CHAPTER 6

MIX PROPORTIONING OF SCC

6.1 GENERAL

Design of a SCC mix requires complete knowledge of the various properties of the constituent materials, the implications in case of change on these conditions at the site, the impact of the properties of plastic concrete on the hardened concrete and the complicated inter-relationship between the variables. All these make the task of mix design more complex and difficult. Self-compactability may be largely affected by the characteristics of materials and the mix proportion. SCC mix proportions depend on their application. Requirements for hardened properties, filling ability, passing ability and segregation resistance vary widely by the application. These factors must be considered prior to starting the mix proportioning of SCC.

Every mix proportioning method of SCC must ensure adequate yield stress and plastic viscosity of the concrete. According to Yahia et al. (1999), a low yield stress is important for filling ability while high mortar plastic viscosity is necessary for placement in highly congested sections. High deformability can be achieved by limiting the coarse aggregate volume while segregation resistance can be achieved by controlling the mortar rheology through reducing the w/p ratio, increasing the powder content and adding VMA.
6.2 PRINCIPLES OF MIX DESIGN

SCC has a higher content of fine particles and improved flow properties than conventional concrete. Mix proportioning of SCC may be broadly classified into three approaches, based on the method of achieving sufficient viscosity and segregation resistance. They are

i) Powder type of mix proportioning of SCC

ii) VMA type of mix proportioning of SCC

iii) Combination type of mix proportioning of SCC.

In powder type of mix proportioning of SCC, the powder content is relatively high and w/p ratio is low. In VMA type of mix proportioning of SCC, the powder content is reduced and the w/p ratio is increased relative to powdertype of mix proportioning of SCC and VMA is added to ensure segregation resistance. The paste volume may not change significantly between the two types. Combination type of mix proportioning of SCC combines both moderately high powder content and the use of a VMA.

According to the Japanese Society of Civil Engineers (1999), the powder content in powdertype of mix proportioning of SCC should be approximately 16%-19% of the concrete volume (500-600 kg/m³ based on cement only) and can comprise a wide variety of powders such as fly ash, slag, and limestone filler. The water powder ratio of powdertype of mix proportioning of SCC typically ranges from 0.28 to 0.37.

The powder content of VMA type of mix proportioning of SCC is typically 300-500 kg/m³ (9.5 to 16% of the concrete volume based on only cement) and composed entirely of portland cement. The water content of
VMA type of mix proportioning of SCC may be greater than 18% of concrete volume.

In combination type of mix proportioning of SCC, the powder content is typically greater than 13% of the total concrete volume and the w/p ratio is restricted to a narrow range.

According to an analysis of 68 SCC case studies conducted by Domoneet al. (2006), mix proportions for SCC differ widely such that there is not a unique solution for any given application. The analysis found that coarse aggregate contents varied from 28 to 38% of concrete volume, paste content varied from 30 to 42% of concrete volume, powder content ranged from 445 to 605 kg/m$^3$, water-powder ratio ranged from 0.26 to 0.48 and fine aggregate content varied from 38 to 54% of mortar volume. The majority of case studies used maximum coarse aggregate sizes of 16 to 20 mm. In general, the SCC mixture proportions when compared to conventional vibrated concrete were characterized by lower coarse aggregate contents, increased paste contents, higher powder contents, low water-powder ratios, high HRWRA dosages and the use of VMA is most cases.

6.3 MIX PROPORTIONING METHODS OF SCC

A number of methods exist to optimize the concrete mixture proportions for SCC. These methods differ widely in the overall approach, in the range of materials and performance characteristics considered, also in the level of complexity. Following are some of the mix proportioning methods currently available for SCC
6.3.1 Rational Mix Design Method

The Rational Mix Design Method was originally developed in Japan and has been presented in various forms by several authors including Okamura and Ozawa (1995), Ouchi, Hibino and Okamura (1997), Edamatsu, Nishida and Ouchi (1999), Okamura and Ouchi (2003). The use of the method has been suggested by organizations around the world, including EFNARC.

