Evaluation of Mechanical Properties of Self-Consolidating Concrete

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EVALUATION OF MECHANICAL PROPERTIES
OF SELF-CONSOLIDATING CONCRETE

by

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A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Civil and Construction Engineering

Western Michigan University
Kalamazoo, Michigan
December 2005
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2005
ACKNOWLEDGMENTS

I would like to acknowledge and thank Dr. Sherif A. Yehia, Dr. Osama Abudayyeh and Dr. Ahmad Jrade of Western Michigan University, Department of Civil and Construction Engineering, for the continuous and enthusiastic support for the entire thesis work.

I would also like to thank all of my colleagues, technicians and all the undergraduate students of Department of Civil and Construction Engineering for the generous support and help for the completion of the thesis.

Lastly, I would like to thank my parents, friends here in United States and Nepal for their support throughout my thesis.

Bhusan Basnet
The concept of Self-Consolidating Concrete is a fresh and rapidly ramping technology in USA, but in some other continents such as Japan and Europe it is in fully fledged stage. The development of this technology has a high potential to economize construction minimizing labor, scheduled time and equipment eliminating consolidation process. In USA, construction professionals are reluctant to its in-effect application because of lack of deliberate and methodological steps for production and applications. The lack of study of its durability characteristics and confusion in design and production process are seems to be vital factors hindering full scale production and application of SCC in USA.

After the literature review and development of a number of SCC mixes in the lab optimization phases, a general procedural model layout for design and optimization of SCC was developed. The final developed SCC was selected among the various SCC mixes based on the developed design and optimization model layout and proposed for the full scale commercial production.

The results obtained from the evaluation of mechanical properties showed that the developed SCC has comparatively better durability characteristics than the conventional concrete. The Cost analysis phase has concluded that the commercial production of SCC is feasible and cost effective in comparison to that of conventional concrete.
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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

The construction industry is refining process and technology relentlessly to obtain higher efficiency by saving cost and time. In the world of concrete, besides the cost of material, lengthy process and number of labor involvement to handle it have highly increased the overall cost of construction. Moreover, lack of skilled labor working with concrete has increased the problem. In some of the continents having harsh weather condition, the scheduled construction time use to be very short, so people look for the methods to accelerate the process. The reduced scheduled time and labor cost have high effect on reduction of the overall cost of construction.

The evolution of Self-Consolidating Concrete (SCC) has opened the possibility to reduce both scheduled time and labor cost providing ease in construction. It has also increased the feasibility of construction in those areas lacking number of skilled concrete labor. However, people still have confusion in its long term performance which is hindering the production and its widespread use. Some of the countries such as Japan, other Scandinavian countries have already established guidelines and standards of its production depending upon their own research and started the application in high scale successfully. Whereas, most of the countries including the United States have not started full scale production and application of SCC. Different standard establishing agencies in US have also not established any guidelines for the production of SCC which could be the greatest reason retarding its application.
During the development stage of SCC people have come up with different approaches to enhance its feasibility and production process that differ only by some of specific localized benefits. The development of various approaches definitely spreading the idea in construction industry but concurrently it's also creating confusion on producers for finding the best one to follow. People are still not convinced and informed enough to its application. However, its widespread research interests on construction related people and different agencies have increased the potential of its application. The research on SCC is become important not only to introduce this new concept in construction but also to evaluate its performance and benefits in comparison to the conventional concrete.

This thesis has established a common methodology strictly sticking to the codes and standards for the production of SCC summarizing various approaches. The testing and performances validation ease a producer of any location to convince and adapt this new technology.

1.2 THESIS OBJECTIVE

The objectives of the thesis work mainly cover four areas of study which are:

- Investigate the feasibility of the production of SCC using locally available materials.
- Evaluate parameters affecting the fresh stage properties of SCC with materials conditions.
- Establish guidelines for the SCC mix design depending on codes and previously developed approaches.
- Evaluate the mechanical properties of SCC.
1.3 METHODOLOGY

To achieve the previous objectives, the work in this thesis was divided into four steps:

- Literature search
- Establishment of requirements and guidelines
- Optimization, which consists of three phases:
  - Phase -1: Optimization; to achieve the material properties.
  - Phase -2: Development of general procedural model layout for SCC mixes design and optimization.
  - Phase -3: Development of SCC mixes on the basis of developed mix design and optimization model layout and selection of optimized mix.
- Extensive evaluation of the Mechanical properties of the optimized mix.
- Validation of results

In the first step, a vigorous literature search is conducted that helps to establish the requirements and guides for the further optimization and experimental works. On the basis of the literature search, the required information for the initial mix design and quality control in production are gathered. The initial mix design is used to perform the optimization process where a practical experience is gained to establish a guideline to come up with more efficient SCC mixes and a final mix for the full scale testing.

During the entire experimental works, materials available in the local area are used to enhance the feasibility of the SCC production. The results achieved from the full scale test of the optimized SCC mix are compared with standard codes and the results obtained by previous researchers for validating its performance.
1.4 THESIS ORGANIZATION

This thesis is mainly divided into nine chapters. The second chapter provides a brief historical development including definition and the application range of SCC. It also shows a current stage of this concept around different continents and pictures why SCC is benefiting in comparison to the conventional concrete and also its limitations. Chapter third includes the search of principles and approaches of SCC mix design developed in different countries. Chapter four mainly discusses about the materials and admixtures required for the production and its effect on the performance of SCC. Discussion of different tests required at fresh and hardened stages, quality control in production, handling and placing methods, short environmental and ecological aspects of SCC are discussed in chapter five. Chapter six includes mix design optimization process conducted in the lab. On the basis of literature review and lab optimization a procedural guideline layout of mix design and optimization is developed. In this phase, a mix with better performances among different mixes developed on the basis of the procedural model layout is proposed as a final developed SCC mix. Chapter seven covers the extensive evaluation of Mechanical Properties of the developed SCC. Benefit-Cost analysis for the commercial production of the developed SCC in comparison to the conventional concrete is discussed in chapter eight whereas Conclusion and recommendation is presented in the final chapter nine.
CHAPTER 2

SELF-CONSOLIDATING CONCRETE

2.1 HISTORY AND DEVELOPMENT OF SELF-CONSOLIDATING CONCRETE

After the invention of Portland cement in 1824 in England, the concept of concrete began in construction. Numerous researches and studies on this concept have provided adequate information and possibility of its application in almost all types of construction. The importance and widespread use of concrete have after effected people involving in this industry to seek for new method and technology to apply concrete in an economic and efficient way. Any industry is cultured by continuous improvement in process and techniques to achieve required performance and satisfaction. The concept of continuous process and quality improvement in industries has been upbringing new ideas and technologies. The invention of SCC is also the result of seeking improved and efficient methodology in construction industry. The adaptation of any new technology in industries requires very deliberate and methodological steps to ensure its in-effect application. As the concept of SCC is also a fresh and rapidly ramping technology in concrete, lack of proper benchmarking is hindering the range of applications and cropping hesitations. Different researchers and organizations are continuously working to cultivate this concept and establishing different regulations and the followers are also achieving a fruitful results yet but still uncertain about long term performances.

The research and development of SCC was begun in 1980's in Japan at University of Tokyo. Okamura proposed this concept in 1986, who was the first proposing this new technology, and the paper was authorized by Ozawa et al in 1989. The main objective of the research was to overcome quality issues and to
reduce skill labor at the construction site. The reduction in skill labor to consolidate the concrete in Japan was hampering to achieve the expected performances, so the development of SCC was a better alternative to get over it. Its interest started ramping up internationally after the presentation of this concept formally at an international conference on concrete in Istanbul in 1992, whereas the first international workshop of SCC was held in Kochi, Japan in 1998. The Japanese civil community quickly accepted and embraced this technology soon after its development. As a result two big support anchorages of the Akashi-Kaikyo suspension bridge shown in *figure-1*, a suspension bridge with the longest span in the world, were successfully built using 512,000 and 250,000 metric tons of SCC following other many bridges, towers, dams, girders, building as well as tunnel since 1990’s.¹ ³¹

![Akashi-Kaikyo Suspension Bridge](image)

*Figure-1: Akashi-Kaikyo Suspension Bridge³¹*

With the development of SCC in Japan, large companies started in-house research and development facilities to develop their own SCC production and testing technologies. They also kept it secret for their business advantages and started using under different commercial names as Non-Vibrated Concrete of Kajima Company, Super Quality Concrete of Maeda Company, Biocrete of Taisei Company etc. The
average annual production of SCC in Japan for the last decade was around 350,000 m$^3$ including both ready-mix and prefabricated as shown in figure-2.$^2$

![Figure-2: Annual Production of SCC in Japan](image)

The application of SCC started spreading in European continent since last decade where, France and Scandinavian countries come first in its use constructing a number of bridges. Norway initiated its development in 1998 lunching different chemical admixtures to simplify its production.$^{2,7}$ The research and development of SCC in Europe is highly connected to the activity of RILEM and its technical committee TC 145-WSM on 'workability of fresh special concrete mixes'. It is founded in 1992 aiming to look the production stage of special concretes to identify special parameters of the mixes in fresh stage that provides a reliable performance and economic production. In 2002, the SCC market share was five percent in RMC and PC in Sweden, and was almost doubled in 2003. The Swedish National road administration is continuously involving in the application of this technology in houses, tunnels and bridges construction. In Netherlands and Germany, different precast and prestressed concrete companies are the main involving in the study and
development of SCC. The expected market share of SCC in Netherlands in 2003 was eight percent.29

In USA, SCC is still not being used successfully in construction yet but some of precast industries have started this concept in practice applying in bridges and road pavements.2 It was estimated that the annual production of SCC in USA in the first quarter of 2003 would be around 8000m³ i.e. 1% of total ready-mix concrete production but the actual production was exceeded by higher amount at that time. The total production and application of SCC in USA until the end of 2005 is estimated 130,000 cubic yards.41 A survey in 2000 shows, several state departments of transportation (23 according to the survey) were involving in the study of SCC.28 Its interest has more accelerated in USA after the first North American conference on the design and use of SCC held in 2002. Till now many states have tested and applied in small scale construction successfully. The involvement of ASTM, PCI certified precast industries such as Rotondo Precast have been contributing remarkably in the development of SCC in USA.41

The research and application of SCC is also started in Canada. They have started using high flowable concrete in practice since 1990s. They have applied the concept of high flowable concrete in the Plaza Bridge and Confederation Square rehabilitation project and completed successfully in 1999. Some of the institution highly involving in the research and development of SCC in Canada are Institute of Research in Construction, Canadian Precast/Prestressed Concrete Institute, CONMET-ICON, and ISIS.30
2.2 DEFINITION OF SELF- CONSOLIDATING CONCRETE

The concrete that consolidates itself is Self-Consolidating concrete but different people have defined it differently on the basis of materials used and the purpose of production. Originally, it was defined in Japan as the concrete that can be consolidated into all the spaces and corners of formwork only by means of its own weight without need for any vibration. Defining it at different stages, it is self compactable in fresh stage, avoids initial defects in early stage and protects against external factors when it gets hardened. Norwegian SCC developers have defined it on the basis of its properties as the concrete that compacts by its own weight, it flows highly persisting stability. It acts out like under water concrete but flows rapidly with no segregation and bleeding.

2.3 APPLICATION OF SELF-CONSOLIDATING CONCRETE

The research and development of SCC have been concurrently following by wide range of its application in construction. At this stage, precast and pre-stressed concrete industries are predominant in its use. The construction industries of Japan have been using this new technology in almost all type of structures such as building, bridges, tunnels, towers, road pavements etc. SCC was first used in Japan for the construction of a building in 1990, and then it was used in towers of a prestressed concrete cable-stayed bridge in 1991. In 1992, light weight SCC was used to build main girder of a cable-stayed bridge. Later on the use of SCC in Japan increased everyday in almost all types of construction. In Argentina, people have applied this concept successfully in industrial area to build huge panels, construction of bank vault to ensure security, columns in high rise buildings. In Sweden, construction of Sodra Lankan project is one of the best examples of application of SCC. They have applied
SCC for constructing bridges, concrete box tunnel, and retention walls lining rock tunnels, road pavement and other many types of structures.\(^8\)

The possibility of use of SCC is higher than the traditional concrete in the sense of its high range of applicability. The properties and performance of SCC have eliminated down its limitations and increased the range of its application. Internationally this technique has been successfully used in structural as well as architectural purposes. This concept has solved the limited use of traditional concrete providing more flexibility in application. From very thin wall to heavily reinforced mass concreting, it is successfully used achieving better performances. Different architectural section with smooth surface finishing can easily be cast without any difficulties and extra works.

2.4 ADVANTAGES OF SCC

The reason SCC has many advantages; it has been spreading as a better alternative to the traditional concrete. Some of the major advantages it provides are mentioned below:

2.4.1 Saving Construction Time

As it doesn’t need any extra vibration to consolidate, it reduces the casting time. It also avoids the problems associated with compacting equipment resulting delays. The placing of SCC is a continuous process; it highly reduces the time gap between consecutive batches. Use of SCC gives a smooth finishing, it reduces the finishing time. It has relatively high early strength, it minimizes the interference time with other activities. It also reduces the curing time, as it doesn’t need a long time curing as in traditional concrete because of the early strength gaining properties. In the construction of two piers (250,000 m\(^3\) and 512,000m\(^3\)) of ‘Akashi-Kaikyo’ bridge
in Japan, which was opened in April 1998, the use of SCC reduced the anchorage construction period by 20%, from 2.5 to 2 years.\textsuperscript{4,7} They were able to apply different options in site to accelerate the construction. Similarly, in the construction of a large LNG tank (12000m\textsuperscript{3} of concrete) using SCC in Japan in 1998, the total construction duration was shortened from 22 months to 18 months.\textsuperscript{7} It is estimated that normally, using SCC, the construction will be 40% faster than using traditional concrete.\textsuperscript{9}

The application of one new technology increases the possibility of application of other techniques in sites, and addition of each technique extremely helps to accelerate the construction and the cumulative effect is always significant. It can also be rephrased as the indirect benefits of SCC in reduction of construction time.

2.4.2 Cost Reduction

Construction cost savings can be achieved by avoiding delays and saving in labor cost as well. As we have seen a significant reduction in time can be achieved in construction, time highly influence the construction cost. It minimizes the involvement of manpower and equipment needed for consolidation which also led to reduce cost. It also minimizes finishing cost. Normally, it reduces about 10% of cost of construction which is significant.\textsuperscript{14}

<table>
<thead>
<tr>
<th>Traditional concrete (6&quot; slump)</th>
<th>Rheodynamic Self-Consolidating Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 hours to pour 520 ft. bed</td>
<td>2 hours to pour 520 ft. bed</td>
</tr>
<tr>
<td>42.25 labor hours</td>
<td>22.0 labor hours.</td>
</tr>
<tr>
<td>Total labor hours / foot = 0.081</td>
<td>Total labor hours / foot = 0.042</td>
</tr>
</tbody>
</table>

Saving = 0.081-0.042 = 0.039

Table-1: Comparison of Labor Hour Required for SCC and Conventional Concrete\textsuperscript{32}
The initial cost of mix is usually a bit higher than the traditional concrete because of higher fine content and provisions of admixtures but if proper method of mix design is adopted then the traditional mix can be replaced by SCC without any extra cost to achieve the same performances.\textsuperscript{10}

The most important benefit of SCC is labor saving. A research shows there could be a labor hour saving of 0.039 per foot in concrete laying if compared to 6 in. slump conventional concrete with a rheodynamic SCC as shown in Table-1.\textsuperscript{32} The SCC in casting on specifically configured structures like difficult to placing, consolidating areas, highly reinforced structures etc is an optimized technical solution and cut down overall cost. A full scale cost analysis of SCC in another study also showed a possible of 10% saving only in concrete operation cost can be achieved replacing traditional concrete to SCC.\textsuperscript{33}

2.4.3 Improved Quality and Durability

Usually, SCC mix is developed using high amount of fines adding different filler materials. Addition of such fines such as pozzolanic materials increases the durability of concrete specially when subjected to chloride ion and shrinkage. When it is subjected to cast in a heavily reinforced section as shown in figure-3, SCC is the better alternative overcoming the filling and consolidating issues.\textsuperscript{34}

Addition of superplasticizing admixture and air entraining agent increase the freeze-thaw and scaling resistance too. Because of its uniform consolidating nature, filling up all voids, it reduces permeability.\textsuperscript{12} It helps to avoid joints in different bends in complex structural segments casting monolithically that increases the durability of the structure. It performs better in hardened stage with high strength, better in shrinkage, early strength gaining and other major properties too.
2.4.4 Avoid Environmental and Health Hazards

The noise emission by the use of vibrator in the site is eliminated after SCC that benefits people health by different ways. It prevents worker from white finger syndrome. This concrete is proved to be environmentally sound on the basis of different environmental impact categories. The study of different environmental impact of SCC on factors like greenhouse potential, ozone depletion potential, acid rain potential, renewable energy requirement, oxidant generation potential etc. with comparing to the traditional concrete, SCC is found to be more appropriate.¹³
2.4.5 Improve/Optimize Surface Appearance

Figure-4: Surface Comparison of Tradition Concrete and SCC

Since it reaches all over the formwork filling every corner uniformly, an improved surface finishing will be obtained reducing patch work. The amount of fines in SCC is relatively higher that increases the volume of paste and provides uniform and smooth surfaces, corners, and other many architectural shapes as shown in figure-4.35,41

2.4.6 Improve Safety and Working Conditions

The communication between people will be easy on site because of low noise level, people don't have to go inside formwork to consolidate it, and these factors improve working condition and safety.

2.4.7 Utilization of Industrial ‘Dusts’

The disposal cost of dust from different industries is high and it also causes environmental effects because of lack of its proper disposal. The production of SCC needs high volume of dusts and fine materials which we can utilize the industrial dust solving the problems of its disposal and is a disposal cost saving as well.37
2.4.8 Thixotropic Characteristics

Thixotropic characteristics means it stays in semisolid state at rest but after disturbing or agitating, it will gain fluidity again. It helps to retain consistency so that it ensures fluidity during the placing period.\(^{39}\)

2.4.9 Increase Life of Formwork

Use of SCC increases life of formwork due to reduction in wear and tear from vibration. Usually SCC gains high early strength so that the stripping of formwork can be done early.

