=[40;20;40];
x(:,17)=[30;40;30];
x(:,18)=[30;30;40];
x(:,19)=[20;60;20];
x(:,20)=[20;40;40];
x(:,21)=[20;20;60];
x(:,22)=[10;80;10];
x(:,23)=[10;45;45];
x(:,24)=[10;10;80];
b(1,1)=0.607;
b(2,1)=0.670;
b(3,1)=0.674;
b(4,1)=0.540;
b(5,1)=0.546;
b(6,1)=0.575;
b(7,1)=0.523;
b(8,1)=0.627;
```

```
b(9,1)=0.654;
b(10,1)=0.646;
b(11,1)=0.676;
b(12,1)=0.668;
b(13,1)=0.679;
b(14,1)=0.652;
b(15,1)=0.658;
b(16,1)=0.686;
b(17,1)=0.641;
b(18,1)=0.665;
b(19,1)=0.610;
b(20,1)=0.624;
b(21,1)=0.620;
b(22,1)=0.559;
b(23,1)=0.562;
b(24,1)=0.607;
for i=1:1:m
    for j=1:1:m
        v=(x(:,i)-x(:,j));
        y=(norm(v,2));
        A(i,j)=y^r;
  end
end
c=inv(A)*b;
y=zeros(3,9)
y(:,1)=[10;0;90]
y(:,2)=[20;0;80]
y(:,3)=[40;0;60]
y(:,4)=[50;0;50]
y(:,5)=[60;0;40]
y(:,6)=[80;0;20]
y(:,7)=[90;0;10]
y(:,8)=[90;10;0]
y(:,9)=[80;20;0]
y(:,10)=[60;40;0]
y(:,11)=[50;50;0]
y(:,12)=[40;60;0]
y(:,13)=[20;80;0]
y(:,14)=[10;90;0]
y(:,15)=[0;90;10]
y(:,16)=[0;80;20]
y(:,17)=[0;60;40]
y(:,18)=[0;50;50]
y(:,19)=[0;40;60]
y(:,20)=[0;20;80]
y(:,21)=[0;10;90]
y(:,22)=[20;10;70]
y(:,23)=[30;10;60]
y(:,24)=[40;10;50]
y(:,25)=[50;10;40]
y(:,26)=[60;10;30]
y(:,27)=[70;10;20]
```

```
y(:,28)=[70;20;10]
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y(:,30)=[50;40;10]
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y(:,32)=[30;60;10]
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y(:,59)=[50;45;5]
y(:,60)=[40;55;5]
y(:,61)=[30;65;5]
y(:,62)=[20;75;5]
y(:,63)=[10;85;5]
y(:,64)=[5;90;5]
y(:,65)=[5;85;10]
y(:,66)=[5;75;20]
y(:,67)=[5;65;30]
y(:,68)=[5;55;40]
y(:,69)=[5;45;50]
y(:,70)=[5;35;60]
y(:,71)=[5;25;70]
y(:,72)=[5;15;80]
y(:,73)=[15;15;70]
y(:,74)=[25;15;60]
y(:,75)=[35;15;50]
y(:,76)=[45;15;40]
y(:,77)=[55;15;30]
y(:,78)=[65;15;20]
y(:,79)=[70;15;15]
```

```
y(:,80)=[60;25;15]
y(:,81)=[50;35;15]
y(:,82)=[40;45;15]
y(:,83)=[30;55;15]
y(:,84)=[20;65;15]
y(:,85)=[15;70;15]
y(:,86)=[15;65;20]
y(:,87)=[15;55;30]
y(:,88)=[15;45;40]
y(:,89)=[15;35;50]
y(:,90)=[15;25;60]
y(:,91)=[25;25;50]
y(:,92)=[35;25;40]
y(:,93)=[45;25;30]
y(:,94)=[35;35;30]
y(:,95)=[25;45;30]
y(:,96)=[25;35;40]
x1=zeros(3,1);
for k=1: 96
  x1=y(:,k);
J=0;
I=0;
for i=1:1:m
    v=(x1-x(:,i));
    z=(norm(v,2));
    if y= =0
        J=0;
    else
    J=c(i,1)*(z^r);
    end
    I=I+J;
end  I
end
```

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LIST OF PAPERS SUBMITTED ON THE BASIS OF THIS THESIS

Journal Papers

1. Nanthagopalan, P., M. Haist, M. Santhanam, and H. S. Müller (2008) Investigation on the influence of granular packing on the flow properties of cementitious suspensions, *Cement and Concrete Composites,* 30, 763 -768.

2. Nanthagopalan, P. and M. Santhanam (2008) A new approach to optimisation of paste composition in self-compacting concrete, *Indian Concrete Journal,* 82, 11–18.

3. Nanthagopalan, P. and M. Santhanam. A new empirical test method for the optimisation of viscosity modifying agent dosage in self-compacting concrete, *Materials and Structures* (Article in press)

4. Prakash Nanthagopalan and Manu Santhanam, Experimental investigations on the influence of paste composition and content on the properties of Self-Compacting Concrete, *Construction and Building Materials* (Article in press).

5. Prakash Nanthagopalan and Manu Santhanam, An empirical approach for the optimisation of aggregate combinations for self-compacting concrete, *Materials and Structures* (under review)

Conference paper

1. Nanthagopalan, P. and M. Santhanam (2006) A study of the interaction between viscosity modifying agent and high range water reducer in self-compacting concrete, Proceedings of *International conference on Measuring, Monitoring and Modeling Concrete Properties*, Greece, 449-454.

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