The Rational Mix Design Method consists of six steps, discussed as follows.

a) First, the desired air content is established. Usually the air content is set at 2% unless air entrainment is required.

b) Second, the coarse aggregate volume is set at 50 to 60% of the solid volume. The exact amount depends on the aggregate’s maximum size and shape, with smaller aggregates and rounded aggregates used in higher volumes.

c) Third, the fine aggregate volume is set at 40-50% of the mortar volume.

d) Fourth, the water powder ratio for zero flow in paste is determined by measuring the slump flow in pastes at various w/p ratios and extrapolating the w/p ratio for zero flow.

e) Fifth, the optimum water-powder ratio and HRWRA dosage are determined in the paste, based on measurements with the slump cone and V-funnel.
f) Sixth, tests are performed on trial batches of concrete to finalize the mixture proportions.

In Rational Mix Design Method, the fine and coarse aggregate contents are selected based on specific multiples of bulk density. This is a unique method of selecting optimum paste rheology with slump flow test and V funnel test. The method is rather restrictive in the way it sets the coarse and fine aggregate contents and establishes the target paste flow properties. The resulting proportions may not be optimal in concrete.

6.3.2 Particle Matrix Model

The Particle Matrix Model was originally developed by Ernst Mortsell for conventionally placed concrete (Mortsell, Maage and Smepllass 1996) and has since been extended to SCC with mixed success (Smepllass & Mortsell 2001). The model is based on paste volume, paste rheology and aggregate properties. The paste rheology is characterized with the flow resistance ratio. The aggregates are characterized with the air voids modulus which depends on the aggregate volumes, fineness moduli and empirically determined aggregate parameters.

\[
H_m = v_1 \left[ \frac{H_s}{Fm_s^{0.5}} + T_s \right] + v_2 \left[ \frac{H_p}{Fm_p^{0.5}} + T_p \right] \quad (6.1)
\]

where

\[
\begin{align*}
H_m & = \text{Air void modulus} \\
v_1 & = \text{Volume fraction of fine aggregate} \\
v_2 & = \text{Volume fraction of coarse aggregate} \\
H_s & = \text{Void contents in the compacted fine aggregate}
\end{align*}
\]
\( H_p = \) Void contents in the compacted coarse aggregate

\( T_s = \) Aggregate parameter for fine aggregate

\( T_s = \) Aggregate parameter for coarse aggregate

\( Fm_s = \) Fineness modulus of fine aggregate

\( Fm_p = \) Fineness modulus of coarse aggregate

Workability is measured at various paste volumes for each flow resistance ratio and air void modulus. The resulting equations are used to predict the effects of changes in mixture proportions. The flow resistance ratio and air voids modulus are unique parameters describing the paste rheology and aggregate characteristics respectively. The model has been applied with mixed success. The developer of the model has stated that more work is needed in optimizing the paste rheology. The air void modulus is complicated to compute, particularly in determining the aggregate parameters. The flow resistance ratio may not be the best parameter to characterize paste rheology. The flow resistance ratio and air voids modulus has limited physical meanings.

6.3.3 CTG Mixture Proportioning Method

The CTG Mixture Proportioning Method was developed at the Technical Center of Italcementi Group (CTG) in 1997 and has been used worldwide by Italcementi Group (Vachon, Kaplan, Fellaki 2002). This method involves four steps.

a) First, the paste composition is designed for strength requirements.
b) Second, the paste volume is selected to achieve necessary fluidity and resist segregation. This paste volume which constitutes water, air and all particles smaller than 80 μm is set at 37% in most cases as a starting point.

c) Third, the aggregate is selected to prevent segregation and blocking.

d) Fourth, the HRWRA dosage and if necessary, the VMA dosage are selected. Values for the paste content and aggregate grading are established empirically based on testing or previous experience.

The paste composition is designed for strength and the paste volume is set for workability. The aggregates are selected to achieve segregation and blocking resistance. The method is simple and typically relies on previous empirical experience.