2.4.10 Pumpability

Because of its high fluidity and use of smaller nominal maximum size of aggregate, it can be pumped very easily and for a longer distance than the conventional concrete. In construction of a bridge in Japan, they have pumped SCC for 200 meters distance with a number of pipes 4-5 meters apart in rows which is almost impossible if traditional concrete were used.\(^{27}\)

2.4.11 Architectural Use

Its self-flowing and consolidating nature eases to produce different architectural shapes. More intricacy and complicated shapes increase difficulties in placing and consolidating, SCC eliminates this problems.\(^{2}\)
2.4.12 Decrease Insurance Premium

The involvement of manpower in big construction is very high. The provisions of health and life insurance of worker increases overhead cost highly. In some of the countries, use of SCC decreases the cost of insurance at construction site.\(^{25}\)

2.5 LIMITATIONS OF SCC

Besides its benefits, SCC has some of the limitations too. A careful selection of materials and admixtures is very important. Small change in environmental conditions and variation in proportions result a considerable difference in its properties, so, expertise is necessary for designing and optimizing the mix to achieve the required performances. A careful supervision and inspection is compulsory at every stage like batching, mixing, testing, transporting, placing etc. The material cost slightly increases due to the use of different admixtures and fines. The cost of SCC mix as in other concrete mixes will be a function of strength, flow radius required and other admixtures that have been added. On average, a general increase of 5% to 10% over the cost of a 6-inch slump concrete can be expected. A high quality formwork required for SCC so the cost of formwork material and fixing cost also increased.\(^{4}\)
3.1 BASIC PRINCIPLE OF SCC MIX DESIGN

The main objective of SCC mix design is to achieve compactability of the mix without vibration. The compaction can only be achieved when the concrete bears high deformability and flows easily without segregation. So, the basic principle of SCC mix design is to increase fluidity of concrete without losing the viscosity. The variation in water content, aggregates amount and superplasticizer amount are the most important factors that control the deformability and viscosity of the mix.

The sufficient fluidity of the mix and resisting segregation are the main factors controlling the design concept of SCC as shown in figure-6. The first necessary factor is the fluidity of the mortar that helps to flow concrete easily and reach every corner of formwork filling voids conforming consolidation.

![Figure-6: Principle of Achieving Self-Compatiblity](image)
The fluidity can be accomplished either by the use of superplasticizer or limited proportion of coarse aggregate and increasing paste volume or both. High powder content in the mix acts as a lubricant for the coarse aggregate maintaining viscosity.³

In increasing the fluidity of mix by using superplasticizer or high water content, the mix becomes vulnerable to segregate. Here, the use of limited coarse aggregate, reduced water content and high fine content on the mix highly help to control segregation. The use of viscosity modifier is also another effective way, whereas applying both of the measures is preferable.³ This will be discussed in Chapter-4.

3.2 MIX OPTIMIZATION

Because of the lack of standard guidelines needed for the mix design as in the case of traditional concrete, mix optimization process is very important to obtained SCC mix design with the required performances. This process helps to develop a mix using locally available materials. Many researchers have developed different optimization processes based on the material availability and performance required.

In general there are three basic approaches to produce SCC mixtures³²:

- **Use of high range water reducing admixtures and viscosity-modifying admixtures:**

  In this approach, the required deformability of mix is achieved by using High Range Water Reducing Admixtures and the stability of the mix at high fluidity level is controlled by using Viscosity Modifying Agents. Normally, in this method, the initial design of mix is done using same method as in the design of traditional concrete. Whereas the required fluidity of mix is achieved by adding High Range Water
Reducing agent and the segregation is controlled by adding Viscosity Modifying Agent.

- Use of High Range Water-Reducing agent and high fine content:
  The use of HRWRA provides high fluidity to the mix whereas the cohesiveness is achieved by increasing amount of cementitious materials and fine aggregate to resist segregation.

- Combination of both methods stated above.

  The basic principle of all of the methods is to obtain the required fluidity of the mix to ensure self-compactability without segregation. Selection of method depends upon the availability of materials and admixtures. The procedure of mix optimization can be explained by the figure-7

\[\text{figure-7: Mix Optimization Process}\]

Mix optimization process starts with fixing the performance required on the basis of the purpose of construction. Consideration of performances that required on
both fresh and hardened stage of concrete is equally important in this process. In fresh stage, its flowability and compactability without segregation are basically important, and other different durability factors at hardened stage are also important to be considered. The selection and availability of materials as per the required performances is the next step of the optimization process as the availability of materials has high influence on the cost factor and its feasibility as well. In the third step, the trial mixes will start, where the performances are tested in the lab and try to achieve them by adjusting proportions, use of alternative materials etc. until satisfactory results are obtained. Once the test results matches to the targeted then the mix is verify on the big scale production on plant or at site.

This way the process of mix optimization is conducted to obtain an efficient mix that fulfills the requirements set up in the beginning. During the process, a careful inspection is very necessary as a small variation in material proportion cause a significant difference in results. The process should follow a careful and detail study of materials properties, such as grading of aggregates, moisture contents, absorption, specific gravity and all other that directly effect on fixing proportions.

3.2.1 Mix Optimization Approaches Developed in Different Countries

Mix optimization or fixing the proportion of materials as per the required performance is the major process involved in the development of SCC. Different countries have developed the approaches in their own way based on the same principle to achieve high deformability without segregation.

3.2.1.1 Japanese Approach

In Japan the research and development of SCC is in progress concurrently with its high scale production and application in almost all types of structures. The
current research and development on the concept of SCC mix optimization has been refining the primitive approach, however, the concept is still the same. Japan has been applying SCC in construction in large scale every year. This method of SCC optimization is effectively used in different types of construction. In Japan, only in the year 2000, it was produced around 400,000 m³ including ready mixed and prefabricated for the construction of towers, bridge piers, buildings, and road pavement.¹⁴

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**Figure-8: Primitive Approach of Mix Optimization in Japan**

The mix component was mainly divided in three categories; the first part is coarse aggregate (CA) of which bulk volume is recommended as 50% of total concrete volume or 35% net volume of total volume of concrete. Second category is the volume of fine aggregate (FA) which is out of 65% of mortar volume, 40% is assumed. The rest, third category, is the volume of paste made of cement and water that is adjusted to achieve the required fluidity of the mix as shown in figure-8.³⁶

This approach is initially proposed by Okamura and Ozawa in 1986 and is very simple. They proposed that the self-compactability of the mix can be achieved by adjusting the water to cementitious material ratio and by addition of superplasticizer on a fixed coarse and fine aggregate volume. Whereas at that time they have not provided any measures that gives an idea about the amount of paste volume to ensure
the passing ability of aggregate through the reinforcement which is studied later on by other different researchers.\textsuperscript{7}

3.2.1.2 Swedish Approach

The Swedish Cement And Concrete Research Institute, CBI, has developed a model for mix design and optimization called ‘Minimum micro mortar volume model’. This model is developed on the basis that the concrete is a particle suspension in both macro as well as in micro aspects. All the aggregate greater than 0.125 mm is considered to be in solid state in macro concrete whereas micro mortar is the fluid or continuous phase in concrete. The micro mortar is considered to be formed by the particles smaller than 0.125mm, water and air. This model mainly deals with design optimization with minimum micro mortar volume that minimizes cost compared to traditional concrete, as micro mortar consist costly products. It is also benefiting in the sense that it takes consideration of the actual aggregate types available at any site without any specific grading or particle shape. This model gives a detail idea of design than the approach that Japanese has developed. It evaluates different criteria as well as performance to obtain required minimum micro mortar volume that provides required properties to the mix.

The minimum micro mortar volume required to ensure the flow of mix without blocking is fixed considering mainly four factors as shown in figure-9, they are:

- Design criteria
- Detailing of reinforcement
- Blocking criteria
- Void content
Water cement ratio is the one that provides an idea about the required strength of the concrete, which is fixed under design criteria and later on, while considering all other criteria, this requirement is maintained not to disturb the required durability.\textsuperscript{15}

Figure-9: Mix Design Model for SCC \textsuperscript{15}

The another criteria that this model has considered is the void content of the mix on the basis of packing properties of components where the void content at different gravel to aggregate ratios is measured. So, for a specific proportion of aggregate in a mix, the void content can be figured out. On the basis of which the minimum micro mortar volume required to fill up the void and the excess micro mortar that ensures the flow can be determined as per the relationship that this model has developed as shown in figure-10.
This relationship helps to fix the minimum paste volume for specific gravel to total aggregate ratio for different types of aggregate. It helps to avoid the unnecessary volume of the paste providing a minimum required volume for achieving the required flowability.\textsuperscript{15}

The amount of least micro mortar volume is again correlated with the spacing of aggregate that it provides to avoid risk of blocking. For a wide range of aggregate size, with certain spacing in mix, the related volume of aggregate is given in the \textit{figure-11}. This figure shows the blocking volume for a specific size of aggregate is

---

\textbf{Figure-10: Minimum Paste Volume Required as per the Amount of Gravel}\textsuperscript{15}

\textbf{Figure-11: Relationship between Clear Spacing and Blocking Volume Aggregate}\textsuperscript{15}
lesser in the case of rounded aggregate than crushed aggregate since they have less surface friction. The maximum total aggregate volume to avoid blocking on the gap of reinforcement can be calculated using the equation-1 given below: 

\[ \text{Risk of blocking} = \sum \left( \frac{Na}{Nab} \right) = \sum \left( \frac{Va}{Vt} \right)/ \left( \frac{Vab}{Vt} \right) = 1 \]

Equation-1

Where, \( Va \) = volume of aggregate taken

\( Vab \) = blocking volume of aggregate

\( Vt \) = total volume of aggregate.

This model developed in Sweden is also basically the elaborated form of the original Japanese concept of providing enough paste for achieving the required rheological properties of the mix. This model has economized the mix by avoiding the unnecessary paste volume which consumes the major part of costly material. A wide range of locally available material has studied and a quantitative method of its application is developed highly increasing the possibility of SCC application in construction.

3.2.1.3 SCC Mix Design in Germany

This approach is developed by the research team in university of Rostock, Germany. It is based on the determination of optimum water content for each component of the mix in lab and the total optimum water demand of the SCC mix is the addition of calculated amount of water demand for each component. The optimum water demand of any component is the amounts of water at which the materials form a complete agglomeration with a thick water film on the surface of all particles and is determined correspond to the optimum power consumption of the mixer driver while continuously adding water to the respective material.

*figure-12* shows the graph plotted between w/c and power consumption for two different types of cement. While in dry stage the power consumption is less since
The shear stress is lower due to lower adhesive force between particles. While adding water the particles start forming agglomerations as the adhesive force and shear stress increase. At a point the power consumption start decreasing while achieving a peak and the optimum water content is the amount corresponding to the peak power consumption. After finding the corresponding water demand of each component, the required deformability of the mix is obtained by addition of high range water reducing agents during the test batches.\textsuperscript{16}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{optimal_water_demand.png}
\caption{Optimum Water Demand for Two Different Cements\textsuperscript{16}}
\end{figure}

The initial proportion of the mix is taken as per the proportions originally given by Okamura, Japan. The amount of each component is calculated so as to obtain the maximum packing density by trial batches and after fixing the proportion the amount of water demand is calculated for each of the total amount of component. Application of this method is very effective on mix optimization without any special consideration and assumptions. With a little lab work, it is not hard to achieve the accuracy.

However this approach doesn’t consider the passing ability and the amount of paste required to maintain the flow as is considered in the approach developed in
Sweden. It only shows the water required forming paste but the amount of fines required. Here, the paste content is varied only with variation in material proportion and type; it doesn’t consider the reinforcement criteria which is very necessary to take into consideration to ensure the passing ability of the concrete through reinforcement.

3.2.1.4 SCC Mix Design in Taiwan

The Taiwanese concrete industries have developed a different approach to the design of SCC mix which is different than ACI method and they named this method as ‘Design by Densified mixture Design Algorithm’ (DMDA). They have successfully implemented this approach on the construction of eighty-five story T & C tower in Kaohsiung, Taiwan.¹⁷

The essence of this method is also to minimize void by maximizing unit weight of mix and to obtain maximum flowability by increasing fines. This method mainly has three steps in mix design as shown in figure-13.

In the first step, the amount of each material (fly ash, fine aggregate, coarse aggregate), beside cement is calculated as needed to achieve least void and maximum unit weight. In the second step, as per the durability and strength factor, w/cm ratio is fixed as in the conventional way. The last step is to fix the amount of cement, water and super plasticizer as per the performance needed and some of the criteria mentioned for w/c ratio and water content.¹⁷

This method is almost reverse to the process of the conventional ACI mix design and is also able to achieve the required properties of self compacting and leveling as well.
3.2.1.5 SCC in USA, Paste Rheology Model

SCC matrix has complex properties that are critical in its production. The prediction of matrix properties should be done critically. This approach is based on a paste rheology model considering different criteria of minimum apparent viscosity, minimum flow and optimum flow-viscosity ratio which is related to average aggregate spacing, aggregate diameter and void content of aggregate. In this study, the effect of aggregate interaction is considered assuming a new paste model of SCC. The properties of the paste matrix are characterized by measuring flow and apparent viscosity. The proposed model is developed by testing different mix with varying paste content, water to binder ratio, cement, fine aggregate content, fly ash type, and coarse-to-total aggregate ratio. It is related to average aggregate spacing (Dss) and average aggregate diameter (Dav). The main principle used in this concept is, the rheology of the mix depends on aggregate volume corresponding to paste volume (Vp), particle size distribution of fine and coarse aggregates, aggregate shape, fine-coarse aggregate ratio, aggregate surface characteristics, and density difference.
between aggregate and paste. These parameters have influence on void content and average diameter of aggregate and eventually affect the spacing between the surfaces of the aggregates.

![Diagram showing the clear distance of aggregate for different paste flow diameter.](image)

Figure-14: Clear Distance of Aggregate for Different Paste Flow Diameter

The average diameter of aggregate can be calculated using equation-2 and the average spacing of the aggregate surface can be calculated by using equation-3 as mentioned below:

\[
D_{av} = \frac{\sum D_i M_i}{\sum M_i} \quad \text{Equation-2}
\]

\[
D_{ss} = D_{av} \left[ 3 \sqrt{1 + \left\{ \frac{(V_p - \text{Void})}{(V_c - V_p)} \right\} - 1} \right] \quad \text{Equation-3}
\]

Where, \(V_p\) = Volume of paste

\(\text{Void}\) = volume of voids

\(V_c\) = total volume of concrete

With the calculated average spacing of the aggregate, again, apparent viscosity and flow diameter of the mix can be estimated by the relationship given in figures-14, and figure-15.
Figure-15: Apparent Viscosity of Mix for a Given Clear Spacing of Aggregate

The result of the study has proposed a range of deformability at different levels of viscosity and flow of the mixes with addition of fly ash, superplasticizer and viscosity agent as shown in *figure-16*.  

Figure-16: Flow of the Mix with Given Viscosity

This new approach combines the criteria for minimum flow diameter, minimum viscosity to optimum flow-viscosity ratio of paste. This model can be used for different coarse to total aggregate ratio, cement contents and different water to binder ratio.
CHAPTER 4

FILLER MATERIALS/ ADMIXTURES

4.1 EFFECT OF USE OF FILLER MATERIALS ON SCC

Different pozzolanic materials can be used as a filler material in the production of SCC. Use of filler material has a significant effect on increasing the deformability of the mix. The desired viscosity of SCC is achieved either by adding VMA or by increasing cement content. The increased cement content highly increases the cost of the mix, so, supplementary cementitious material can be use as the replacement of cement to increase the viscosity. Addition of supplementary cementitious material is the best alternative of VMA to control segregation of the mix and achieving early strength too. These pozzolanic substances also have cementitious qualities, so, it can be used as a replacement of cement. Generally, the supplementary cementitious materials have lower specific gravity than the Portland cement, so, the replacement of cement by it provides more volume of fines in mix and the higher fine content in the mix results improved segregation control of SCC.

4.2 FLY ASH

It is a by- product of pulverized coal, which is non-burnable residue remains as either slag or airborne particles on burning coal in the furnace. Fly ash is widely used processed pozzolanic material as filler materials since long, even in traditional concrete. As the particles of fly ash are spherical, use of it highly increases the mobility of the mix. It also increases the easiness of placement and achieving smooth surface finishing. The strength development is lesser for the first week but after a week it is in the higher rate than the concrete with only OPC and achieved an
equivalent strength after around 28 days as shown in figure-17. The choice of either C or F type of fly ash doesn’t have a significant effect in final strength but use of type C has a higher early strength than type F.\textsuperscript{18}

![Figure-17: Influence of Fly Ash in Compressive Strength \textsuperscript{18}](image)

The use of fly ash is limited to the range of minimum 5\% to the maximum of 25\% of the replacement of cement after maintaining the minimum cement content on mix.\textsuperscript{36} Use of fly ash has other many advantages as mentioned below.\textsuperscript{61,63}

- It improves long term strength
- It provides more fluidity that helps to reduce water content in the mix
- It increases the cohesiveness of mix preventing segregation.
- It helps to reduce heat of hydration
- It helps to produce denser concrete that decreases permeability
- It improves workability
- It improves sulfate resistance
- It resists alkali – aggregate reaction. Etc.
4.3 NATURAL CALCINED POZZOLAN

Use of natural pozzolan in SCC can reduce the cement content by a significant amount, in an experiment conducted by Rotondo Precast in the USA, the optimum pozzolan content is found to be 30% for achieving good results in preventing segregation and sufficiently early age strength. They have used pulverized calcined shale as a replacement of cement. The specific gravity of this natural calcined pozzolan was around 2.63 replacing the cement having sp. Gravity of 3.15; this property provided a higher amount of fines in the mix and facilitated to achieve the required Rheological properties of SCC easily. The slump spread is found to be 2.2 inches greater than only using Portland cement at equal water content. Air content is increased by 0.2% without any differences in strength than the mix with only OPC. The replacement of OPC by PCS increased T20 from 2-2.5 seconds to 5-7 seconds ensuring lower tendency for segregation. It is easy to maintain an efficient production schedule when achieving early strength of concrete. For a precast industry, early age strength is very important for quick stripping of formwork and handling. The use of the natural pozzolanic material highly reduces the alkali-silica reactivity as well as the mix will be high sulfate resistant.\(^{21}\)

4.4 SILICA FUMES

Silica fume is also a good filler material for SCC to improve the paste to avoid segregation. It is also same as any other filler material in many aspects, but use of it cause more vulnerable to shrinkage. A Norwegian study on use of it shows its content of 4-10% by cement weight doesn’t significantly affect the drying shrinkage. The excessive use of it might cause increase in drying shrinkage for the first 2-3 weeks as the figure-18 shows.
A careful study on shrinkage is necessary whenever silica fume is used as a filler material since it doesn’t have a uniform influence to predict accurately. On the basis of graph above, we can say that on increasing its amount, the mix will more vulnerable to shrinkage. Silica fume is very effective to use as a filler material in SCC specially when considering relatively higher water to cementitious ratio to attain sufficient resistance against segregation.\textsuperscript{22}

4.5 LIGNITE FLY ASH (LFA)

Lignite fly ashes are fine residues produce after burning lignite in power plants. It is also a good fine material and has a better possibility to replace cement in the production of SCC providing more flowability and compactability. Its vulnerability in application is because of high content of free lime and sulfate, so a careful examination is necessary to fix its proportion avoiding concrete fault. However we can use treated lignite fly ash in SCC more effectively to reduce the vulnerability. When the raw lignite fly ash is treated with water, the free lime will changed into calcium hydroxide and becomes inert which prevent the production of high heat of hydration in the mix. The study of lignite fly ash produced from one of power plants in Germany in 2000, has discussed the use of treated and untreated
lignite fly ash on the production of SCC. When using untreated LFA, the initial and final setting time is significantly shortened because of high heat of hydration, and the mix is also susceptible to consistency loss. The concrete is found to be strongly swollen when use more than 30% in proportion. Whereas the strength is found to be approximately equal to that made of only ordinary Portland cement when untreated LFA is used upto 20%. On the other hand, the use of treated LFA has very good results on both workability and durability even at the proportion of LFA in mortar is upto 50% by volume. The use of treated LFA results a very good control on swelling due to the absence of free lime, but the increase in its amount in mix cause reduction in compressive strength in early as well as old ages as shown in figure-19.