6.3.4 Compressible Packing Model

The compressible packing model developed by Larrard (1999) has been applied to SCC (Sedran et al. 1996, Sedran and Larrard 1999). The intent of the model is to reduce the high paste volumes sometimes associated with SCC. The method includes a detailed packing model to optimize aggregate packing. The model includes equations to compute concrete yield stress, plastic viscosity and segregation resistance. In addition, a parameter has been developed to predict filling/passing ability.

For proportioning SCC mixtures, the required inputs are the size distributions, specific gravities and packing densities of the constituents and the saturation dosage of the HRWRA. Because several constants in the
compressible packing model depend on the HRWRA, approximately 10 trial batches with different HRWRA and water contents must be tested for rheology and segregation resistance in order to determine these constants. The model equations are used to compute yield stress, plastic viscosity and parameters describing filling/passing ability and segregation resistance. Limits are established for each of these four parameters. Gap-graded mixtures must be avoided to ensure segregation resistance even though they may result in high packing density. Requirements for hardened properties must also be included. The initial trial proportions are optimized numerically by the model and must then be verified with laboratory trial batches.

The method uses a detailed packing model to optimize aggregates and includes the ability to compute yield stress, plastic viscosity, and parameters for filling/passing ability and segregation resistance. The use of the model requires proprietary software. The calculation of yield stress and plastic viscosity is based on empirical measurements with the BTRHEOM, which typically gives higher values than other rheometers.

6.3.5 Excess Paste Theory

Oh, Noguchi and Tomosawa (1999) applied the concept of the excess paste theory to SCC. The excess paste theory requires the determination of the excess paste volume which is the paste in excess of that needed to fill the voids between the aggregates. This excess paste is divided by the surface area of the aggregates to determine the thickness of the excess paste. The relative thickness of excess paste is computed and used to predict the yield stress and plastic viscosity of the concrete relative to the paste.

The model has been shown to predict both yield stress and plastic viscosity of SCC accurately, based on the aggregate properties, paste volume, and paste rheology. Various approaches are available for determining
aggregate surface area. The approach suggested by the authors is computationally intensive, especially when fine aggregate is considered. The yield stress and plastic viscosity must be determined in a consistent manner on both the paste and concrete so that they can be related.

6.3.6 High Strength SCC Mix Proportioning Method

Gomes et al. (2001) presented an empirical method for developing high strength SCC mixture proportions. The method considers SCC as a two-phase material consisting of paste and aggregate. Each phase is optimized separately.

In the first step, the paste composition is optimized by determining the optimum ratios of water/cement, silica fume/cement, HRWRA/cement and filler/cement. In the second step, the aggregates are selected by determining the blend of fine and coarse aggregates that result in the lowest voids content. With the optimum paste composition and aggregate blend selected. The third step involves selecting the appropriate paste volume. Concrete mixtures with various paste volumes are measured for filling ability, passing ability, and compressive strength. The minimum acceptable paste volume is selected.

The optimum paste composition is determined with the V funnel and slump cone, subject to limits on strength. The blend of aggregates resulting in the lowest voids content is selected. Various paste volumes are tested to achieve the optimum workability and compressive strength. The application of procedures to optimize the paste composition to achieve high strength is unique for SCC. The method is mainly intended for high strength SCC. The aggregate combination giving the minimum voids content may not be the optimal for workability. The approach for selecting the optimum paste composition may not result in the lowest paste volume. Accordingly, in
selecting the paste volume, it may be appropriate to alter the paste composition to achieve lower paste volume.

6.3.7 Su, Hsu, and Chai (2001) Method

This mixture proportioning method developed by Su, Hsu, and Chai (2001) consists of selecting the aggregate volume and then filling the voids between aggregates with paste of the appropriate composition.