![Figure-19: Influence of Lignite Fly Ash in Compressive Strength](image)

It shows the variation in compressive strength on increasing the amount of treated fly ash. Here, a significant reduction of 20 MPa can be noticed when the amount is increased from 20% to 40% ; so, when using treated fly ash in the production of SCC, a careful consideration of the required strength is necessary while fixing the proportion.
4.6  FINE POWDER FROM RECYCLED AGGREGATES

The use of fine powder from recycled aggregates produced by grinding demolished concrete is found to be performed well to use as a filler materials in the production of SCC. It also helps to reduce segregation and increase compressive strength much better than fly ash. The effect of this material in compressive strength is very similar to that of silica fume. In other hand, it benefits people in utilization of demolished waste.37

4.7  EFFECT OF ORGANIC ADMIXTURES ON SCC

Now days, use of admixture in construction is not a fresh idea. We have been applying different types of admixtures to achieve required performances of the traditional concrete since a long ago. The most often used chemical admixtures in traditional concrete are to maintain air content, accelerate or decelerate setting time and to maintain heat of hydration.

The invention of different admixtures has benefited the production and development of SCC. The development in the concept of SCC and the concurrently ongoing search of effective types of admixtures has breded more applicable admixtures widening the range of possibility to produce SCC confirming various performances. Normally, SCC needs two types of admixtures, one is to increase the deformability at low water to cement ratio called Superplasticizer or High Range Water Reducer (HRWR), and the other one is to maintain viscosity confirming segregation control while increasing deformability known as viscosity modifying agent (VMA). As we know the bleeding capacity of concrete is the function of slump since in increasing the slump, the bleeding also increases. In the absence of admixtures, the slump of concrete increases when the amount of mixing water is
increased. In a study conducted in Italy shows concrete made without any admixtures with a specific cement content of 300, 350 and 400 kg/m3 results excessive bleeding when slump is more than 175 mm as shown in *figure-20* and *figure-21*, and ACI 1973 has also standardized the slump value of concrete not more than 175mm.\textsuperscript{37}

*figure-20* shows the relationship between slump and bleeding capacity for three different concrete mixes. The bleeding is excessive when the slump is more than 175 mm. but after the invention of superplasticizer, it became possible to obtain mixes with very high slump value with controlled bleeding. In the same study in Italy, the bleeding capacity with corresponding to the slump was studied for concrete mixes with addition of superplasticizer and found no bleeding with a slump upto 250 mm as shown in *figure-21*.\textsuperscript{37}
So, the invention of superplasticizer in concrete industries has facilitated people to have a higher slump and flow value with controlled bleeding and segregation as well.

4.8 INNOVATIVE HIGH RANGE WATER REDUCING AGENT (HRWRA)

The High Range Water Reducing agent significantly increases the flowability of concrete by its dual mechanism of electrostatic and steric repulsion. It not only increases the deformability but also helps to disperse cement particle uniformly on the mix. This chemical mainly remains sticking with the cement particle during mixing and batching imparting negative charge on the cement particles that cause to repel (electrostatic repulsion) each other as shown in figure-22. The repulsion between particles increases mobility as well as helps to disperse throughout the mix. As the chemical stick around separating the cement particles, that reduces the chance of water to come in contact preventing cement from hydration and led to increase setting time which is the main disadvantage of use of HRWR. However, more research and refinement in the production of innovative HRWR have overcome this drawback producing advanced synthetic (polycarboxylate) high range water reducers (SHRWR). It creates steric hindrance while attaching to cement particles such that it allows more surfaces of cement particles to contact with water which is shown in figure-23.

![figure-22: Electrostatic Repulsion between Particles](image-url)
It helps for the complete hydration, improved dispersion of cement particles, and produces more workable concrete with a normal setting time.

This SHRWR impart the fluid characteristics of SCC allowing the mixture to easily flow into place, even in the presence of dense reinforcement. A major role of these admixtures is to facilitate consolidation without vibration because of their powerful cement dispersing and fluid imparting characteristics. But there are other important roles that these admixtures can play with respect to the desired SCC performance for a given application. For example, a concrete producer would get the most benefit by choosing a controlled set SHRWR admixture product for a high strength concrete application because it would provide the ability to produce very low water-cementitious materials ratio SCC with moderate slump life and normal setting properties far superior to that achieved using traditional HRWR admixtures. 24

![Figure-23: Working Phenomena of Advance Synthetic Water Reducer](image)

4.8.1 Controlled Set Synthetic HRWR

This is a premier HRWR admixture which can provide a water reduction of up to 40%. It facilitates the mix to achieve normal setting characteristics. 24
4.8.2 Controlled Slump Retention Synthetic HRWR

It is also a premier admixture similar to the controlled set, but in addition to that it provides extended slump retention so that the mix doesn’t lose flowability quickly and provide a sufficient time for placement.\(^{24}\)

4.8.3 High Early Strength Synthetic HRWR

This product is developed with slightly modified mechanism. The molecule of this admixture provides relatively longer side chains and shorter main backbone. The short backbone of the admixture’s molecule binds and covers less of the surface of the cement grain than the other synthetic HRWR admixtures as a result more rapid cement hydration and strength development will be achieved.\(^{24}\)

Besides these admixtures, other different admixtures with different commercial names are commercially available. Especially in US, Master Builders has developed three HRWR in three different commercial names in liquid ready-to-mix form that help to reduce 5% to 40% of water content in concrete.\(^{32}\)

4.8.4 Glenium 3030 NS

The recommended dosage of this type is 3 fl oz/cwt (195 ml/100 kg) to 18 fl oz/cwt (1170 ml/100 kg) for different purpose. Application if this admixture has not a significant effect on setting time as well as slump retention in comparison to the plain concrete as well as concrete with traditional superplasticizer. It gives a high and significant early strength in comparison to others.\(^{32}\)

4.8.5 Glenium 3000 NS

It is applied in the dose of 4-12 fl oz/cwt (260-780 ml/100 kg) of cementitious materials. The application of this admixture also increase significantly the early ages compressive strength but it doesn’t effect the setting time and rate of hardening.
remarkably in comparison to the cases of plain and concrete with traditional water reducing agent.\(^{32}\)

4.8.6 Glenium 3200 HES

This admixture is very effective in production of concrete with very high early strength requirements. It provides extremely high early strength to the concrete. In comparison to the plain and concrete with traditional water reducing agent, it has a less slump retention. The concrete should be placed within 20 minutes after addition of this admixture to ensure the required flow and a field trial mixture is highly recommended before its application.\(^{32}\)

4.9 INNOVATIVE VISCOSITY MODIFYING AGENT (VMA)

Viscosity Modifying Agent (VMA) is very effective admixture to provide stability to the highly deformable concrete. As its name says, it modifies the viscosity of the mix as per the requirement and contributes required viscosity to the mix to prevent it from segregation. Its invention and application in SCC has facilitated the production in a high range of deformability as required. Increasing the amount of HRWR admixture in constant water to binder ratio, the fluidity of mix will also increases concurrently with its vulnerability to segregate whereas, after the application of VMA, the vulnerability can be avoided effectively.

The use of VMA can be benefited in many ways by concrete producers and contractors as it provides the possibility to use gap-graded or manufactured sand in its production and also facilitates easy pumping, placing, and finishing. As in practical cases, the moisture content of coarse as well as fine aggregate changes daily as per the environmental condition, the fluidity of mix also varied and may cause trouble in controlling the segregation. At this time, the use of VMA in varying dosage can
overcome these deficiencies by controlling the segregation and bleeding. In the cases, where one cannot increase the fine content in the production of SCC, use of VMA make it possible to control segregation without increasing the volume of paste as it facilitates flexibility in proportioning the mix.

There are mainly two types of innovative VMA commercially available which can be used without disturbing the setting time of concrete.\(^\text{24}\)

4.9.1 VMA Thickening Type

The main function of this type of VMA is to thickening concrete by increasing the viscosity. It doesn’t significantly affect the deformability of the mix and provides stability reducing segregation.\(^\text{24}\)

4.9.2 VMA Binding Type

This type of admixture provide more viscosity to the mix than the thickening type as it binds water within the mix and prevent from bleeding as well as segregation. The additional benefit of this admixture is, it facilitates the concrete to have thixotropic properties which means the mix gel up when left undisturbed and resumes its fluidity re-mixing again.\(^\text{24}\)

The viscosity modifying agents in US can be available mainly in two brand names developed by Master Builders in liquid ready-to-use form.

4.9.3 Rheomac VMA 358

It is the one which is thickening type as discussed above. A slight reduction in slump spread can be noticed after its use, but not that significant and the flow can be easily offset by slight increase in water reducing agent. In the recommended dose of 2-10 fl oz/cwt (130-650 ml/100kg), it doesn’t effect the setting time as well as compressive strength significantly.\(^\text{32}\)
4.9.4 Rheomac VMA 450

It is binding type that provides thixotropic characteristics to mix facilitating stability during transport and placement. It also cause a slight decrease in slump spread but still can resume the flow by a little increase in the amount of water reducing agent. A slight higher dosage of air entraining is required to achieve desired level of air content after this VMA whereas its application has almost no effect in setting time and compressive strength. 32

4.10 ULTRA FINE AMORPHOUS COLLOIDAL SILICA (UFACS)

In some of the practices this UFACS is also found to be used in the production of SCC. It is based on the silica particles 5-50nm in size which is much smaller in size than the particles of silica. It is found in the form of opalescent liquid solution (10-50% of solid content). It also helps to reduce bleeding and control segregation at the dosage of 3% to 5% of cement content. It also helps to enhance the stability of concrete due to its high surface area and spherical shape. 37
CHAPTER 5

QUALITY CONTROL IN PRODUCTION OF SELF-CONSOLIDATING CONCRETE

5.1 INTRODUCTION

The choice of Self-Consolidating Concrete in place of traditional concrete will eliminate the quality defects caused by human errors and provides improved properties in both fresh and hardened stage only if the production process is followed by a suitable process, inspection and required tests. Before SCC is produced and used, the mix should be designed and tested to make sure that the mix fulfills the demanded value of workability, segregation and passing ability. It is necessary to prepare a program for spreading information and training that helps to understand the new product and also gain experience how to handle it. The evaluation and discussion after its use is also important for future process and quality improvement. A planned and suitable process should be followed at every stages of activity during its production. As in the case of tradition concrete, there are several stages during concrete production and application as mentioned below: 27

- Mix design and optimization
- Mixing
- Transportation
- Formwork inspection
- Receiving
- Placing
- Curing and treatment after placing
- The every stage should follow by different tests to ensure it fulfills the required performance and its quality is not disturbed.
5.2 MIX DESIGN AND OPTIMIZATION

Mix design should always be followed by tests to find suitable results and other different criteria that help to refine the design process. Before mix design is performed, a thorough idea of the availability and types of equipment at plant and at the job site, evaluation of equipments nature and type, materials availability and properties, manpower availability, environmental conditions and all other related factors that directly affect the mix design should keep in mind. As the whole expected performance is depend on the design of the mix, a little variations in design process highly influence the outcome results. The selection of materials, and proportions should be done on the basis of different performance needed, as mentioned below: 27

- Homogeneity of mix
- Workability required
- T-50
- Slump flow
- Workable time period after mixing
- Passing ability as per the reinforcement detailing
- Segregation control
- Strength development
- Temperature development
- Sensitivity to changes of material used
- Form pressure
- Pumpability etc.

After all these properties are confirmed during mix design and optimization process the results of all of these tests should filed at the plant, and the different mix designs,
tolerances or allowable variations should also mentioned as per the relevant factors.

The report of mix design should at least contain: 27

- Amount of cement
- Amount of fine and coarse aggregate
- Amount of filler materials and its type
- Amount of admixtures and its type
- Amount of total water
- Mixing time and sequences
- Expected strength at different time frame
- List of tests to be carried out during production
- Batch volume
- Allowable variation of water content, and
- Slump flow
- Mixture type and properties.

A proper report and documentation of the variation in results at plant and the job site should also noted and report. The timely re-evaluation and discussion of documentation help to improve process and optimize more realistic design.

5.3 SCC PRODUCTION

The people involving for the production of SCC should be instructed and trained in the beginning to make sure they are following the correct process to handle during the production and delivery. The documented mix proportions and instruction should check prior to begin the production. Since the mixture type has effect on water demand and admixture demand, it should be fixed as it is mentioned in the mix optimization and design process.
The mixture should be thoroughly clean and moisten before start mixing. The free water should avoid since a little change in water content has a high influence. The batching process should also follow on the basis of the designed parameters. In the process of production, different tests to ensure the targeted performance are necessary to conduct at a certain time interval such as:

- Moisture content of aggregates: it can be varied due to the variation in the environmental condition and the supplier’s constraints and the variation of moisture content in aggregate effect the water needed as per the design. It should be measured in the accuracy of 0.5%.

- Aggregate grading: grading curve for aggregate and filler is also checked at least once in a day or as requirement.

- For every batch, the water content on the mix after mixing should check on wattmeter reading if possible.

- Slump flow test should perform for every batch usually for 3 consecutive batches at the start up and after that for every 10th batch.
• L-Box, U-Tube test to ensure the passing ability for the same batches taken for the slump flow tests.

• Segregation test for the same batch taken for the slump test.

These tests usually confirm the fresh stage performance required during the production, and should follow by documentation of each result. 27

5.4 FORMWORK

The shape and size of formwork has a significant effect on the flowing property of SCC as it should ensure a smooth flow throughout the entire formwork. It should confirm a leveled surface as far as possible whereas it has a higher viscosity than the traditional concrete, tightness of formwork has no effect on the surface finishing. The pressure on the wall of formwork is relatively high in the beginning so it should be strong enough to withstand the lateral pressure during placement. The placement techniques used is also very important to be considered. The uniform flow in all places and directions also depend on the method of its placement. The formwork surface quality dictates the smoothness of SCC surface finish. For the bottom surface of slab or the surfaces of column, the smoothness can be achieved by providing smooth and water absorbent surfaced formwork. It is necessary to plumb and level the formwork perfectly before placement of concrete. Mainly three types of materials can effectively be used in the design of formwork they are:

• Steel

• Plywood

• Wood

Some of the researches in Canada said that formwork built of plywood or wood gives smooth surface finishing because of its absorbent property. For better result different types of demoulding agent can be applied on the surface of the
formwork. The demoulding agents most often used are mineral, vegetal, synthetic oils and wax. The use of vegetal oil can be efficient choice on achieving smoothness while choosing steel or plywood whereas, due to the absorbent property of wooden formwork, the demoulding agents has not a significant effect. But on the plywood formwork, if the material is new, there is no effect of demoulding agent on the smoothness of surface whereas providing epoxy cover on the surface less voids with highly smooth surface can be achieved as shown in \textit{figure-25}.  

![Image](image25.jpg)

\textbf{Figure-25: View of a White Wall of the Peter Apostle Church in Pescara Cast Applying Epoxy Cover}  

If the skin of formwork is colder than the concrete, then more voids in surface will appear so during winter when temperature is below $5^\circ F$, it is preferred to insulate outside of the formwork to maintain the temperature and normal setting time.

The pressure on the formwork and its variation during different time frame is another most important factor to be considered on designing formwork since SCC has a higher lateral pressure than in the case of traditional concrete. More importantly, the
lateral pressure applied by the plastic concrete controls the design of formwork on vertical faces of high raised columns. The development of lateral pressure varies depending upon different factors such as consistency of concrete, size and shape of aggregate, temperature, placement method, concrete depth, pore water pressure, rate of pouring, cement type etc. A test conducted for an SCC having 650 mm spread shows the variation of pressure depending on different criteria. By reducing the casting rate, the maximum initial lateral pressure will slightly reduce and the influence of section size shows that by increasing the section size, the lateral pressure will also increases.26

During the test in Sweden, the pressure in formwork is not found higher than the normal as found in Canada under the different method of placing, whereas during the tests in France, the form pressure is found to be the same as the hydrostatic pressure. So, it is recommended that on designing the formwork hydrostatic pressure should be considered.35

The pattern of hydrostatic pressure development and variation with respect to time for different height seems to be the same as the nature of the curve for two different heights shown in *figure-26* are nearly same. The lateral pressure increases proportionally attaining nearly the hydrostatic pressure up to a certain age and then starts reducing abruptly as exceeding the age until the concrete takes the pressure itself.26

The age during which the lateral pressure increases proportionally is almost the same as the initial setting time of the concrete. The peak lateral pressure is slightly less than the hydrostatic pressure as the high viscosity of concrete itself reduces its effect. In the case of reinforcement concrete, as the reinforcement also takes part on holding a certain amount of concrete pressure, it slightly reduces the lateral pressure
as well. The lateral pressure also slightly varies with rate of placement of concrete. As the hydration of concrete increases, the lateral pressure will reduce in slower rate.\textsuperscript{26}

![Figure-26: Development of Pressure in Formwork in Different Ages\textsuperscript{26}](image)

5.5 TRANSPORTATION AND PLACING OF SCC

The transportation of concrete depends upon the volume of concrete needed in the site. It is necessary to confirm a continuous placement as far as possible by the transporting agent. Normally transport by truck mixture is preferred if the concrete is produced outside the construction site. The driver should properly educated and given a written instruction about how to handle SCC and the effects of different driving conditions. Use of pump, chute is preferred to deliver concrete from truck to the formwork and concrete hoppers is not recommended.\textsuperscript{35} During transportation, it should avoid agitation to prevent segregation. If the truck driver himself is responsible to add admixtures, a written instruction of amount and method of addition should provided to him. At the place of SCC receiving, before placing concrete, it should check visually or by slump spread test to ensure its required flowability and also
inspect for the segregation. The delivery note should mainly include the target value of slump spread and its acceptance range with production date.