a) In the first step, the coarse and fine aggregates are proportioned based on their loosely packed densities. The masses of coarse \( W_{\text{coarse}} \) and fine \( W_{\text{fine}} \) aggregates are calculated as follows:

\[
W_{\text{coarse}} = PFXUW_{\text{coarse-loose}} x \left[ 1 - \frac{S}{A} \right] \quad (6.2)
\]

\[
W_{\text{fine}} = PFXUW_{\text{fine-loose}} x \frac{S}{A} \quad (6.3)
\]

where

\[
UW_{\text{coarse-loose}} = \text{Loosely packed density of coarse aggregate}
\]

\[
UW_{\text{fine-loose}} = \text{Loosely packed density of fine aggregate}
\]

\[
\frac{S}{A} = \text{Sand-aggregate ratio}
\]

b) In the second step, the cement content is selected based on strength requirements.
c) In the third step, the water content required by the cement is calculated from the water-cement ratio needed for strength.

d) In the fourth step, the total volume of fly ash paste and slag paste to fill the remaining volume of the concrete is determined.

e) Lastly, trial batches are evaluated and the proportions are adjusted.

The fine and coarse aggregates are set as the loosely packed densities, increased by a packing factor. The cement content and water powder ratio are selected based on the strength requirements. Fly ash and slag pastes are added to fill the remaining volume. The water demand of fly ash and slag are determined separately with the flowtable test.

The method uses a packing factor to select the contents of sand and coarse aggregate. Not all of the values needed for selecting initial proportions are well defined. Several factors such as the packing factor, sand aggregate ratio and relative amounts of slag and fly ash must be chosen initially. Water is selected in three separate processes and does not take into consideration the combined effect of the total water content on strength or workability until trial concrete proportions are evaluated.

6.3.8 University of Rostock (Germany) Method

The mixture proportioning method developed at the University of Rostock in Germany aims to determine the optimum water content for SCC based on the water demand of the individual solid components (Marquardt, Diederichs & Vala 2001; Marquardt, Diederichs & Vala 2002).

a) In the first step, the aggregate grading is selected. Concrete is assumed to comprise three volumes: the volume of aggregate $V_g$,
the volume of the paste required to fill the voids between the aggregates \((V_{LHP})\), the volume of the surplus paste \((V_{LU})\). The total paste volume \((V_L = V_{LHP} + V_{LU})\) is related to by a factor \(\kappa\).

\[
\kappa = \frac{V_L}{V_{LHP}} \tag{6.4}
\]

The value of \(\kappa\) depends on the shape and size of the aggregates and is normally set between 1.9 and 2.1 for SCC. To determine the total paste volume needed, the compacted volume of aggregate \((V_{GO})\) and the volume of voids between the compacted aggregates \((V_{HPO})\) are measured for the selected grading. The values of \(V_{LHP}\), \(V_G\) and \(V_L\) are calculated as follows:

\[
V_{LHP} = \frac{1000}{\kappa + \frac{V_{GO}}{V_{HPO}}} \tag{6.5}
\]

\[
V_G = \frac{V_{LHP}V_{GO}}{V_{HPO}} \tag{6.6}
\]

\[
V_L = \kappa V_{LHP} \tag{6.7}
\]

b) In the second step, the volumes of paste and aggregate in the concrete are determined.

c) In the third step, the cement type and quantity is selected based on hardened property requirements.
d) For the fourth step, the types of additives such as fly ash or limestone powder, the type of HRWRA, the type of VMA and the air void content are selected.

e) In the fifth step, the water demand of all solid components is determined.

The aggregate blend is selected and the paste volume is selected based on a factor $\kappa$ which depends on the size and shape of the aggregates. The water demand of each solid component is determined separately. These water contents are added to select the total water content and establish the final mixture proportions.

This method evaluates the voids between the aggregate but does not suggest that the aggregate blend with minimum voids be selected. This method uses a unique approach for the selection of the paste volume and the determination of the water demand of the solid components.

This method computes a single water content which may produce an inappropriate viscosity. Further, the water demand of the concrete mixture may vary as the paste volume is varied. Limited guidance is given on selecting an aggregate blend. The determination of water demand for aggregates by centrifugation may not be feasible for all labs.

6.3.9 Statistical Design of Experiments Approach

Multiple researchers have used statistical design of experiments (DOE) techniques to evaluate the effects of mixture proportions, select trial proportions and optimize proportions. DOE techniques provide a way to evaluate the effects of different factors in a statistically sound manner and
with a minimum number of mixtures. Regression models are fitted to the results of each measured response.

A central composite response surface is the commonly used approach. Some prior knowledge of both the materials to be used and SCC proportioning is required to select the values of factors used in the experiment design such that all or most mixtures exhibit SCC or near-SCC flow characteristics. Although the absolute values of the modeled responses may change when different materials are used, the general relative trends illustrated for a certain set of materials and proportions may remain consistent when a different set of materials is used (Ghezal & Khayat 2002). Similarly, Nehdi et al. (2001), developed artificial neural networks to predict SCC performance based on mixture proportions.

Statistical design of experiments techniques are used to evaluate the effects of 4-5 parameters in a statistically efficient way. Regression models are used to evaluate data and optimize proportions. The resulting regression models are specific to only the materials and range of proportions considered. In some cases, many of the mixtures in the reported test plans do not exhibit SCC flow characteristics. Some prior knowledge of the materials and SCC proportioning is required to establish the test plan.

6.3.10 Swedish Cement and Concrete Research Institute (CBI) Model

The Swedish Cement and Concrete Research Institute (CBI) Model is based on the assumption that SCC is a suspension of aggregates in paste (Billberg 2002). The model incorporates aspects of the Minimum Paste Volume Method developed by Van Bui (Bui & Montgomery 1999).

a) In the first step, the aggregate grading is selected.
b) Second, the micro-mortar rheology is established based on rheometer measurements.

c) Third, the performance of trial concrete mixtures is evaluated.

The blend of fine and coarse aggregate is selected to achieve the minimum void content. The paste volume is selected based on the voids between the aggregate or the blocking criteria. The paste composition is selected based on rheology measurements. The mixture is finalized based on trial concrete batches.

This method has detailed criteria for ensuring passing ability. Criteria for the selection of micro mortar rheology and the amount of micro mortar are not well established.

6.3.11 Minimum Paste Volume Method

Minimum paste volume method is based on the investigations of several researchers. Saak et al. (2001) introduced the concept of a self-flow zone in terms of a range of paste yield stress and apparent viscosity values necessary to achieve both self-flow and segregation resistance. In this mix proportioning procedure, the minimum paste volume is selected based on either the solid phase (blocking) or liquid phase (segregation, flowability, form surface finishability) criteria. The paste rheology is then determined on the basis of laboratory testing. To ensure segregation resistance and self-flow simultaneously, an analytical model of a single aggregate in cement paste was developed. Based on this model, they defined a self-flow zone in terms of paste yield stress and paste apparent viscosity. The zone was defined by a minimum yield stress and apparent viscosity for segregation resistance and a maximum yield stress and apparent viscosity for self-flow. The concept of a
self-flow zone, defined in terms of paste yield stress and apparent viscosity, is introduced to ensure segregation resistance and flowability.

This concept was later modified by Bui et al. (2002) to include the effects of aggregates by expanding on the Minimum Paste Volume Method, which was developed earlier by Bui & Montgomery (1999) and Bui (2002). The minimum paste volume to satisfy the solid phase criteria is based on the aggregate grading and reinforcement size. The maximum aggregate volume ($V_{ab\text{max}}$) is computed as follows.

$$V_{ab\text{max}} = \frac{\rho_g + (\rho_s - \rho_g)N_{ga}}{\sum_{V_{abm}} P_{vgm}N_{ga}\rho_s + \sum_{V_{abn}} P_{vsn}(1 - N_{ga})\rho_g}$$

(6.8)

where

\begin{align*}
\rho_g & = \text{Specific gravity of coarse aggregate} \\
\rho_s & = \text{Specific gravity of fine aggregate} \\
N_{ga} & = \text{Ratio of coarse aggregate to total aggregate} \\
P_{vgm} & = \text{Volume ratio of coarse aggregate in aggregate group m (i.e. between two sieves) to the total coarse aggregate content} \\
P_{vsn} & = \text{Volume ratio of fine aggregate in aggregate group to the total fine aggregate content} \\
V_{abm} & = \text{Blocking volume of m group of coarse aggregate} \\
V_{abn} & = \text{Blocking volume of n group of fine aggregate}
\end{align*}
The method provides detailed equations to compute the paste volume required for blocking resistance and liquid phase criteria. However, assumptions must be made regarding average spacing between aggregates. Limited guidance is available for selecting the average spacing between aggregates and for optimizing paste rheology.