As the properties of Self-Compacting Concrete are different than the traditional concrete, the placing of this concrete in formwork needs different special techniques and consideration. The performance of SCC highly depends upon the placing method adopted. The techniques assumed mainly depend upon the characteristics i.e. size and shape of formwork and nature of reinforcement. The required fluidity of concrete to achieve the required performance also depends on the placement technique adopted and the element characteristics. Reducing labor force on handling the concrete is one of the main goals of SCC so, casting and consolidating SCC with minimal effort cutting down the number of labor makes the method adopted for casting or placing critical.25

5.6 PLACING TECHNIQUES FOR DIFFERENT SECTIONS

5.6.1 Double-Tee

While producing Double-Tee, it's preferred to start placing concrete on the stems first and towards the flanges pouring on the middle to let it flow both sides uniformly. Normally, a slump spread value of 23-26 inches is taken for this purpose.14 The placing method also depends upon the length, width and the reinforcement level of the Double- Tee section. If the section is longer and highly reinforced then the pouring point could be more than one to avoid the aggregate blocking and separation. Screeding and bull floating process can be followed after pouring and the final finish of broom texturing or tinted surface can apply after the surface seems to be achieved initial set.
5.6.2 Modules and Walls

It is hard to achieve a smooth and void fewer surfaces using SCC on this type of thin elements. If the thickness is less than the size of pump pipe and cannot take inside the formwork it will be more difficult. The free fall should avoid as far as possible providing a chute or path to reach the concrete at the bottom first and then slowly moving towards the top. Specially manufactured deflectors or breaker board can be used to guide concrete flow avoiding free fall. A continuous flow should maintain which helps concrete virtually attain a ‘column of transport’ like an elephant trunk that protects separation of aggregate and honeycombing.\footnote{14}

5.6.3 Vertical Column

These are also deep elements where free fall of SCC on forms can create voids and honeycombing. In this case also a continuous flow of concrete is necessary forming its own ‘Column of Transport’. It is good practice to pump SCC on the bottom and let it rise up to avoid bug holes and segregation.\footnote{14}

5.6.4 Beams

Beams having heavy reinforcement, type V or I with height more than 8 ft; found in some of the practice in the construction of bridge girder which are difficult to cast. In most of the cases, the point of pouring SCC is near the one end of the beam section and kept there until the whole section is filled up. For the taller beams, same technique as in modules and wall section mentioned above can be followed.\footnote{14}

5.6.5 Slabs

The points of pouring SCC for slabs are not specific as normally SCC is poured at a point to let it flow towards all directions and leveled itself before changing
to another pouring point. This practice reduces screeding and bullfloating to level the concrete.\textsuperscript{14}

5.7 CURING

Mostly, SCC is produced by using different types of admixtures which is in some of the cases reduces or eliminates the heat curing process to achieve early strength as in conventional concrete. The ingredients in SCC are not different than in conventional concrete so, curing of SCC is essential in the same ways that is mentioned in ACI established guidelines.\textsuperscript{14}

5.8 ENVIRONMENTAL AND ECOLOGICAL ASPECT OF SCC

The environment compatibility of production and use of different construction materials has been under question since long time. The environment and ecological effect due to the exploitation of different materials has taken under consideration only in some of the acute environment condition. Since the 1980s, the general environmental harmony of building materials increasingly being questioned and is highly accelerated in 1990s as a result the optimal use of resources examined. Some of the aroused questions which are still difficult to answer are which building material, in what composition is advantageous in the ecological sense when it is applied for a specific purpose. People are still studying the effects of production and use of concrete on environment aggressively but assessed conclusively yet.

SCC is not a composite of all new materials than what a traditional concrete used to have, but certainly the invention and use of different admixtures, fine materials and change in proportions of other normally used materials have differed it from the traditional concrete. The properties in its hardened stage and the process of
production and application have aroused the interests for studying its ecological and environmental effects.\textsuperscript{13}

If SCC is compared with the standard traditional concrete for its ecological and environment effect, a multiple results will be obtained. in some of the factors like performance, strength, chloride diffusion, gas permeability, capillary suction, SCC is found to have a positive effect whereas it has a worse effect on greenhouse potential, acid rain potential, oxidant generation potentials, and non renewal energy requirement. So, in comparison to the traditional concrete, none of the researchers have found out a solid result to differentiate SCC in terms of its ecological and environmental aspects.\textsuperscript{13}

5.9 TESTS OF SCC

The main basic through which we confirm the performance before we practically implement SCC in field is different tests conducted in lab in its fresh as well as hardened stages. There are some of the tests specially developed for testing SCC in its fresh stage and are not used for the traditional concrete testing yet like slump spread, L-Box, U-Tube, and J-Ring tests. The tests of SCC in hardened stage are not more different than the traditionally used tests for the traditional concrete.

5.9.1 Fresh Stage

At the development stage of SCC there were just a couple of tests available to ensure the fresh stage properties. Slump spread tests was first used during 1980s in Japan with the development of SCC. At the same time, Okamura developed L-Box and U-Type test to check the passing ability, viscosity as well as segregation test. Later on in 1990s other different researchers developed J-Ring test which is widely used by Tviksta in 2000 during his study to test the flowability and passing ability of
steel fiber reinforced SCC. During a study conducted in Kochi University, Japan in 2003, in addition to U-Type and L-Box type tests, Funnel test is used effectively for evaluating specially the material segregation resistance of SCC. The test T-50 is also widely used from the beginning to measure the viscosity of SCC till now.

In the Concrete Producer magazine, Ramburg, 2003, has discussed and compared the inverted slump flow test method with the usual upright slump flow test where a survey was also conducted where 55% of respondents were found using inverted slump flow test. The process of this method is to invert the slump measuring cone while testing. It is found to be more rugged test since a pile of aggregate is used to accumulate at the center of spread but on the basis of the responses, inverted cone method is found to be highly used in US. Countries like Sweden, Norway, Taiwan, Germany, Argentina, Italy and other many European as well as American countries are basically using usual slump spread, L-Box, U-Box, T-50 tests to ensure the fresh stage performances of SCC yet.

The selection of suitable test to be conducted for measuring a specific property is an important factor. There are many tests which are correlated to one another. The selection of tests also depends on the purpose of concrete production like architectural, residential building construction, casting of heavily reinforced elements or for the mass concreting. The suitability of different test method for SCC is suggested in the table-2. 27
Table-2: Suitable Tests of SCC at Fresh Stage

<table>
<thead>
<tr>
<th>Suggested test</th>
<th>Flowability</th>
<th>Passing ability</th>
<th>Viscosity</th>
<th>Segregation</th>
<th>Fiber distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump Flow</td>
<td>**</td>
<td>X</td>
<td>X</td>
<td>*</td>
<td>X</td>
</tr>
<tr>
<td>L-Box</td>
<td>X</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>X</td>
</tr>
<tr>
<td>U-Type</td>
<td>X</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>X</td>
</tr>
<tr>
<td>T-50</td>
<td>X</td>
<td>X</td>
<td>*</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fiber content test</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>*</td>
</tr>
<tr>
<td>GTM stability sieving test</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>**</td>
<td>X</td>
</tr>
</tbody>
</table>

* = Less suitable  
** = Most suitable  
X = Not applicable

The table above shows that slump spread test is very suitable for the flowability test and can also be used for segregation test. Whereas, L-Box and U-Tube tests are mostly used for checking passing ability but these test also give an idea about the segregation and viscosity of SCC. T-50 test is solely used for checking the viscosity of the mix.
5.9.1.1 Slump Flow Test

The slump flow test is used to determine filling ability or flowing ability and it also can indicate the segregation resistant of SCC. The procedure used in this test is according to ASTM C 143 Standard Test Method for Slump of Hydraulic Cement Concrete.

![Figure-27: Slump Spread Test Holding Cone Upright Position](image)

The concrete having slump flow range from 18 in. to 30 in. is said to be SCC and the requirement depends upon the type of construction. The suggested flow range required for different purposes are mentioned in the table-3. It shows on increasing the intricacy of element, the required flow is greater. It is obvious that more congested and reinforced thin wall need more flowable concrete to fill up uniformly avoiding voids.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Suggested range of slump flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inches</td>
</tr>
<tr>
<td>Slabs</td>
<td>18-28</td>
</tr>
<tr>
<td>Lightly reinforced elements</td>
<td>18-28</td>
</tr>
<tr>
<td>Architectural elements</td>
<td>24-30</td>
</tr>
<tr>
<td>Heavily reinforced elements</td>
<td>24-28</td>
</tr>
</tbody>
</table>

Table-3: Suggested Slump Spread Range for Different Purposes
People in USA have been using this slump flow test in a different way called ‘Inverted slump flow test’. The only difference between the usual and inverted slump test method is to keep the cone inverted as shown in figure-28. Since SCC is more flowable concrete, on inverting the cone it provides more room to pour SCC on the cone and prevents spilling the concrete out.

![Figure-28: Slump Test by Inverted Cone Method](image)

This method of slump spread test is seems to be interesting only to save spilling out of the concrete but there are no significant benefits mentioned by the author. Soon after this article is published in ‘The concrete producer’ in 2003, T.C. Holland criticized it saying this new method of slump test is interesting but it misses too much more important points. This test doesn’t purport to tell the user and the measure of flow also doesn’t relate to the actual flow during placement.  

The slump flow depends upon the material used to produce concrete. Water to cement ratio, use of filler material, admixtures, fine to coarse aggregate ratio etc. are the main parameters for the variation of the flow. There are no specific relationships of slump spread with any of these parameters mentioned above, since it can vary with variation of any of these parameters. We can take some of the examples of studies conducted by different researchers and evaluate the nature of slump spread with variation in proportions.
Example - 1

On the behalf of ‘The International Centre for Sustainable Development of Cement and Concrete’ a study on SCC using high volume of fly ash type ‘F’ was conducted in Canada in 2001, where they have developed 10 SCC mixes and their performances were studied, and compared. Here, from second mix to third mix, the w/cm is reduced from 0.45 to 0.4 with 40% of fly ash in both cases, and the amount of superplasticizer is increased from 1.2 to 2.9 L/m3. The result shows the slump flow was found the same. From third mix to fourth mix, the w/cm is again reduced to 0.35 but amount of superplasticizer is increased to 2.9 l/m$^3$, the result shows an increment in slump flow by 25mm. from fourth to fifth mix, they have increased the amount of fly ash to 50% and w/cm is also increased to 0.45 but the amount of superplasticizer is lowered to 0.4 l/ m$^3$, a significant reduction of 130mm slump flow results.$^{10}$

So, this review says amount of superplasticizer plays a vital role on the variation of flowability no matter the water content is. The increase in amount of superplasticizer significantly increases slump flow value even w/cm is reduced at the same time. In fact, the variation in water content varies slump flow but not significantly as superplasticizer does. The final effect of increasing either w/cm or superplasticizer, or both, increases spread. Increase in the amount of fine also has an effect on slump flow. The increased amount increases viscosity of the mix and reduces the flow.

Example -2

In 2003, A study on performance evaluation of SCC in the University of Virginia in cooperation with U.S. Department of Transportation, Virginia was conducted on both laboratory and plant phases.$^1$ Here, during laboratory phase, 15 different SCC mixes were developed and two major mixes were developed in plant
phase. Their performance in fresh as well as hardened stages were evaluated and compared. In laboratory phase, type F fly ash was used by 20% of cementitious material in all mixes. All of these laboratory phase mixes were developed without using any admixtures. All the performances were achieved only by varying amount of cementitious material, w/cm, and fine aggregate to total aggregate ratio.

From first to second mix, reducing FA/TA from 0.57 to 0.50 keeping both cementitious material and w/cm constant the slump flow is found to be unchanged but the mix is more segregated. Whereas in third mix, keeping FA/TA and w/cm same as in the first mix, only cementitious material is reduced, as a result slump is reduced by 3 inch but a bit of improvement in segregation is found. On the fourth mix, keeping other proportion constant in comparison to third, only amount of fine aggregate is reduced, a higher slump flow with more segregated mix resulted. The results of first four mixes conclude that by increasing amount of fines reduces slump flow but control segregation because of increased paste volume and more viscous nature of the mix.

In another three mixes, where w/cm, and FA/TA are kept constant but amount of cementitious material are varied comparing to the first mix. On reducing cementitious material, the slump spread is also reduced and segregation is also controlled. Here it can be concluded that on reducing amount of cementitious material, which includes fly ash that enhances flowability, the slump flow also reduces.

From both of the above examples, it can be concluded that, water reducing agents have a greater influence on the variation of slump spread. A little bit change in the amount will cause a significant slump spread value. Change in water content, amount of fine aggregate and filler materials are also the factors that influences slump
spread value as well as segregation. The slump spread value can be maintained without the use of admixtures. Use of filler materials and high FA/TA can also increase the flowability of mix. So, to obtain a satisfactory result, different trials with changing the proportion of material are necessary until achieving the required performance.

5.9.1.2 U-Tube Test

This test is originally recommended by the Japan Society of Civil Engineers and is developed by Centre of the Taisel Corporation; Japan. This test is used to measure the filling and passing ability of self compacting concrete.

The theory of this test is the interpretation of difference in concrete height in two column of the u-tube box as shown in figure-29. When the concrete flow freely like water the height difference will be zero, so the interpretation of the value of height difference is, lower the value higher will be the passing and filling ability of SCC.

The interpretation of the results of U-Box test on the different studies by different researchers doesn’t give any specific variation of its value with respect to any other parameters. So it is hard to conclude what is the specific parameter one can change to achieve a certain value of U-Box test.

![Figure-29: A Typical Schematic of U-Tube Testing Device](image)
Example-3

As we can take the same study discussed in Example-2 of section 2.6.8.1.1 above where the variation of U-Tube value is random. In this study they have achieved U-Tube value ranging from 10.3 inches to 14.3 inches. At the spread values of 25 inches to 28 inches with U-Tube values 13.5 inches to 14 inches, they have found mixes with better workability and no segregation. Whereas in Plant stage of the study, they have achieved values ranging from 11.5 inches to 13.0 inches and the performance of the SCC were outstanding. So, we can take the U-tube values ranging from 10.3 inches to 14.3 inches as the reference for achieving better performance. The study conducted in Kochi University says concrete with the filling height of over 300 mm (11.8 inches) can be taken as self compacting. 7

5.9.1.3 L- Box Test

This test was first developed in Thailand to test the blocking criteria of SCC, in which the concrete is allowed to flow through a set of vertically placed reinforcement bars across the flow. 43 Figure-30 shows a schematic of L-box and figure-31 shows a wooden built L-Box. 27, 44.

Figure-30: A Typical Schematic of L-Box Device 36
This test is being used broadly in Europe, Asia pacific region and USA and is taken one of the reliable tests of passing ability of SCC. The set up of the L-box device is manufactured in such a way that permits the adjustment of clear spacing of bars to make the test more realistic for different condition of reinforcement. Quantitatively, the ratio of the passing ability is defined by the ratio of $H_1$ and $H_2$ shown in the figure-30. Higher value of the ratio implies better passing ability through the reinforcement.  

**Example-4**

A study on passing ability by Tviksta, 2000 recommend the value of the ratio $H_2/H_1$ in between 0.80 to 0.85 for better performance and says sometimes as below as 0.60 also give a satisfactory result. In France, the French Civil Engineering Association has recommended this ratio not less than 80% to achieve a satisfactory passing ability. The time required reaching the distance of 20cm and 40 cm is also
measured as T20 and T40 and is also the indication of the flow of SCC. Lesser the time better will be the flow is considered. In the research work of Sonebi and Bartos, 2000; has indicated the time T20 and T40 as 1-2 seconds and 0.6 to 1.2 seconds for housing and civil engineering construction purposes respectively.46

5.9.2 Hardened Stage

The performance of SCC at hardened stage is certainly influence by the fresh stage performances. Once from different trial, the proportion can be fixed to achieve the fresh stage performance but it should also confirm the required hardened stage performances. Here also, w/cm, cement content, type of filler material, cement, amount and gradation of coarse aggregate and fine aggregate influence the hardened stage properties of SCC at different stages of age. People mainly focus on compressive strength, flexural strength, performance in freeze and thaw, creep, and bond strength development of the SCC in its hardened stage.

5.9.2.1 Compressive Strength

The standard test method used for this test is as specified in the ‘ASTM C 39 standard test method for compressive strength of cylindrical specimen’. It is done in the same manner as for the traditional concrete for different stages of age. Almost all researchers have tested compressive strength of SCC at different stages to confirm its hardened stage performance, and have achieved excellent results on testing compressive strength of SCC. The variation in every constituent has found to have an effect on compressive strength. Mainly, w/cm ratio, deformability, use of filler material, use of viscosity modifying agent are found to have significant effect in variation of compressive strength. The trend of results obtained by various researchers are compared and discussed below in the examples:
Example-5

The study of SCC for civil engineering construction and for housing purposes, done by the group of authors Sonebi, Bartos, Zhu, and Tamimi in May 2000, have compared the performance of SCC at hardened stage and confirmed the required properties. They have developed different mixes in different proportions. For the Civil Engineering SCC, they have taken w/c ratio of 0.58 and the type of cement used is OPC (42.5). Viscocrete 2 of 1.6% of cement content was also added as a viscosity modifying agent. The fine to total aggregate ratio (FA/TA) used was 0.53 with 20mm NMA size. Whereas for the housing purpose they have used w/c, w/cm ratios of 0.68 and 0.36 respectively with ordinary Portland cement 42.5 and limestone powder as a filler material. Viscocrete 2 of 1.5% of cement content was added and fine to coarse aggregate ratio of 0.53 is taken. With these proportions of mix, they have achieved an outstanding 28 days compressive strength of 47 MPa and 79.5 MPa for housing and civil engineering SCC respectively. The strength development of civil engineering SCC is much higher than that of housing SCC as shown in the curve in figure-32. It is because of the lower w/c ratio in the civil engineering SCC. The use of high amount of Viscocrete could also be the reason for achieving the higher strength of Civil Engineering SCC.
Figure-32: Compressive Strength Development of Civil Engg SCC and Housing SCC$^{46}$

Around 80% of 28 days strength was achieved within 10 days that shows a very good early strength development of the mix. Use of filler material helped the mix to achieve high early strength.

Example-6

In the test mentioned in the Example -2 in section 5.8.1.1. above during laboratory phase, the w/cm in different mixes is varied from 0.33 to 0.47 with fine to total aggregate ratio varying from 0.50 to 0.57 and type F fly ash content of 20%. They have achieved all samples exceeding the minimum specified 28 days strength of 4000PSI, where the strength of all the mixes were almost similar irrespective of the compacting effort confirming Self-Compactability of the mixes.

In the plant phase, the moist cured case in plant phase -2 has higher strength than the moist air cured specimen. The early strength development rate in air cured (phase -1) is better for the first week but it is much better in moist cured (phase -2).
Figure 33: Compressive Strength Development of Two Different SCCs

The w/cm for the phase -1 is taken 0.41 whereas for phase -2 it is taken 0.36 with the same type of ordinary Portland cement type III. The high strength development in the phase -2 is also because of lower w/cm ratio than it is in phase -1. In phase -1 about 30% of filler material of total cementitious material is taken and in phase -2, around 40% of filler material of total cementitious material is taken. Higher amount of filler material has shown higher rate of early strength development in figure 33.

Example 7

The test and data provided for Rhedynamic SCC by Master Builders 2002 has also developed several SCC mixtures with and without applying different admixtures and compared the strength at different ages. The obtained compressive strengths of all of those developed SCC mixes are shown within the feasible range and even higher than the designed value. They have taken same w/cm ratio of 0.37 and filler material content 20% of cementitious material to develop all of the SCC mixes. With the same w/cm ratio of 0.37, filler material content of 20% and fine to total aggregate ratio of 0.47, one of the mixes produce by adding Rheomac VMA 358 as viscosity modifying agent has 1 day and 28 days strength of 5120 psi and 9380 psi respectively.
and other one produce just without the VMA has 1 day and 28 days strength of 3920 psi and 8890 psi. Here, we can see a significant difference in compressive strength caused by the use of VMA. Usually, use of VMA significantly increases the strength. The another mix developed has also the same w/cm ratio, filler material content as in the mixes discussed above but the FA/TA ratio is reduced to 0.44, and they have achieved 1 day and 28 days compressive strength of 4600 psi and 8030 psi respectively. This shows the reduction of strength in reducing amount of fine aggregate. \(^{32}\)

5.9.2.2 Bond Strength

The bond behavior between concrete and reinforcement bars considerably influences the properties of reinforced cement concrete. Generally pull out test is performed to evaluate the slips of reinforcement bar and required force at different stages of concrete age to find out bond stress development.

The main factors that influence the bond behavior of rebar are found to be surface characteristics of the rebar, the number of load cycles, the mix design, the direction of concreting, and the geometry of the test specimen. \(^{3}\) Comparatively, bond strength of SCC is found to be higher than the traditional concrete from the discussion of results mentioned in examples of work done by different researchers below:

Example -8

The study on ‘SCC time development of the material properties and bond behavior, 2000’ shows the relationship between bond stress and slips at different ages of concrete under monotonic loading condition and is found the SCC Performing well. In this test, the mix was prepared with w/cm ratio of 0.41 and filler material of around 40% of cementitious material blended with fly ash and quartz powder was
taken. The fine to total aggregate ratio was taken 0.5 and polycarboxylateether as a superplasticizer was added by 1% of cement content.³

![Specimen](image)

**Specimen**

**Electro mechanic pull out testing machine**

Figure-34: Bond Strength Testing Machine and the Standard Specimen³

The results they have achieved are shown in the figure-35. The withstand capacity of SCC is found much higher than that of traditional concrete after 28 days of casting.

![Graph](image)

Figure-35: The Corresponding Bond Strength with Different Amount of Slip³

Normally, the compressive strength of the concrete highly influenced the bond strength of the concrete. As the SCC is found to have higher 28 days compressive
strength, it has higher bond strength too. The higher compressive as well as bonding strength is because of sufficient compacting of concrete.

Example -9

In the study mentioned in Example-5 above, the bonding behavior of rebar and SCC is also compared with the traditional concrete. The ‘pull out’ test was carried out for the study of bonding strength, and the study was done for the two diameters 12 mm and 20 mm rebar. The pull out test was terminated either when pull failure occurred, or reinforced steel began yield, or the surrounding concrete cover failed in split. But for most of the mixes with 10 Db and 6 Db of development length, failure was found because of splitting of cover.

The bond strength of the SCC mix designed for both housing as well as civil engineering purposes were found much higher than the reference traditional concrete as shown in the figure-36, and on increasing the diameter of the bar, the bonding strength is obtained relatively lower. The other interest of the researcher is to study the top bar effect which is the phenomenon of reducing the bond strength on the top portion of concrete. Here, the result of test shows the top bar effect within acceptable range. Comparatively, the SCC mixes have significantly higher bonding strength than the traditional concrete as shown in figure-36. The higher bonding strength of SCC is the indication of uniform and homogeneous distribution of constituent and better compactness as well.
Figure-36: Comparison of Normalized Bond Strength of SCC and Traditional Concrete at Different Ages

Example-10

Holschemacher and Klug, 2002, have also studied the hardened properties of SCC where they have compared the bonding behavior of normally vibrated concrete and SCC as shown in figure-37.

This results indicates the withstand capacity of SCC until longer slip than the normal concrete. Even after reaching highest bond stress, there will be a uniform slip with a negligible stress reduction in case of SCC. Whereas in normal concrete failure
occurred quickly after reaching the peak bond stress condition. Moreover, the lower settlement of SCC in the formwork due to self-de-aeration during flowing provided homogeneity and avoided the top bar effect better than in normal concrete.  

5.9.2.3 Freeze and Thaw Resistance

The method of resistant to Freeze and Thaw test is done referring to ‘ASTM C 666 Standard Test Method of Concrete to Rapid Freezing and Thawing’ document. The performance of properly developed SCC mixes in Freeze and thaw resistant is also found to be acceptable by SCC developers. Some of the results obtained by researchers are discussed below in the given examples:

Example-11

For the SCC mix discussed in Example -5 above, the researchers have studied Freeze and Thaw analysis too. The results that they have obtained are a little bit different for the housing SCC and Civil Engineering SCC. In this case, Civil Engineering SCC is comparatively found to have better performance than the housing SCC. The variation of Ultra Sonic Pulse Velocity (UPV) is very small in the case of civil engineering SCC.

There were no mass loss in any of the SCC they have developed. The civil engineering SCC showed no drop in ultra sonic pulse velocity (UPV) and performed a better resistant to Freeze and Thaw. The UPV reduction after 125 cycles of freeze and thaw was only 5%. The housing purpose SCC mixes performed lower resistant to freeze and thaw action since the UPV value was reduced by 71% after 125 cycles as shown in figure-38. It could be because of higher strength of Civil Engineering SCC and lower of that of housing SCC. The no losses in mass and insignificant reduction in UPV indicate the SCC mix has better freeze and thaw resisting property.
Example 12

The curve of coefficient of relative dynamic elasticity corresponding to the Freezing and Thawing cycles plotted in a study of ISHPC, 2003 shows small variation during 300 cycles count.

The variation of value is not high but reducing after 50 counts by small amounts. As the concrete get older the stress due to freeze and thaw is reducing which shows a favorable performance. The coefficient of dynamic modulus of elasticity varies with the ratio of average UPV at zero cycles and certain number of cycles. The
variation of UPV with cycle is found to be almost constant according to the given curve in Example-11, here, if the average UPV at different cycles is nearly constant, the coefficient of relative dynamic modulus of elasticity should also be nearly constant. The curve found in this study also gives nearly constant UPV value that indicates the SCC performing better in Freeze and thaw cycles.

Example 13

The Transportation Research Division of Maine Department of Transportation has conducted the durability study of SCC and standard concrete and the results are compared in October 2003 for applying the concept of SCC in a bridge replacement project. They have achieved an excellent performance of SCC in comparison to the standard concrete and successfully applied for the project.

The SCC mix they have developed had a w/c ratio of 0.38 with type-III OPC. The constituent contained fly ash as filler material by 15% of cementitious material. The fine to total aggregate ratio was 0.48 with ½” nominal maximum size of aggregate. The slump spread of the SCC was 18” to 24” in different cases. The average relative dynamic modulus of elasticity of the SCC was found to be 99.33 %, mass loss of 1.1% and length change of 0.0064%. These values for standard concrete were obtained 97.016%, 4.3% and 0.013% respectively. The mass percentage loss and length change percentage indicates that the SCC mix performed as well or better than the standard mix.12

5.9.2.4 Drying Shrinkage and Creep

The standard document that we refer to this test is ‘ASTM C 512 Standard Test Method for Creep and Shrinkage in Compression’. Comparatively early age shrinkage of SCC is found to be higher when a higher fine to total aggregate ratio is taken. A lower fine to coarse aggregate ratio helps to control the shrinkage.
The research team mentioned in *Example -5* above has also studied shrinkage and creep analysis of the SCC. They have developed two SCC mixes for the shrinkage and creep analysis. The first mix was prepared with w/c ratio of 0.53, filler material of 34% of the cementitious material. In the second mix, they have w/c ratio of 0.35, and filler content of 10% of cementitious material.

![Figure-40: Strain Due to Shrinkage on SCC](image)

The rate of shrinkage for the both of the mixes is almost found to be same for around 350 days. The initial rate of the first mix is lower than the second for the first 3-4 weeks, but after that the rate is higher for the first mix. The shrinkage of the first and second mixes at around 28 days is almost 350 µm/m and 375 µm/m respectively. The rate of shrinkage for both of the concrete is very small after 350 days. After this study, they have concluded that SCC exhibits slightly higher but under an acceptable range by comparing the drying shrinkage properties of these SCC mixes to the traditional concrete.\(^{46}\)
Strain development because of creep for both of the SCC mix is found to be same until it reaches the value of almost 450 um/m at around 28 days. Then, the strain is found to be higher in the second mix as shown in the figure-41. The rate of increase is almost zero after 350 days for both of the mixes.

![Figure-41: Strain Due to Creep in SCC](image)

The higher strain on the second mix on both shrinkage and creep could be because of the higher cement content and higher fine to total aggregate ratio on the mix. The SCC performs a little bit poor in shrinkage and creep analysis in comparison to the traditional concrete but it still falls under the acceptable region if design properly.46

Example-15

The study of SCC by Master Builder as discussed earlier in Example-7 above also shows the shrinkage and creep analysis of the mix they have developed and compared the value with the conventional concrete. The early stage drying shrinkage
of SCC is found to be almost same as conventional concrete whereas at 28 days, it is found remarkably higher but at the age of 180 days it is found to be even less than that of conventional concrete.\textsuperscript{32}

![Graph of Drying Shrinkage Comparison](image)

**Figure-42**: Comparison of Drying Shrinkage of SCC and Conventional Concrete\textsuperscript{32}

On comparing and analyzing the pattern of drying shrinkage value of SCC and conventional concrete, it can be predicted that SCC has not outperformed and almost same like conventional concrete. The drying shrinkage of SCC is still within the normal range.

5.9.2.5 Modulus of Elasticity

The method specified in ‘ASTM C 469 Standard Test Method of Elasticity and Poisson’s Ratio of Concrete in Compression’ is followed for the evaluation of modulus of elasticity.

The value of Modulus of Elasticity of concrete is required for sizing of structural member and establishing the quantity of reinforcement too. It is the relationship between stress and corresponding strain of hardened concrete, and also provides the relationship between lateral to longitudinal strain so that the additional stress because of the increased strain can be find out. There are several tests
conducted by different people to analyze modulus of elasticity of SCC and found to be under normal range, even better results than conventional concrete. The study of ISHPC in 2003 shows the range of Modulus of Elasticity 30 GPa (4.35 x 10^6 psi) to 36 GPa (5.22 x 10^6 psi) for SCC with 28 days compressive strength of 40 MPa to 80 MPa which is found to be acceptable if checked according to the ACI guideline. The Masters Builder's test result of SCC hardened properties also shows the value of Modulus of Elasticity ranging from 2.54x 10^6 psi (17 GPa) to 3.28x 10^6 psi (22 GPa) after 1 day, and 4.52 x 10^6 psi (31 GPa) to 4.83 x 10^6 psi (33 GPa) at 28 days for different SCC developed in various range of proportions with different typed of admixtures. The researchers group Sonebi, Bartos, Zhu, Tamimi, 2000 have achieved Modulus of Elasticity for SCC that they have developed in various proportion of materials and admixtures in between 34 MPa to 42 MPa during the age of 4 months to 11 months. So, these values of static Modulus of Elasticity corresponding to their compressive strength are comparable and validated if refer to the ACI guidelines.
6.1 INTRODUCTION

The purpose of this phase of the study is to optimize SCC mix and to evaluate its performances with the values and results found during literature review. There are many guidelines and methods developed for the design and optimization of SCC on the basis of which many researchers have developed and applied SCC practically in construction successfully. In this phase, several SCC mixes were developed according to the available guidelines and were tested for their performances.

Since one of the objectives of this research is to develop different quantities of materials within SCC mix with the materials locally available. The influence of material characteristics on the properties of SCC was very effective. The properties of available coarse aggregate, fine aggregate, types and availability of filler material, admixtures were the most important factors to be considered before designing SCC. Basically when SCC mix is decided to achieve using admixtures, the selection of suitable type is very important. Admixtures play vital role on changing the fresh as well as hardened stage performances. A careful study of admixture properties and its influence on the mix should be done before selecting the types.

The experimental investigations in this study consist of three phases they are briefly explained below:

- Phase- 1: In this phase the methodologies, strategies and results obtained from the development of proportions of SCC mix were studied and evaluated.
- Phase- 2: Based on the evaluation and recommendation of mix design for SCC by other researchers, an analysis model was developed in this phase. Effects of
different elements on the development of w/cm, amount of cement, volume of water reducers and quantity of aggregates was developed. Based on these studies, a trial mix was developed and its properties were evaluated.

- Phase- 3: keeping in view the developed model and the trial mix carried out in phase -2, several trial mixes were tested in this phase of study. Applying the evaluation criterion, different trial mixes were carried out and the optimum amount of materials to be used in the final mix for extensive evaluation of mechanical properties was selected. Workability, segregation, and bleeding were the evaluation criterion

6.2 PROPERTIES OF MATERIALS USED IN SCC

Same materials were used in SCC as other conventional concretes with different proportions. During trial mixes, the optimum amounts of the materials were developed and their effects on the properties of the concrete mix are explained in detail below:

6.2.1 Admixture

The admixtures used were ‘Glenium 3000 NS’ as an HRWR and ‘Rheomac VMA 362’ as a Viscosity Modifying Agent, the innovative products of Master Builders which is widely available and used by the local concrete producers. The available HRWR helps to increase the early strength of the mix. These two agents are shown in figure-43. It reduces almost 40% of water demand without effecting the setting time and rate of hardening remarkably. The maximum amount of HRWR added during experiments was 60 ml per cubic ft. volume. The VMA available is the binding type, it increases the viscosity preventing segregation and bleeding. It also
provides the mix to achieve thixotropic characteristics. The maximum amount added to the mix on experiments was 8ml per cubic ft. volume.\textsuperscript{32}

Figure-43: Innovative HRWR- Glenium 3000 NS and VMA- Rheomac VMA 362

6.2.2 Cementitious Materials

Cementitious materials easily available in the local market and used for the optimization of SCC were Ordinary Portland Cement and type C Fly Ash as a filler material. For the final optimized mix, type C fly ash was used but in the beginning of the optimization process, type F Fly Ash was also used. There was no significant difference in the outcomes on using either of the fly ashes. So, on the basis of local availability and early strength gaining property, type C was used for the final mix. The use of fly ash at a certain amount of cement by weight in a SCC mix is highly recommended. It is because at one end it economizes the mix by reducing the amount of cement and on the other end it fulfills the requirements of fines that are needed in the SCC mix. Fly ash also helps to provide mobility to the mix since its particles are spherical and very fine in shape. The replacement of cement by fly ash also prevents the mix from alkali-silica reaction, sulfate attack, and provides cohesiveness preventing segregation.

6.2.3 Aggregates

Sources of aggregates:

- Crushed limestone aggregate: Portland in Michigan
• Natural sand: AGG industries quarried from Marshal, Michigan.

The aggregates were delivered from local supplier. Crushed limestone with 1” (25mm) NMA was used as coarse aggregate. The gradation curve shown in figure-44 shows that the coarse aggregate was well graded. The fine aggregate used was well graded natural sand. The fine and coarse aggregate were separated by 2.76 mm sieve. The crushed aggregate has angular shape that helps to increase the tensile and flexural strength of the concrete and also increases the bonding strength.

The results of the sieve analysis shows, the rough fineness modulus of fine aggregate is 5.2 and that of coarse aggregate is 3.6. For achieving the optimum packing density, the fineness modulus of both of the aggregate should close or equal to each other. Moreover, according to ASTM C 33-90, the fineness modulus of aggregates should fall within the range of 2.3 to 3.1 for achieving good results in concrete. Here, the aggregates available have different properties. The high fines from use of filler material facilitate the aggregates to achieve high packing density in the case of SCC.

![Figure-44: Gradation Curve for Fine and Coarse Aggregates](image)

During the material investigation, the properties of the material used for the mix optimization is also tested. It shows, the unit weight of fly ash is very low than that of cement. The replacement of cement having higher unit weight by fly ash
provides high amount of fines in the mix, that helps to achieve SCC performing good as mentioned above. The unit weight of both coarse and fine aggregate is almost equal and, relatively higher, that helps to withstand aggregates in high strength requirements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Unit weight (Lb/ft³)</th>
<th>Sp. Gr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly Ash</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table-4: Material Properties

6.3 EQUIPMENT USED DURING THE OPTIMIZATION PROCESS

The SCC mix optimization process needed almost same types of equipments and devices as in the case of traditional concrete. Only some of the equipments such as L-Box, U-Tube to test the filling and passing ability of the mix are necessary beside the usual ones.

Slump spread test, filling and passing ability tests and check for segregation are the most important tests to confirm the performance of SCC in fresh stage. Sometimes, air content test is also important while using concrete in special situations such as in very cold weather where higher air content is necessary. During optimizing
process, compressive strength test is necessary whereas other long term durability tests are performed for only the optimized mix.

In the fresh stage, normal Abraham's cone was used for testing the spread with a 30"x 35" wooden base plate. It was conducted in normal upright position as shown in figure-45.

![Slump Spread Testing Equipments on the Left and Pressure Type Air Content Testing Device in the Right](image)

Since SCC can have up to 30" of spread, the wooden base should have enough space to accommodate the flow of concrete. Before testing, the wooden plate was thoroughly saturated so that it does not any more water from the mix. Before moving up the cone, the concrete spilled out to the plate were cleared for avoiding blockage to the flow of concrete. The test was performed soon after mixing process completes. The measurement of spread was taken in two perpendicular directions and the average value was considered as spread value. While testing slump spread, the flow of concrete was carefully watched to check the separation of materials and bleeding. In the fresh stage, the air content of the mix was also measured using pressure type air content measuring device as shown in figure-45.
After testing for the slump spread, segregation and air content, the concrete was used for casting cylinders for the compressive strength test. Cylindrical specimen of 6” x 12” was cast for the compressive strength test as shown in figure-46.

Figure-46: Specimen Cast for Compressive Strength Test

In the hardened stage, compressive strength test was performed during optimization. The results of some of the mixes were found to have higher strength than the capacity of the machine, so the test was performed on higher capacity strength testing machine as shown in figure-47 mainly for the specimen older than 14 days.

6.4 EXPERIMENTS AND RESULTS

In the first phase, a SCC mix already developed by a former SCC researcher was taken and compared the outcome. Since the material condition and types used in
this experiment were different than that the researcher used, the nature of variation in outcome results on changing material conditions are compared and taken as a reference for optimizing mix in the second phase.

6.4.1 Phase- 1

The former researcher has developed five SCC mixes and tested successfully. Here one of the mixes was taken in this phase to begin the optimization process. The w/cm ratio taken in this mix was 0.34 and FA/TA was 0.50 with 1” (25mm) NMA size of aggregate. The type C fly ash as filler material was used at 40% of cementitious material. The HRWR and VMA used were 45 ml and 5 ml respectively. The mix was found homogeneous, not segregated well mixed but the slump spread was achieved only 16”. It was not even within the range of SCC.

The variation in results is because of the variation in material conditions. It can be observed here the difference in deformability of mix on changing the coarse aggregate size. The previous researcher has used 20 mm NMA coarse aggregate whereas here 25mm NMA size was used. The effect of change in size of aggregate was found consistent to the summarized properties of SCC shown in table-4.