6.3.12 Densified Mixture Design Algorithm Method

This method was developed in Taiwan for high-performance concrete and has been extended to SCC.

The Densified Mixture Design Algorithm (DMDA) for proportioning high-performance concrete (Chang 2004) has been applied to SCC (Hwang & Chen 2002; Li & Hwang 2003; Chen, Tsai & Hwang 2003; Hwang & Tsai 2005). This method aims to maximize the volume of solid materials and minimize the contents of water and cement.

In the first step, the densities of various blends of aggregates are considered in order to select the blend with the maximum density. In this mix proportioning procedure, fly ash is considered as part of the aggregate and not the paste. The blends are evaluated in a multi-step process. First, the blend of fly ash and fine aggregate resulting in the maximum density is determined. Then, this optimum blend of fly ash and fine aggregate is blended with various amounts of coarse aggregate to select the maximum packing density of all three components. In the second step, the volume of paste (V_p) is calculated by increasing the volume of voids between the aggregate (V_v) by a factor (N), which is given in the following equation:

\[
N = \frac{\frac{V_P}{V_V} = 1 + \frac{S_t}{V_V}}
\]

(6.9)
where

\[
S = \text{Surface area of aggregates} \\
t = \text{Thickness of paste around aggregates}
\]

The optimum blend of aggregate and fly ash resulting in the lowest voids content is selected. The paste volume is set as the volume of voids between the aggregates and fly ash increased by a factor \( N \). The composition of the paste is selected for hardened properties. This method is primarily intended for high-strength concrete. The aggregate/fly ash combination giving the minimum void content may not be optimal for workability.

### 6.3.13 Concrete Manager Software

The method was developed by Roshavelov (1998) and incorporated into a software package. It is similar to the solid suspension model / compressible packing model proposed by DeLarrard. The “Concrete Manager” software program utilizes a theoretical model to predict concrete rheology and to optimize the proportions of concrete mixtures (Roshavelov 1999, Roshavelov 2002, Roshavelov 2005). The model used in the software includes both a packing model and Mooney’s equation for the relative viscosity of concentrated suspensions. The packing density is first computed from the packing model and then used in Mooney’s equation to predict the relative viscosity which can be related to empirical measures of concrete workability.

The development of trial mixture proportions is completed by the Concrete Manager software. First, the desired relative viscosity is selected based on factors such as placement methods, formwork configuration and reinforcement confinement. Second, the software is used to design an initial
trial mixture that both achieves the required viscosity and optimizes proportions. In the third step, a trial batch is mixed and rheological parameters of yield stress, plastic viscosity and apparent viscosity are measured with a unique capillary rheometer. For the fourth step, the results from the trial batch are compared to the computer calculations and adjustments to the mixture proportions are made as necessary. According to Roshavelov (2005), the predicted apparent viscosities match measured apparent viscosities well.

The method includes the ability to predict apparent viscosity. A unique capillary rheometer is used to evaluate trial concrete batches. The selection of proportions must be completed in the software. The necessary calculations are complex.

6.3.14 ICAR Mixture Proportioning Procedure

The ICAR mixture proportioning procedure (Koehler & Fowler 2007) was developed to incorporate more fully the effects of aggregate characteristics on SCC. The method is based on a representation of SCC as a concentrated suspension of aggregates in paste which provides a consistent framework for evaluating and selecting mixture proportions. The method consists of three steps.

a) First, aggregates are selected on the basis of maximum size, grading and shape and angularity.

b) Second, the paste volume is selected for filling ability, passing ability and robustness.

c) Third, the paste composition is established for workability and hardened properties by selecting the relative amounts of water, powder and air and the blend of powder.
The water-powder ratio is used for evaluating workability, the water-cement ratio for early age hardened properties and the water-cementitious materials ratio for later age hardened properties. Supplementary cementitious materials and mineral fillers are used to ensure sufficient paste volume, minimize cement content, enhance durability, and modify workability.