While comparing the compressive strength, the early strength was found to be less in our case but in older ages, because larger sized aggregate was used the strength was found to be higher. The strength also depends on the gradation of the aggregates, the packing density, fineness modulli etc. Sieve analysis result shows the packing density in our mix is higher because of the use of well graded aggregate. So, the old stage strength was found to be higher. With same w/cm ratio, if a mix has high flowability than other, the early strength will be higher as mentioned in the literature summary, so the reference mix found to have high early strength since it has high flowability but same w/cm ratio.
Figure-48: Comparison of Compressive Strength of Reference and Tested Mix

Later on in this phase of experiments, proportions were changed tending to achieve higher deformability. In this phase, Three SCCs were developed and the results were analyzed as shown in table-5. The first SCC was found to have 19” slump spread which is very good SCC for simple lightly reinforced structures. As we can see in the second SCC, the w/cm ratio is increased; amount of fine aggregate is also increased with decreasing amount of VMA intending to achieve higher flowability. As a result, a spread of 24.5 inches was obtained but the mix was found to be segregated and noticed some bleeding. Again in the third SCC, the w/cm, FA/TA, and VMA kept constant as in first SCC but amount of HRWR is increased to obtain higher flow value. As a result, a spread of 25 inches was obtained, whereas the mix was segregated but no bleeding was noticed.

<table>
<thead>
<tr>
<th>Mix no</th>
<th>W/CM</th>
<th>FA/TA</th>
<th>HRWR ml</th>
<th>VMA ml</th>
<th>Spread inch</th>
<th>Segregation</th>
<th>Bleeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.36</td>
<td>0.49</td>
<td>30</td>
<td>5</td>
<td>19</td>
<td>no</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.51</td>
<td>30</td>
<td>2.5</td>
<td>24.5</td>
<td>no</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>0.36</td>
<td>0.49</td>
<td>40</td>
<td>5</td>
<td>25</td>
<td>yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table-5: Results of SCC in Phase-1
The higher spread value in second SCC than in first is because of the increased water content in the mix and increase in fine aggregate. Since SCC is known to have very high influence in flowability with variation in water content, the highly increased w/cm ratio from first to second SCC increased the flow significantly. Moreover there was bleeding in the mix. The increased amount of fine aggregate increases mortar volume, which also tends to provide more fluidity to the mix and at the same time the reduced amount of coarse aggregate, reduces the friction in the mix enhancing flow. Whereas in third SCC, only amount of HRWR is increased, the flow found to be increased significantly and the mix was segregated too.

So here, the effect of water, HRWR, changing amount of aggregates, VMA gave a consistent results as reviewed in the literature summary. These results have validated and broadened the concept of SCC mix development and also helped to optimize the designed SCC mix in the second phase of optimization process.

6.4.2 Phase- 2

In this phase, summarizing the information from literatures and experience gained from the optimization process in Phase- 1, a general model for the SCC mix design optimization procedure is developed. The flow chart of the model shown in figure-49 can discuss in three steps.

- **Step- 1**

Material and performance requirement are the main factors to be considered in the beginning of the mix optimization procedure. The performance needed and material selection process should proceed concurrently. In the first step, the availability of different materials needed is important to achieve the feasibility of SCC production. It is necessary to select commercially available admixtures and filler material in the local market. After the availability survey of materials, properties
investigation of each of them is necessary to find out effect of the materials on the performance. The flowability and passing ability of the mix should be according to the target application of its use. A careful review of reinforcement detailing is important for the selection of passing and flowing ability of the mix. Higher the amount of reinforcement in a structure, higher flowability and passing ability should tend to achieve. The Nominal Maximum Aggregate (NMA) size should be according to the reinforcement spacing. So, the first step of the mix optimization process is to check the availability, and investigate the properties of available materials and set up the performance needed. It can be referred for the recommended value of slump spread range, value of U-Tube and L-Box for different purposes as discussed in the earlier chapter.

This procedural model layout is developed on the basis of the lessons learnt throughout the vigorous experimentation and literatures review phase. This layout, which is mainly consisted of three steps, can be used as a guideline for the initial SCC mix design and optimization which is entirely developed by the author. The properties of materials available in any locality are thoroughly investigated in the first step. The second step is the design for the SCC which is based on the previous step to compare the required performance. The final step is to change material proportions until achieving the required performance which is called trial mixing process.
Mix optimization process

Material

Coarse aggregate
Fine Aggregate
Cement
Admixtures

Availability

Properties Investigation

Chemical admixtures
Filler materials

Availability

Properties Investigation

Design material Proportions, W/C

Mixing
Properties testing

STEP-1

Mixing
Change Proportions
Properties testing

STEP-2

Mixing
Change Proportions
Properties testing

Not OK

STEP-3

TRIALS

OK

Optimized SCC Mix

STEP-3

Figure-49: SCC Mix Design Optimization Procedural Model
• Step- 2

To find out the optimum amount of the materials and their effect on final concrete mix a model layout is developed and shown in the *figure-50*. The physical properties and the ingredients of the material can be finalized on the basis of the reasons and causes shown at the right side of the layout. The element shown at the left side is in the categorical order and the reasons and causes shown at the right sides are taken from the literature review.

**Figure-50: Procedural Guidelines for SCC Mix Design**
• **Step-3**

The final step is to obtain an optimized SCC with required performance. This step is performed in 'Mixing – Testing performance – Changing proportion' mode until a required performance is achieved after testing. The initial mix proportion obtained in Step-2 is taken to begin the trials. And the proportion is changed on the basis of action – effect relations as shown in *table-6*.

<table>
<thead>
<tr>
<th>Action</th>
<th>Filling ability</th>
<th>Passing ability</th>
<th>Segregation resistance</th>
<th>Strength</th>
<th>Shrinkage</th>
<th>Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase superplasticizer</td>
<td>Increase</td>
<td>Increase</td>
<td>decrease</td>
<td>Increase</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Increase Water Content</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase paste volume (increase filler material)</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase mortar volume</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase NMA</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Increase</td>
<td>Reduce</td>
<td>Reduce</td>
</tr>
<tr>
<td>Increase fineness moduli Of fine aggregate</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>-</td>
<td>Increase</td>
<td>-</td>
</tr>
<tr>
<td>Increase VMA</td>
<td>Reduce</td>
<td>Reduce</td>
<td>Increase</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table-6: Effect of the Amount of Material Change in the Properties of SCC*

The amounts of material were kept changing till the desired performance was acquired.

6.4.3 **Phase- 3**

In this phase, an initial trial SCC mix is design on the basis of *Step-2* of *Phase-2* mentioned above.
Initial Mix design

A. Volume of Concrete taken = 1 ft$^3$

B. Targeted 28-days strength = 7000 psi

C. w/cm = 0.33 for the targeted 28-days strength for NMA = 1" (Portland Cement Association)

D. Targeted air content = 4.5%
   a. For frost resistant: ACI, Table: 4.2.1: Air content = 4.5% for moderate exposure.
   b. For freezing and thawing: ACI R4.2.1: Moderate Exposure: cold climate, concrete only occasionally contact with moisture prior to freezing. The Value from ACI, table 4.2.1. should follow.
   c. ACI 4.2.1: The tolerance in air content can take ± 1.5%

E. Water Content:
   a. Guideline of Portland Cement Association:
      i. 18% of concrete by Volume = 11.23 lb = 0.18 ft$^3$. (180kg/ m$^3$)
   b. EFNARC Guideline:
      i. Maximum limit = 200 kg/m$^3$ (OK with E.a.i.)

F. Cementitious Material Content:
   a. 34.03 Lb/ ft$^3$, @ w/cm = 0.33
   b. EFNARC Guideline:
      i. Cement content range = 21.9 lb/ ft$^3$ – 28.09 lb/ ft$^3$
   c. Master Builders Guideline:
      i. Fly ash content:
         1. usually 20% of Cementitious materials

3. ACI 4.2.3/ table 4.2.3. - Concrete exposed to deicing chemicals, maximum = 25% of total cementitious material.
   
   ii. Taking Fly ash content = 20% of CM = 6.81 lb = 0.04 ft³
   
   iii. Amount of cement = 34.03-6.81 = 27.23 lb = 0.14 ft³
   
   iv. (Ok with E.a.i. & E.b.i.)

G. Volume remaining for Coarse (CA) and Fine aggregate(FA) = 1 - (0.14 + 0.04 + 0.18) = 0.64 ft³

H. Taking Fine Aggregate(FA) to Total Aggregate(TA) ratio = 0.54
   
   a. Amount of FA = 0.54 x 0.64 = 0.345 ft³ = 56.50 lb/ ft³
   
   b. Amount of CA = 0.64 - 0.345 = 0.295 ft³ = 48.81 lb/ ft³

   i. EFNARC Guidelines:
      
      1. CA content range = 28% - 35% by volume of concrete.
      
      c. So, let's take CA = 30% by volume of concrete = 0.30 ft³ = 49.608 lb/ ft³
      
      d. FA = 0.64 - 0.30 = 0.34 ft³ = 55.58 lb/ ft³

   l. The final FA/TA = 0.53.

   J. HRWR (High Range Water Reducer) = 3g per kg of cementitious material = 36.858 ml. = 40 ml Approx.

The designed mix was tested and again the proportions were adjusted to achieve better performance. Several mixes were tested in this phase, out of which three mixes could be classified as SCC. The fresh stage properties of developed SCCs are shown in table-7.
Table 7: Properties of SCC Developed in Phase-3

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>W/CM</th>
<th>FA/TA</th>
<th>HRWR ml</th>
<th>VMA ml</th>
<th>Spread inch</th>
<th>Segregation Visual</th>
<th>Bleeding Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC-1</td>
<td>0.33</td>
<td>0.53</td>
<td>40</td>
<td>5</td>
<td>19</td>
<td>no</td>
<td>No</td>
</tr>
<tr>
<td>SCC-2</td>
<td>0.39</td>
<td>0.52</td>
<td>45</td>
<td>5</td>
<td>19.5</td>
<td>no</td>
<td>No</td>
</tr>
<tr>
<td>SCC-3</td>
<td>0.39</td>
<td>0.52</td>
<td>60</td>
<td>-</td>
<td>25.5</td>
<td>no</td>
<td>No</td>
</tr>
</tbody>
</table>

The proportion of materials in SCC-1 was designed on the basis of guidelines developed and referral codes for concrete design. The variation of material proportions to develop second and third SCC mixes were done referring to the summarized effects of materials variation in properties of SCC as discussed earlier and also from Phase-1 of the experimental works. The result, here in the phase-2 was also found consistent to the previous works.32

The SCC-1 and SCC-2 have relatively lower spread value, which can effectively be used for the casting of lightly reinforced structure. The SCC-3 could be used for densely reinforced structures as it has high spread value.

The SCC-1 found to have higher compressive strength than other two, because of the lower w/cm ratio taken. The SCC-2 and SCC-3 have almost equal strength and the pattern of strength development is also found to be almost same. Comparatively, SCC-3 has a little bit higher strength than SCC-2 as shown in figure-51; it’s because of higher amount of HRWR in SCC-3.
Figure-51: Comparison of Strength of SCC Mixes Developed in Phase- 3

The strength of all SCCs developed exceeded the design strength, so they performed well in 28-day's compressive strength test. All of the mixes were not segregated and no bleeding was noticed.

Usually, to confirm self compactability and filling ability mix with high spread value is preferred. The SCC having high flow value is possible to use at any cases of reinforcement. In comparing the results of SCCs developed, SCC-3 has higher spread value. As SCC-3 has better performance in fresh stage and also satisfactory performance in strength, this mix is termed as the optimized mix will be evaluated for the further extensive mechanical properties in the next phase.
CHAPTER 7

EXTENSIVE EVALUATION OF MECHANICAL PROPERTIES OF THE OPTIMIZED SCC MIXTURE

7.1 INTRODUCTION

The mix design and optimization process has provided Properties of SCC mixture that satisfies the requirements of Self-Consolidating. In addition to the workability requirements the proposed mixture maintains a higher compressive strength. Achievement of a higher compressive strength of the developed SCC is a result of proper consolidation of the mix by itself.

The study of the long-term performance of the developed SCC under discrete weather condition is very important to authenticate its durability. As the alteration in the properties of the concrete during its service time frame is obvious, the change in properties within an acceptable range is the validation of its durability. Some of the essential properties that the concrete should pose for its durability are resistant to shrinkage, performance in bending stress, deterioration resistant under freezing and thawing, development of compressive strength etc.

In this phase, specimens are cast by producing a required volume of the developed SCC in a local concrete production plant and tested extensively to evaluate the mechanical properties to confirm the durability.

7.2 SCC PRODUCTION FOR FULL SCALE TEST

The full scale test includes test at the fresh stage and hardened stage as well. For the full scale tests, the SCC mix was planned to obtain from the Statler Ready-mix, a local Ready-mix Company. Crushed limestone 25mm NMA and natural sand from the same sources of south west Michigan were used as course and fine aggregate with same gradation as in the optimization phase.
A trial mix of 1 ft³ volume was conducted with the materials supplied by the production plant prior to obtain the full mix volume to check the approximation in the materials properties and adjustment if needed. The moisture content of the provided sand was found to be higher so, the mix was found to have high slump spread of 28.5” resulting segregation. After the amount of water was adjusted to fit with the moisture content of the sand the mix was found to have 24” slump spread without segregation. The U-tube value was found to be 11.5 inches, and H2/H1 ratio in L-box test was 0.81. The test results obtained were consistent to the required value mentioned in different guidelines. So the provided materials and the mix proportion found to be feasible for the full scale test production.

Figure-52: Casting of Specimens

With the given proportion of materials and mixing instructions, the full scale test mix was delivered to the construction materials lab at WMU for casting the specimens. The transportation time from the plant to the lab is 25 minutes. The mix was found to have less flowability with only 17” slump spread. It could be because of the difference in moisture content of fine and coarse aggregates than adjusted during trial mix and loss of consistency during transportation. The mix obtained was adjusted in three trials adding calculated amount of HRWR until achieving the required flowability. The mix was homogeneous and not segregated.
The optimized mix proportion is presented in *table-8* which is taken for the evaluation of mechanical properties.

<table>
<thead>
<tr>
<th>Cement Type I lb.</th>
<th>Fly ash Type C Lb.</th>
<th>CA Lb.</th>
<th>FA Lb.</th>
<th>Water Lb.</th>
<th>HRWR Ounce</th>
<th>w/cm</th>
<th>FA/TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.23</td>
<td>6.81</td>
<td>49.61</td>
<td>52.96</td>
<td>13.19</td>
<td>2.02</td>
<td>0.39</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*Table-8: Proportion of Material for 1 ft³ Volume*

7.2.1 Test Preparation

For the fresh stage test of the developed SCC mix, the following test setups were prepared:

- Slump Spread
- L-Box
- U-Tube
- Air Content
- Unit Weight

For the slump spread test, Abraham’s cone with the base plate as shown in previous chapter was set up. It was decided to use normal upright position method for the test.

The L-Box was fabricated with steel according to the design and dimension as shown in previous chapter. The spacing of reinforcement was fixed at the minimum value calculated for No.-5 rebar as per the ACI code, which is 38mm. The rebar are welded to a detachable plate to ease the replacement and change orientation.
For the U-Tube test, the U-Tube was fabricated with same orientation of rebar as in the L-Box. In this device, the rebar are also welded to a plate to ease its replacement. The U-Tube was fabricated as per the design and dimension shown in previous chapter. For the air content test, the pressure type air content testing device as shown in previous chapter was used as in optimization process, and the base cylindrical mould of the air content testing device was used to measure the unit weight of the SCC.

For evaluating mechanical properties at its hardened stage, specimens were cast for Freeze and Thaw analysis, and Shrinkage analysis, Flexural Strength, Modulus of Elasticity and cylinders for compressive strength. The dimension and
numbers of samples were decided referring to ASTM standards. Steel and wooden formworks for casting the specimen were fabricated as per the standard size requirements shown in figure-55.

Figure-55: Formworks for Flexural, Freeze and Thaw, and Shrinkage Test Specimens

7.3 TESTS OF FRESH STAGE PROPERTIES

Tests at fresh stage were conducted following recommendation of the EFNARC, “Specification and Guidelines for Self-Compacting Concrete”, 2002. The following are the observations during casting:

- Specimens were cast without application of vibrator or any other mechanical consolidation tools.
- The mix was found to be flowing smoothly filling all the formworks evenly.
- Minimum bull-floating was required for finishing the surface.
- As the operation was continuous, the pouring process required very short time period. The fresh stage properties measured and the required range are presented in table-9.
Slump Spread

<table>
<thead>
<tr>
<th>Slump Spread (Inches)</th>
<th>L-Box</th>
<th>U-Box</th>
<th>Air Content</th>
<th>Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H2/H1</td>
<td>T 20 Sec</td>
<td>T 40 Sec</td>
<td>Filling ht. (In.)</td>
</tr>
<tr>
<td>23</td>
<td>0.81</td>
<td>0.8</td>
<td>1.1</td>
<td>11.9</td>
</tr>
<tr>
<td>(18-30)</td>
<td>(0.8-0.85)</td>
<td>(0.6-1.2)</td>
<td>(0.6-1.2)</td>
<td>(10.3-14.3)</td>
</tr>
</tbody>
</table>

The range in the parenthesis are the recommended range of properties of SCC.\(^1,7,32,49\)

Table-9: Fresh Stage Test Results

7.3.1 Slump Spread

After adjustments of the mix, the slump spread obtained was 23”. The measurement was taken in two perpendicular directions and average value was taken as the final value. The spread was uniform without any heaving, bleeding and segregation around the circumference. The paste and aggregate were homogeneously spread around forming a circle.

The spread values that most of the researchers have obtained are 18 inches or more than that to confirm self consolidating. The suggested range of SCC is 18 inches to 30

Figure-56: Testing Slump Spread
inches. On the basis of the recommended spread values, a range of 18 inches to 28 inches slump spread can be taken for casting of slabs and lightly reinforced elements.\textsuperscript{32} The spread value obtained of the developed mix shows it can wisely apply for casting lightly reinforced elements to achieve Self-Consolidation.

7.3.2 L-Box

To confirm passing ability, the recommended value of $H_1$ to $H_2$ ratio is 0.80 to 0.85 for a better performance and sometimes a value of 0.60 also gives satisfactory results. The recommended value of $T_{20}$ and $T_{40}$ are 0.6 sec. to 1.2 sec. respectively depending on spread.\textsuperscript{27,46} The obtained value of the ratio $H_1/H_2$ of 0.81 confirms the passing ability through the designed reinforcement since the value is found to be within the recommended range in literatures. The $T_{20}$ and $T_{40}$ values of 0.8 sec. and 1.1 sec also fall within the prescribed range. It shows the developed SCC mix has sufficient passing as well as flowing ability through the reinforcement.

![Figure-57: Testing on L-Box](image)

7.3.3 U- Tube

The value of filling height ranging from 10.3 inches to 14.3 inches is recommended for confirming the filling ability of SCC. In some studies, a filling height more than 11.3 inches is recommended.\textsuperscript{1,7}
The filling height obtained of 11.9 inches of the developed SCC mix shows it has the property of filling all the corners of the formwork through the reinforcement properly.

7.3.4 Air Content

The SCC is found to have enough air content of 3% without provision of any air entraining agent. The table 4.2.1 of ACI code specifies for freezing and thawing condition and concrete subjected to deicing chemicals, air content should be 4.5 ± 1.5%. In this boundary, the SCC mix is found to have the required air content to resist freezing and thawing condition and deicing chemicals.

7.3.5 Unit Weight

For the maximum aggregate size of ¾”, the range of unit weight of plain concrete is given 145 lb/ft³ to 150 lb/ft³. For the plain concrete having strength less than 4000 PSI, lower value of 145 lb/ft³ and for the higher strength concrete a higher value of 150 lb/ft³ is recommended. 49

The SCC mix is found to have a unit weight of 151 lb/ft³. Since the SCC mix is designed for higher strength, the expected unit weight was around 150 lb/ft³. But the obtained value exceeded by small value. It could be because of larger maximum
size of aggregate of 1” in the developed SCC. It is still not a heavy weight concrete, and can use in a usual way as conventional concrete.

7.4 EVALUATION OF MECHANICAL PROPERTIES

The formworks were stripped off after one day and the specimens were placed in curing tank. The surface of the formwork were new, so there could be no effect of application of demoulding agent on the surface finishing, but synthetic oil was used as a demoulding agent. Following observations were noticed on casting specimen:

- The formworks were demoulded very easily.
- The cast specimens have smooth surfaces with perfect shape.
- There were no potholes and no extra patchworks needed.
- No honeycombing was noticed in any of the specimen.

Figure-59: Curing of Specimen  Figure-60: Surface of Cast Specimen

Dimensions and number of specimens for different tests are summarized in the table-10.
<table>
<thead>
<tr>
<th>Test</th>
<th>No. of samples cast</th>
<th>Required Number</th>
<th>Dimension</th>
<th>Test Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>21</td>
<td>18</td>
<td>6”x12”</td>
<td>1,3,7,14,21, and 28 days</td>
</tr>
<tr>
<td>Freeze and Thaw analysis</td>
<td>16</td>
<td>8</td>
<td>3”x3”x12”</td>
<td>Up to 300 cycles, at every 27-40 cycles</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>12</td>
<td>4</td>
<td>4”x4”x24”</td>
<td>Everyday for a week and once in a week.</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>9</td>
<td>6</td>
<td>6”x12”</td>
<td>1, and 28 days</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>14</td>
<td>12</td>
<td>5.5”x5.5”x21”</td>
<td>7, 14, 21, and 28 days</td>
</tr>
</tbody>
</table>

Table-10: Number and Dimension of Specimens Cast for Testing Mechanical Properties

7.4.1 Normative References for the Mechanical Properties Testing

For the evaluation of mechanical properties, testing procedures for all evaluations are followed referring to ASTM standards as mentioned in the table-11.
<table>
<thead>
<tr>
<th>Test</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive</td>
<td><strong>ASTM-C 23/C 39 M-99 Test Method for Compressive Strength of Cylindrical</strong></td>
</tr>
<tr>
<td>Strength</td>
<td><strong>Concrete Specimens.</strong></td>
</tr>
<tr>
<td>Modulus of</td>
<td><strong>ASTM-C 469-94 Test Method for Static Modulus of Elasticity and Poisson’s</strong></td>
</tr>
<tr>
<td>Elasticity</td>
<td><strong>Ratio of Concrete in Compression.</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Cement Mortar and Concrete.</strong></td>
</tr>
<tr>
<td>Freeze and Thaw</td>
<td><strong>ASTM-C 666-97 Test Method for Resistance of Concrete to Rapid Freezing</strong></td>
</tr>
<tr>
<td></td>
<td><strong>and Thawing.</strong></td>
</tr>
<tr>
<td>Flexural Strength</td>
<td><strong>ASTM-C 78-94 Test Method for Flexural Strength of Concrete (Using Simple</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Bean With Third-Point Loading)</strong></td>
</tr>
</tbody>
</table>

Table-11: Normative References for Hardened Stage Tests

7.4.2 Compressive Strength

The specimens for testing compressive strength were demoulded after a day of casting and cured until testing at 1, 3, 7, 14, 21, and 28 days of age. The SCC was initially designed for a targeted strength of 7000psi. On the basis of *ACI* code table-4.2.2. for the normal weight concrete exposed to chlorides from deicing chemicals, salt, salt water, brackish water, sea water or spray from these sources maximum w/cm of 0.4 can be taken with minimum specified compressive strength of 5000 psi. Here, with a w/cm of 0.39, 28 days strength of 8504 psi was obtained which is significantly higher than the specified targeted strength. The strength development pattern of the developed SCC is presented in figure-61.
The strength development curve in *figure-61* shows a high early strength development during the first week. After a week, the development of strength seems to be almost in constant rate. As the application of fly ash and superplasticizer enhances the strength of the concrete, the resulted high early strength could be because of addition of those materials and also higher cement content on the mix.

The compressive strength development patterns of the developed SCC mix is compared with the SCCs developed by different researchers as shown in *figure-62*. The strength development pattern varies on varying types and proportion of materials in the mix. Most of the researchers have achieved a significant higher strength than the specified targeted strength since most of the SCCs were developed using admixtures that mainly includes superplasticizer and filler materials.

The SCC-1 was developed by Sonebi, Bartos, Zhu, and Tamimi in May 2000. The specified characteristics cube strength of reference SCC-1 was 8702 psi with W/CM of 0.36 but the actual 28-days strength achieved was 11530 psi, which is significantly higher than the specified characteristics strength. The early strength of the developed SCC is much higher than the reference SCC-1; it is because of comparatively higher cement and lower filler material content in it. The developed
SCC has 27.23 lb/cuft of cement content and filler material of 20% of cementitious materials; whereas the reference SCC-1 has 20.6 lb/ft$^3$ of cement content and cementitious material (Ground Granulated Blast Slag, GGBS) of 38%. After about two weeks the strength of the Reference SCC-1 is exceeded the strength of the developed SCC mix. Low w/cm ratio and slow prolonged hydraulic and pozzolanic reaction between cement and GGBS resulting significant increase in strength could be the reason for achieving higher late strength.

![Figure-62: Comparison of Compressive Strength Development](image)

If the strength development of the Developed SCC and SCC-2, developed by Shi, C., Wu, Y., Shao, Y., Riefler, M., 2002,$^{50}$ is compared, the pattern seems to be almost same. The initial strength is less in SCC-2 than the Developed SCC but the 28 days strength of both are comparable. The Reference SCC-2 contains 20.6 lb/ft$^3$ of cement and GGBS of 38% of cementitious materials with w/cm 0.4. Comparatively, the reference SCC-2 contains very low cement and high amount of filler material, GGBS. The lower initial strength of Reference SCC-2 is because of lower cement
content and slow hydraulic-pozzolanic reactivity which highly enhances late strength development.

The Reference SCC-3, Dehn, F., Holschemacher, K., Weibe, D., 2000, has comparatively low w/cm ratio of 0.41 with low cement and high filler material content. It also has the strength development pattern almost same as the Developed SCC, but the lower early strength is because of higher w/cm, lower cement content. The strength development rate of Reference SCC-3 is greater than the developed SCC since the Reference SCC-3 contains higher amount of quartz powder as a filler material that also has slower prolonged strength enhancing property.³

On comparing the strength development pattern of the Developed SCC with other reference SCCs, the results can be taken as consistent and not outperforming. The Developed SCC contains comparatively higher amount of cement causing high early strength. The strength gaining rate is relatively lower because of low filler material content. The outstanding achievement of 28-days strength is the result of better combination of materials proportion and its well consolidation.

### 7.4.3 Flexural Strength

Specimens were tested at 7, 14, 21, and 28 days. The load is recorded at the point when a visible crack developed on the beam. Since the beam specimens were cast without reinforcement it was broken at the same time when crack start developing. In each test, three beams were tested as simple beam at third point loading flexural test and an average load value was recorded as final. The test set up for the test is shown in figure-7.12.
In each test the crack was developed at very close to the center of the beam. To analyze the result, the modulus of rupture is calculated as the ratio of bending moment at the point of failure to section modulus of the beam.\(^49\)

$$\text{Fr} = \frac{PL}{BD^2}$$ \text{ Equation-4}  

Where, \( \text{Fr} \) = Modulus of rupture  
\( P \) = Load at the point of failure.  
\( B \) = width of the beam  
\( D \) = Depth of the beam

The values of Modulus of Rupture at different ages are presented in figure-63. The modulus of rupture at 7-days and 28- days are obtained 656.71 psi and 892.56 psi respectively. Tests conducted by Master Builders have the value from 610 psi to 680 psi at 1-day, and 870 psi to 900 psi at 28-days for the Rhedynamic SCCs.\(^32\) So, the flexural value obtained for the Developed SCC is comparable to the previous results. Using ACI code recommendations modulus of rupture could be calculated as eqn-5:
\[ f_r = 7.5 \left( f_c' \right)^{\frac{1}{3}} \] .................................Equation-5

Where, \( f_c' = 28 \) days Compressive strength of concrete, psi.

\( f_r = \) Modulus of Rupture, psi.

This way, the ACI code, the 28-days modulus of rupture is found to be 691 psi and the tested value is obtained higher than the empirical.

![Graph showing modulus of rupture versus age](image)

Figure-64: Flexural Strength Development

The equation-5 shows modulus of rupture and compressive strength has a parabolic relationship. The relation between these two factors as shown in figure-65 is also found almost parabolic while plotting tested results. The plotted graph shows the flexural strength will also increase concurrently with the development of compressive strength. The development of flexural strength is very low in the early ages in comparing to the rate of increase of compressive strength. Later, the rate of flexural strength increment is higher than that of compressive strength.
So, the obtained results of Modulus of rupture of the developed SCC, and the comparable value achieved from the test and calculation based on ACI code show the developed SCC performs well in flexural stress.

7.4.4 Modulus of Elasticity

The specimens were tested for Modulus of Elasticity at 1 and 28 days of curing. The Chord Moduli of Elasticity and Poisson’s ratio obtained at different ages are presented on table-12

<table>
<thead>
<tr>
<th>Age, Days</th>
<th>1</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity, psi</td>
<td>2,990,617</td>
<td>4,543,729</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.23</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table-12: Modulus of Elasticity and Poisson’s Ratio at Different Ages
The 1-day and 28-days Modulus of Elasticity of the Developed SCC is obtained 4,543,729 psi and 2,990,617 psi respectively and Poisson’s ratio of 0.23 and 0.22 at 1-day and 28- days respectively. The ACI code prescribes empirically the Modulus of Elasticity for concrete having unit weight in between 90 lb/ft$^3$ to 155lb/ft$^3$ as:

$$E_c = 33w_c^{1.5}(f_{c'}')^{1/6}$$

Where, $E_c =$ Modulus of Elasticity, PSI

$w_c =$ Unit weight of concrete, lb/cuft

$f_{c'} =$ Specified Compressive Strength of Concrete, PSI

So, from ACI code the Modulus of Elasticity of the Developed SCC is found to be 5,646,651 psi; which is much higher than the value obtained from experiment. The ACI code says the measured values range typically from 120 to 80 percent of the specified value.

The Modulus of Elasticity obtained is found to be comparable to Dehn, Holschemacher, and Weibe$^3$ who have found 28-days value of 4,365,635 psi (30100
N/mm²) for the SCC they have developed. Sonebi and Bartos⁴⁶ have found modulus of elasticity of 4,945,786 psi (34.1 GPa) to 6,077,081 psi (41.9 GPa) for different types of SCCs. Similarly, while comparing with Master Builders Technical Data for SCC³², they have obtained 2,540,000 psi to 3,280,000 psi and 4,520,000 psi to 4,760,000 psi at the age of 1-day and 28-days respectively, the result obtained for the developed SCC is found to be very close. The Poisson’s ratio of the SCC obtained by Master Builders³² is 0.22 to 0.24 and 0.22 to 0.23 at 1-day and 28-days which is also comparable to the Poisson’s ratio obtained for the developed SCC.

![Figure-67: Stress and Strain Relationship](image)

The Stress and Strain relationship is plotted and presented in figure-67. The result is found to be almost straight line up to the stress, 40% of the ultimate strength. Comparatively, the strain at 28 days is found to be lower than the strain at 1-day to the corresponding stress.

7.4.5 Drying Shrinkage

The samples for testing drying shrinkage were demoulded after one day and placed in curing tank for 14 days. They were then kept for air drying in normal room temperature of 70°F.
Two perpendicular faces of each sample were divided into four segments, two in each face and average reading of two perpendicular faces was taken as the final reading. The readings were taken everyday for the first week and then taken once a week for 28 days.

The drying shrinkage strain of each sample is presented on figure-69. The largest shrinkage strain value is found to be 282.25x $10^{-6}$ after 28 days. Sample 1, 2, and 4 have almost same Shrinkage Strain value after 28 days; comparatively the value is lower in Sample -1.

The plotted curves of shrinkage strain with respect to the age as shown in figure-69 shows, the shrinkage rate is higher for the first week and is reducing with the age. After 2-3 weeks, the rate of increase of shrinkage for all specimens is very low.

In comparing the obtained results of all four samples with the result obtained by Ouchi and Nakamura, 2003, the shrinkage strain of the Developed SCC is found to be lower. The initial rate of shrinkage of the reference SCC and the samples are
almost same during first week but later the rate is higher for the reference SCC. The maximum shrinkage strain established by Ouchi and Nakamura for SCC is $800 \times 10^{-6}$. The Developed SCC has the rate almost negligible below $300 \times 10^{-6}$ of shrinkage strain as shown in figure-70.

![Figure-69: Shrinkage Strain of Samples at Different Ages](image)

The obtained shrinkage value of specimens are also compared with the value calculated using the empirical equation provided as ACI 209 model. The model gives the maximum limit of shrinkage that is permissible for design purpose of normal concrete. In comparing, the Developed SCC found to have higher shrinkage during early ages. After two weeks the shrinkage is found to be less than the limit, which is also presented in figure-70.
Comparatively, lower shrinkage of the Developed SCC than the reference SCC is because of the application of lower proportion of filler material and lower fine to total aggregate ratio in the mix. The Higher shrinkage of the Developed SCC during early ages than the limits calculated for normal concrete is because of higher proportion of fines in SCC. The value is found to be under the limits after two weeks for all samples.

On comparing the obtained values with the result presented by Master Builders technical data for SCC, one of the specimens of the Developed SCC is found to have higher strain at the age of one day. The shrinkage strain values at 7 days are found to be comparable to the reference SCC, whereas the shrinkage of the reference SCC is much higher than the specimens at 28-days as shown in figure-71. The reference SCC has smaller size of aggregate resulting slightly higher shrinkage. The fines content in Developed SCC is higher than in reference SCC, so a higher shrinkage was expected. The slightly lower shrinkage value of the developed SCC could be because of using larger aggregate size.
The shrinkage value of the reference SCC is higher at all ages than the empirical limits provided by ACI code, whereas samples of the developed SCC has a lower value than the ACI limit after two weeks.

7.4.6 Resistance to Freeze and Thaw

Samples were demoulded after one day and placed in curing tank for 14 days. Before placing the samples on the machine, they were kept on ice to maintain the temperature to $40^\circ$F, and initial readings of Ultra Pulse Velocity (UPV) were taken. The empty spaces on the machine after 8 samples were filled with dummy samples to maintain the continuity. The machine is set up to run in between $0^\circ$F and $40^\circ$F for a full cycle. The samples were kept on ice when the machine was stopped for taking intermediate readings after completing a certain number of cycles to maintain the temperature.
Figure-72: Sample at Freeze and Thaw Machine

Weight and dimension of the samples were taken every 27-30 cycles. The samples were placed on the supports separated to a specified distance. The Pickup was placed on the top of a support orienting parallel to the sample whereas the Driver was placed perpendicularly on the other end as shown in figure-74. The Frequency was adjusted and reading was taken when the hair line forms a fine elliptical shape as shown in figure-75. The samples were then quickly placed on the machine again for the next set of cycles.

Figure-73: Weighing Samples
Figure-74: Frequency Testing
When samples start thawing, the graph plotter moves toward center and during freezing, plots away from the center. So, one full cycle completes when the plotter shows one set of graph towards the center and away from the center to the specified temperature level as shown in figure-76.

The samples were tested to 314 cycles. No noticeable weight and dimension change were observed until the end of the cycles since the SCC was not air entrained. Out of eight samples, two of them were broken forming crack before completing 210 cycles which were removed and the spaces were filled with dummies. Later on, only 6 samples were taken for the test consideration.

The crack was formed on the middle of the sample across half height as shown in figure-77. The crack formation could be because of rough handling and improper temperature maintained while taking samples out for the test. The Coefficient of relative Dynamic Modulus of Elasticity of all samples and a reference SCC is presented graphically in figure-78. A maximum reduction in Relative Coefficient of Modulus of Elasticity of 13.7% after 314 cycles can be seen on the sample-2.
Figure - 76: Freezing and Thawing Cycles on Graph

Figure-77: Specimen with Crack Formed Before and After 210 Cycles with a Virgin Specimen
When comparing the result with a Reference SCC-ISHPC, 2003, as plotted in figure-78, the reduction in coefficient of Relative Dynamic Modulus of Elasticity after 300 cycles can be seen around 14%.\(^2\) It can be seen that the reference SCC has no reduction in the value until completing 150 cycles but at 200 cycles the reduction can be seen almost 10% and finally at 300 cycles it is higher than that of Developed SCC. The pattern of reduction of Dynamic modulus of elasticity of the Developed SCC and the reference SCC is comparable.

![Figure-78: Variation of Relative Dynamic Modulus of Elasticity of Specimens and Reference SCC](image)

If the specified number of cycles at which the exposure is to be terminated is taken 300 cycles, then the durability factor for the Developed SCC is found to be 95.96% to 99.6% and an average of all samples is found to be 98.15%. The durability
factor is comparable to the value obtained by Master Builders\textsuperscript{32} (96% to 98% at 300 cycles) and found to be slightly higher than the result obtained by Ramsburg, Barenio, Ludirja, and Masek, who have obtained 96%\textsuperscript{11}.

The limit of durability factor is recommended 60% by Virginia Department of Transportation\textsuperscript{11}. The value obtained for the Developed SCC is found to be within the limit. Since two samples were failed before completing 210 cycles, at the 300 cycles of exposure, the stability of the developed SCC is 75%. 
CHAPTER 8

BENEFIT-COST ANALYSIS

8.1 INTRODUCTION

The feasibility of Self-Consolidating Concrete (SCC) production is highly influenced by its cost effectiveness. The feasibility not only deals with the compatibility of production with the local environment but also with the cost effectiveness in comparison to the alternatives. The developed SCC is found to be a better alternative to the conventional concrete while comparing the mechanical properties and workability as well.

The benefit-cost analysis for the production and casting of Self-Consolidating Concrete is mainly focused in this chapter. A conventional concrete having 28-days compressive strength of 8030 PSI and a slump of 8.75 Inches is taken as a reference to be compared with the developed Self-Consolidating Concrete that has 28-days strength of 8504 PSI with slump flow 23 Inches.

8.2 FACTORS AFFECTING COST OF CONCRETE

Production and casting time, direct production cost, and long term performance are the major factors that influence the cost of application of concrete. The time factor plays a vital role influencing the overall scheduled construction period. It highly influences the cost factor. In other hand production cost mainly includes materials cost, plant running cost, equipment cost, labor charges and transportation. Since the analysis is mainly focused on the production and casting cost, the factors that affect these parameters are enclosed in the broken lines in the tree diagram presented in figure-79. The long term cost effectiveness can be discussed
as the structural performance of the concrete and the maintenance required during its service life which is reflected in the mechanical properties evaluation phase.