### 6.4 SUMMARY OF THE MIX PROPORTIONING METHODS

Although each mixture proportioning method takes a different approach, the methods do share some similarities. Most methods with the exception of the Rational Mix Design Method and Statistical Design of Experiments Approach assume that SCC is a suspension of aggregates in paste. These methods must establish three details - the paste volume, paste composition and aggregate blend. The paste volume is set to be greater than the volume of the voids between the compacted aggregates.

The paste composition is usually designed independently of the rest of the mixture based on measurements of flow properties, hardened properties or both. Each method uses a different series of tests and has different target values for selecting the paste composition. Some methods are very specific about the target paste properties while others are much more open ended. The aggregate blends are often but not always selected to achieve the minimum voids between the aggregates. In the final step, the paste volume, paste composition and aggregate blend are combined for the preliminary trial concrete batch or batches.

The methods also vary widely in their level of completeness. Some of the methods provide limited guidance for selecting and varying the values of some key parameters which increases the number of concrete tests required to establish the effects of these parameters. Other methods focus on specific
applications such as high strength concrete, and do not provide guidance for other applications.

### 6.5 SCC MIX PROPORTIONING IN THE CURRENT INVESTIGATION

Self-compactability can be largely affected by the characteristics of materials and the mix proportion. A rational mix design method for self-compacting concrete using a variety of materials is necessary. Okamura & Ozawa (1995) proposed a simple mix proportioning system. The coarse and fine aggregate contents are fixed so that self-compactability can be achieved easily by adjusting the water-powder ratio and superplasticizer dosage only. In the current investigation, the mix proportioning has been done as per the Rational Mix Design Method proposed by Okamura & Ozawa (1995). Mix proportioning has been arrived at as per the following sequence.

![Figure 6.1 Mix design procedure](image-url)

**Figure 6.1 Mix design procedure**
STEP 1: Designation of desired air content

Air content may generally be set at 2 per cent. In case of freeze-thaw conditions or in cold weather concreting, higher per cent of air content may be specified. In the current investigations, air content has been assumed as 2%.

STEP 2: Determination of coarse aggregate volume

Coarse aggregate volume is defined by bulk density. Coarse aggregate (D>4 mm) should be in between 50% and 60%. If the volume of coarse aggregate in SCC exceeds a certain limit, the opportunity for collision or contact between coarse aggregate particles increases rapidly and there is an increased risk of blockagewhen the SCC passes through spaces between steel bars. The optimum coarse aggregate content depends on the following parameters.

Maximum aggregate size: The lower the maximum aggregate size, the higher the proportion of coarse aggregate.

Crushed or rounded aggregates: For rounded aggregates, a higher content can be used than for crushed aggregates.

STEP 3: Determination of sand content

In mix proportioning, sand is all particles bigger than 125 micron and smaller than 4.75 mm. Sand content is defined by bulk density. The optimum volume content of sand in the mortar varies between 40-50% depending on paste properties.
STEP 4 : Design of paste composition

Initially the water-powder ratio for zero flow ($\beta_p$) is determined in the paste, with the chosen proportion of cement and additions. Flow cone tests with water-powder ratios by volume are performed with the selected powder composition. The point of intersection with the y-axis is designated the $\beta_p$ value. This $\beta_p$ value is used mainly for quality control of water demand for new batches of cement and fillers.