8.3 PRODUCTION AND CASTING COST

Production cost mainly consists of Material cost, cost of Plant and facilities, cost of Equipment required at plant and site, labor and transportation cost. The equipments needed at plant can be included in the cost of plant and facilities whereas the equipment needed at site is mainly the consolidating equipment required during casting process of concrete.
8.3.1 Cost of Material

The prevailing cost of materials is considered for the comparison. Normally used materials for the production of concrete such as Cement, Aggregates (fine and coarse), admixtures (superplasticizer, filler material) are considered whereas cost of water is taken as negligible in this analysis. The unit material cost comparison is shown in table-13.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Conventional Concrete</th>
<th>Developed SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight lb/yd$^3$</td>
<td>Unit cost $/lb</td>
</tr>
<tr>
<td>Cement</td>
<td>622.89</td>
<td>0.052</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>154.98</td>
<td>0.022</td>
</tr>
<tr>
<td>Sand</td>
<td>1243.89</td>
<td>0.004</td>
</tr>
<tr>
<td>Stone</td>
<td>1590.84</td>
<td>0.008</td>
</tr>
<tr>
<td>Admixture</td>
<td>12.42</td>
<td>0.08</td>
</tr>
<tr>
<td>Ounce</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost 1 yd$^3$ of Conventional Concrete</td>
<td>54.502</td>
<td>Total cost of 1 yd$^3$ of Developed SCC</td>
</tr>
</tbody>
</table>

Cost difference per yd$^3$ = $62.174 - $54.502 = $7.672 (12%)

Table-13: Material Cost per yd$^3$ of Production

Comparatively, SCC contains high amount of fines and admixtures to obtain the required flowability. The admixture and high fine content increase the initial cost of the mix, so SCC mix can be expected expensive than normal concrete mix.

The material cost comparison in table-13 shows that SCC mix is expensive by $13.353 per yd$^3$ (16%) than conventional concrete.
8.3.2 Consolidating Equipment

The operation and maintenance cost of a usual electric operated consolidating vibrator is taken for the comparison as a consolidating equipment. The operation cost is $1.5 per hour that mainly includes cost of power consumption, oiling, and cables. The labor cost for the operation of the consolidating vibrator is not considered in this comparison.

<table>
<thead>
<tr>
<th>Vibrator time required for compaction</th>
<th>Conventional Concrete</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time required ( \text{Hr/\text{yd}^3} )</td>
<td>$/\text{hr}$</td>
<td>Cost $</td>
</tr>
<tr>
<td>0.891</td>
<td>1.75</td>
<td>1.56</td>
</tr>
<tr>
<td>Cost of vibrator operation per ( \text{yd}^3 ) of conventional concrete</td>
<td>1.56</td>
<td>Cost of vibrator operation per ( \text{yd}^3 ) of SCC</td>
</tr>
</tbody>
</table>

Costs save per \( \text{yd}^3 \): $2.23 (100\% \text{ saving})

Table-14: Comparison of Cost Needed for the Consolidation

During the casting of the Developed SCC, the consolidation was achieved without application of any mechanical consolidating equipment as required in the conventional concrete. The comparison shows a cost saving of $2.34 per \( \text{yd}^3 \) is found in the case of SCC.

8.3.3 Labor Cost

The overall construction cost is highly influence by labor cost. The major saving in the developed SCC alternative is expected from the labor cost. Since consolidating process is not required in the case of SCC, the labor hour needed for the
casting and finishing is very low. The labor cost includes cost of the labor needed for bull floating, operating vibrator and handling of concrete.

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional concrete</th>
<th>Developed SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hr./yd³</td>
<td>Rate</td>
</tr>
<tr>
<td></td>
<td>$/hr</td>
<td></td>
</tr>
<tr>
<td>Unskilled labor</td>
<td>3.375</td>
<td>10</td>
</tr>
<tr>
<td>Skilled Labor</td>
<td>2.16</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Saving per yd³ = $66.15 - $37.8 = $28.35 (43%)

Table-15: Labor Cost Comparison

The comparison in table-15 shows a significant saving of $28.35 per yd³ (43%) is obtained in the developed SCC alternative.

8.3.4 Cost of Plant/Equipment and Facilities

It includes the cost required for the overall establishment of a new plant that can produce and supply the current demand of the local area. For this purpose, the cost of the facilities and plant set up of the Statler-Readymix, a local medium sized concrete production plant is taken as a reference. The land covered by the plant is 5 acres and the lease rate is $20,000 per acre per year in the rural area of the south west Michigan. The production capacity of the plant in ideal case is 81,250 yd³ per year in ideal case. The actual production capacity of the plant is taken as 80% of the production in ideal case, which is 65,000 yd³ per year. For the transportation purpose it needs sixteen trucks. At least three consolidating vibrators are needed for a plant to
accommodate yearly production. Vibrating equipment cost $16,33.50 each for the consolidation purpose with operation and maintenance (O/M) cost of $9,500 for all three per year including power consumption. The O/M cost of plant itself is $165,000 and that of a truck is $18,300 per year including transportation cost. The comparison of total cost of plant set up and yearly expenses of operation and maintenance cost for both SCC and normal concrete production is presented in table-16. The capital cost includes the cost of plant, equipments, trucks and all other facilities needed for the plant installation.

<table>
<thead>
<tr>
<th>Conventional Concrete</th>
<th>Self Compacting Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital cost $</strong></td>
<td><strong>Yearly expenses $</strong></td>
</tr>
<tr>
<td>Plant 1,800,000</td>
<td>Land lease 100,000</td>
</tr>
<tr>
<td>Truck 2,688,000</td>
<td>O/M(Plant, truck, vibrator) 467,300</td>
</tr>
<tr>
<td>Vibrator 4,899</td>
<td></td>
</tr>
<tr>
<td>Total 4,492,899</td>
<td>Total 567,300</td>
</tr>
</tbody>
</table>

Table-16: Cost Comparison of Initial Capital Investment and Yearly O/M Cost of Plant and Facilities

8.3.5 Benefit –Cost Analysis

Some of the assumptions prior to the analysis are made as mentioned below:

- The compounding rate for all transaction is taken 7.5% including inflation which is the usual local rate.
- Since the point of interest in this analysis is on cost of production and benefit from revenue, only yearly expenses in production and maintenance and sales
revenues are considered to be subjected to the compounding annual percentage rate. The capital cost is not considered as a bank funding and is not subjected to yearly interest rate.

- The analysis is based on the 10 years production period.
- The cost for the installation of environmental provisions required for south west Michigan is considered in the cost of plant and facilities.
- The rate of selling price of SCC is taken same as the price of conventional concrete that includes production, transportation, labor for casting (pouring), consolidating, and finishing.

The cash flow --of the full facilities mainly includes yearly expenses, revenues and the initial cost of plant and facilities installation. The expenses of the production plant include total expenses of production plant and facilities and the interest of the initial capital investment which is presented in table-17.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost per yd³, $</th>
<th>Yearly cost, for 65,000yd³, $</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>SCC</td>
</tr>
<tr>
<td>Material</td>
<td>54.502</td>
<td>62.174</td>
</tr>
<tr>
<td>Labor</td>
<td>66.15</td>
<td>28.35</td>
</tr>
<tr>
<td>Vibrator operation cost</td>
<td>1.56</td>
<td>N/A</td>
</tr>
<tr>
<td>Plant, transportation, and facilities O/M</td>
<td>567,300</td>
<td>557,800</td>
</tr>
<tr>
<td>Total yearly expenses of production plant and facilities</td>
<td><strong>8,511,080</strong></td>
<td><strong>6,441,860</strong></td>
</tr>
</tbody>
</table>

Table-17: Total Yearly Expenses of Production of Concrete in Both Cases

The prevailing selling price of high strength normal concrete is $90 per yd³ including overheads and benefit; excluding cost of consolidating process and the labor cost required for casting and finishing. 52 If the cost of labor for casting and for the
consolidating purpose is also included then the cost of the concrete per yd³ can be increased by the amount as shown in *table-14* and *table-15* for labor cost and vibrator cost respectively per yd³ of concrete.

- The selling price of conventional concrete including production, consolidation, labor cost for casting and finishing (skilled and unskilled):
  
  $90\text{(Production and transportation; including overheads and benefit)} + \$1.56\text{(O/M of vibrator)} + 66.15 \text{(labor for casting and finishing)} = \$157.71 \text{per yd}^3.$

- The selling price of SCC including production, labor for casting and finishing (skilled and unskilled):
  
  $90 \text{ (production and transportation; including overheads and benefits)} + \$37.80 \text{ (labor cost)} = \$127.8 \text{ per yd}^3.$

- Overall cost difference (production, labor, consolidation) = $30 \text{ per yd}^3.$

  If the SCC production plant provides all facilities to customer including production, transportation, consolidation, casting and finishing, and the selling price is still put same as the conventional concrete, a significant saving of $29 \text{ per yd}^3 \text{ can be seen.}$

- The yearly revenue of the plant with a selling price of $157.71 \text{ per yd}^3$:
  
  $65,000 \text{ (yearly actual production capacity)} \times \$157.71 = \$10,251,150$

  On the basis of the calculated total yearly expenses, revenue and the capital cost of installation of plant and facilities, the benefit-cost analysis is conducted for both conventional and SCC production cases.

  The cash flow diagram of conventional concrete is presented in *figure-81*. It shows the capital investment of $4,492,899 \text{ at years zero and later on at the end of each year, there is a yearly expense of $8,511,080 and revenue of $10,251,150 until the end of the tenth year. Similarly in the case of SCC, the capital investment is}
$4,488,000 in the beginning, and the yearly expense and revenue is $6,441,860 and $10,251,150 respectively as shown in figure-81.

The present worth of all the annuities is calculated as:

\[
PW (\text{Present worth of annuities}) = ((1+i)^n) \times A \quad \text{Equation-7}
\]

Where, \( i = \text{Compounding rate} \)

\( A = \text{Annuity, annual expense or receipt} \)

\( n = \text{Number of year} \)

The Benefit-Cost ratio (B/C) is calculated as the ratio of the Present worth of yearly revenue to the present worth of yearly expenses.

Benefit to cost ratio is the criteria to judge if the business is making progress or is going towards bankruptcy. If the benefit to cost ratio is greater than one, it means that the business has much more profit than the expenditures and the business is progressing. If this ratio is less than one, it means that the business is in loss and if this ratio stays like that the bankruptcy of the business is certain.

In this analysis, the production cost of a conventional concrete having 28-days compressive strength very close to that of the developed SCC under the consideration of prevailing cost of all components. This analysis has assumed 10 years of time period for cost analysis.
Figure-80: Cash Flow Diagram of Conventional Concrete Production

Figure-81: Cash Flow Diagram of SCC Production
<table>
<thead>
<tr>
<th>n</th>
<th>i</th>
<th>Conventional concrete</th>
<th></th>
<th>Self-Consolidating Concrete</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td>B/C (Conventional Concrete)</td>
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<td>B/C (SCC)</td>
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Table-18: Analysis of Benefit Cost Ratio for Both Types of Concrete Production
8.4 SUMMARY

In this analysis, the benefit to cost ratio (B/C) in both of the cases are found to be more than one, so both of the businesses are financially feasible. In the case of SCC, B/C found to be 1.38 whereas in the case of conventional concrete, it is obtained 1.16. The benefit-cost ratio in the case of SCC is obtained greater than that of conventional concrete so, it can be concluded that production of SCC is more beneficial in comparison to the conventional concrete in the local area, since the ratio of SCC is significantly higher than that of conventional concrete.

The initial cost of materials is found to be 12% expensive in the case of SCC in comparison to the conventional concrete, and is because of high amount of fines and admixtures content. Whereas, avoiding consolidating process in SCC, 100% saving in cost for that process can be obtained comparing to conventional concrete. Another significant saving of 43% in labor cost can be achieved replacing conventional concrete by SCC.
CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 INTRODUCTION

The development of standard specifications and practice of SCC in construction projects in the USA is not working in the pace as it is going on in Europe and other countries around the world. To evaluate the mechanical properties and performances in light of the previous researches and its comparison to the conventional concretes is the main theme of this study.

In this thesis, different SCC mixes were developed during optimization phase and tested the performances. A final SCC mix with better performances was developed and proposed for the full scale production. To facilitate local production, a general SCC mix design procedural guidelines were developed, on the basis of which a test production was successfully carried out from a local Concrete Ready-mix Company with the proposed mix.

The mechanical properties of the developed SCC were extensively evaluated in the laboratory in accordance to ASTM specifications and a better durability characteristic than the conventional concrete was obtained. The properties of the developed SCC obtained after different optimization trials have confirmed its self consolidating as well as passing and filling characteristics. A careful consideration of different factors is necessary while preparing for the passing and filling ability test since it is very important while applying the SCC for reinforced structures. The availability of L-box and U-tube devices is very rare, so mostly it needs to fabricate by the producer itself. While fabricating those devices, the
dimension and spacing of the reinforcement should fix carefully depending on the requirements of the job.

9.2 CONCLUSIONS

The points that were concluded during the evaluation of the mechanical properties of SCC are briefly described below:

- The developed SCC had 23” spread flow, H1/H2 of 0.81 in L-Box test and 11.9” in U-Tube. All the fresh stage properties of the developed SCC were found to be within the recommended range that showed the developed SCC had enough flowing, filling and passing abilities.

- The 28-days compressive strength of the developed SCC was obtained 8504 psi. The developed SCC had a high early strength and the strength development pattern was consistent with other previously developed SCCs. The high early strength of the developed SCC was the result of a little higher cement content on the mix and also because of the provision of admixtures.

- The 28 days Modulus of Rupture of the mix was obtained 892 psi and was compared with the results obtained for previously developed SCCs and also with the ACI recommended values. The development of Modulus of Rupture was found to be comparable and within the required range.

- The 1-day and 28-days Modulus of Elasticity of the Developed SCC was obtained 4,543,729 psi and 2,990,617 psi respectively and Poisson’s ratio of 0.23 and 0.22 at 1-day and 28- days. The values obtained were very closed and comparable to the values obtained for the previously developed SCCs and was also within the recommended range of ACI code.

- The high fine content in SCC tends to increase the shrinkage. So, SCC is prone to high shrinkage, but a proper combination of materials in the mix can limit it up to
the acceptable range. In this study, the drying shrinkage of the developed SCC was found to be within the recommended range of ACI standard and also found significantly less than the previously developed SCCs.

- In the Freeze and Thaw test of the developed SCC, the total loss in Relative Dynamic Modulus of Elasticity was found to be 14% after 300 cycles of freezing and thawing. The average durability factor was found to be 98.15%. Two samples out of eight were broken during the test before completing 210 cycles and only six samples were exposed to freeze and thaw for 314 cycles. 75% of sample's stability was found in the freeze and thaw exposures. There were no change in weight and dimension noticed until the end of the test. The obtained result showed the developed SCC performs excellent in freezing and thawing exposure.

The remarkable conclusions that are noted during literature, optimization and cost to benefit analysis are listed below:

- Self-Consolidating Concrete is a new and beneficial technology in concrete industry. Although, it is still in the development phase, SCC has been successfully practiced in different types of construction works in different parts of the world.

- For the production of Self-Consolidating Concrete there is no need of any special materials. The usual materials applied for the production of Conventional concrete can effectively be used for its production too.

- Self-Consolidating Concrete flows highly filling the formwork uniformly through reinforcement and consolidates itself. It eliminates high labor hours and accelerates production eliminating consolidation and finishing processes.

- The fresh stage performances of SCC highly dictate its durability. Amount of free water, amount of fines, aggregate properties, nature and amount of admixtures are the major factors controlling fresh stage properties.
• The mechanical properties of SCC were found to be better than Conventional concrete and are consistent with previous results.

• A significant saving of 43% in labor cost is found replacing conventional concrete by SCC; however the initial material cost is found to be 16% expensive while considering the production cost of the locality. In overall, the production of SCC is found to be more cost effective and beneficial under the benefit-cost analysis of 10 years period in comparison to the conventional concrete.

9.2 RECOMMENDATIONS

• Any of the mix design procedure should not be followed directly for the production of SCC. A mix optimization process is very important prior to production.

• To achieve the required flowability it is recommended to monitor this property of SCC before its practical implementation.

• A careful investigation of aggregate properties and moisture content is recommended.

• L-Box or U-Tube test should always be carried out to confirm the passing and filling abilities and to check segregation among the aggregates while using SCC for casting reinforced structures.

9.4 FURTHER RESEARCH

SCC is a low viscous concrete and it covers large area. It makes a flow channel at some point during its flow especially in between longitudinal reinforcement. The detailed study of nature of the flow channel is yet to be clarified. It is useful to verify the distribution of constituent over the entire formwork since SCC is highly prone to separation of constituents. The SCC mix has high flowability
that highly increases the possibility of settlement of aggregate to the bottom. The study of material distribution of SCC is also important to predict the uniformity of aggregates distribution along the depth specially while casting a deep member.

For the extension of the scope of work of the mechanical properties, SCC should be tested for its performance and behavior in the bond strength test and creep analysis.

9.5 CONTRIBUTIONS AND LIMITATIONS

The design and optimization of SCC had some of the questions and confusions such as is it similar to the procedure developed for conventional concrete? What are the recommendations and guidelines for the process if it is needed for the development of SCC mix? Etc. This thesis has developed a model that provides in detail SCC mix design and optimization procedure in a very simplified way. The recommendations and guidelines require for the process are also included in the model layout. Moreover, the extensive evaluation of almost a whole set of mechanical properties is very rare in the locality that the thesis has considered. The evaluation of mechanical properties and benefit-cost analysis have promoted and motivated local concrete producers to adapt this new technology.

The limitations of this thesis are mainly the regional constraints. The area for the whole thesis considered is South-West Michigan of the USA from where a normal source of materials was taken. In some other regions or for design and optimization of SCC with materials quarried from different sources could have different results because of the variations in the properties of materials.

While comparing SCC with the conventional concrete, during the practical implementation of SCC in the field, care needed to be taken care of to control it properties. A well qualified person is needed to be at the field to test and adjust the performance of the concrete before its implementation in the construction projects.
REFERENCES


12. Technical Memorandum ME 03-10, “Experimental Use of Self Consolidating Concrete for Precast Prestressed Box Beams” Maine Department of Transportation, Transportation Research Division, October 2003.


17. Roshavelov, T., "Concrete Mixture Proportioning Based on Rheological Approach." Civil Engineering Higher School, Sofia, Bulgaria, 2002.


Web: http://www.precast.org/publications/mc/TechArticles/01_fall_SCC.htm


42. Ramsberg, P. “The SCC Test: Inverted or Upright?” The Concrete Producer, July 2003, web site: www.worldofconcrete.com


52. Mr. Cronkite, S., General Manager; Mr. Davis, K., Technical services; Statler Concrete & supply co., Personal communication. Ph :(269)-345-7105. E-mail: scronkite@gotostatler.com.

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