STEP 5 : Determination of optimum water powder ratio and superplasticizer dosage in mortar

Tests with flow cone and V-funnel for mortar are performed at varying water-powder ratios in the range of (0.8 to 0.9), $\beta_p$ and dosages of superplasticizer. The superplasticizer is used to balance the rheology of the paste. The volume content of sand in the mortar remains the same as determined above. The target values are slump flow of 24 to 26 cm and V-funnel time of 7 to 11 seconds. At target slump flow where V-funnel time is lower than 7 secs, then decrease the water-powder ratio. For target slump flow and V-funnel time in excess of 11 seconds water-powder ratio should be increased. If these criteria cannot be fulfilled, then the particular combination of materials is inadequate. One can also change the type of superplasticizer. Another alternative is a new additive and as a last resort is to change the cement.

STEP 6 : Finally the concrete properties are assessed by standard tests.

The concrete composition is now determined and the superplasticizer dosage is finally selected on the basis of concrete tests.
6.6 GUIDELINES FOR SCC MIX PROPORTIONS

While determining the mix proportions for various grades of SCC, the following guidelines were considered.

- **Coarse aggregate** < 50%
- **Water / powder ratio** = 0.24 to 0.4
- **Total powder content** = 400-600 kg/m$^3$
- **Sand content** = < 40% of the mortar (by volume)
- **Sand** ≤ 50% of paste volume
- **Sand** ≥ 50% by weight of total aggregate
- **Free water** < 200 litre
- **Paste** > 40% of the volume of the mix

**Table 6.1 Typical range of SCC mix composition**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Typical range by mass (kg/m$^3$)</th>
<th>Typical range by volume (litres/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder</td>
<td>380 – 600</td>
<td></td>
</tr>
<tr>
<td>Paste</td>
<td></td>
<td>300 – 380</td>
</tr>
<tr>
<td>Water</td>
<td>150 – 210</td>
<td>150 – 210</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>750 – 1000</td>
<td>270 – 360</td>
</tr>
<tr>
<td>Fine aggregate (Sand)</td>
<td>Content balances the volume of the other constituents, typically 48-55% of total aggregate weight</td>
<td></td>
</tr>
<tr>
<td>Water-Powder ratio by volume</td>
<td></td>
<td>0.85 - 1.10</td>
</tr>
</tbody>
</table>
With the above parameters, workability tests were conducted and the properties of fresh concrete were verified whether the results were within the acceptance criteria as per Table 7.1. If not, the above parameters were adjusted to get the results confirming to the acceptance criteria.

6.7 SCC MIX PROPORTIONS

The mix proportion of SCC mixes M1 to M8 used in the current investigation is listed in Table 6.2

**Table 6.2 Mix proportion for SCC mixes M1 to M8 (per m$^3$)**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Cement (kg)</th>
<th>Fly ash (kg)</th>
<th>Fine Aggregate (kg)</th>
<th>Coarse Aggregate (kg)</th>
<th>Water (lit)</th>
<th>Superplasticizer</th>
<th>VMA</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>225.0</td>
<td>223.5</td>
<td>892.0</td>
<td>860.3</td>
<td>180.0</td>
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<td>0.400</td>
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<td>M2</td>
<td>271.8</td>
<td>233.1</td>
<td>887.0</td>
<td>863.0</td>
<td>178.0</td>
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<td>851.3</td>
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<td>250.0</td>
<td>819.7</td>
<td>875.0</td>
<td>176.0</td>
<td>2.112</td>
<td>0.634</td>
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<td>254.3</td>
<td>820.7</td>
<td>880.1</td>
<td>175.1</td>
<td>2.474</td>
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<td>764.2</td>
<td>894.0</td>
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<td>276.0</td>
<td>750.0</td>
<td>895.0</td>
<td>175.0</td>
<td>2.778</td>
<td>0.884</td>
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The total weight of copper slag consumed for casting the test specimen was approximately 5500 kg.
6.8 CONCLUSIONS

The main characteristics of SCC are the properties in the fresh state. The mix design is focussed on the ability to flow under its own weight without vibration, the ability to flow through heavily congested reinforcement under its own weight, and the ability to retain homogeneity without segregation. A correctly designed SCC mix with right choice of constituent materials can only exhibit self-compactability characters. Presence of more water may result in bleeding or segregation. Hence testing of characters of SCC in the lab and confirmation at site are mandatory while using SCC in any construction site.