CHAPTER 2 LITERATURE REVIEW

2.1 Introduction
This chapter will outline some of the significant studies conducted on SCC and curing of normal concrete and SCC. The first section will delineate a brief research history of SCC, its advantages and factors affecting making of SCC, mix design, properties of fresh SCC, strength and mechanical properties of SCC; while the second section will be literature related to curing, curing techniques, effect of curing on mechanical properties of SCC and self curing of NVC and SCC.

2.2 Definition of SCC
Self compacting concrete (SCC) is a special type of concrete that spreads through the congested reinforcement, reaches every corner of the formwork, and is consolidated under its own weight. It provides excellent filling ability and passing ability, and exhibits good segregation resistance [Khayat K 1999][78]. SCC is that special concrete, which would give the optimized performance with respect to flow characteristics, strength, transport properties and durability consistent with the requirements of service life under a given set of materials, loads and exposure conditions.

2.3 History of self compacting concrete
The history of self compacting concrete (SCC) dates back to late 1980s. It was proposed for construction by Prof. Okamura in Japan to offset a growing shortage of labour [Ouchi M 1999][119]. Though the concept originally was thought to be a tool to enhance long-term durability of structures having members with congested reinforcements, the excellent user-friendly characteristics of SCC are of great attraction today in traditional construction industry also.

The idea of a concrete mix that can be consolidated into every corner of a formwork, purely by means of its own weight and without the need for external vibration, was first developed in 1983 in Japan, when concrete durability, constructability and productivity became a major topic of interest in the country. During this period,
there was a shortage of number of skilled workers in Japan that directly affected the quality of the concrete. [Okamura 1999]<sup>[119]</sup>.

The guiding principle behind the self compacting concrete is that “the sedimentation velocity of a particle is inversely proportional to the viscosity of the floating medium in which the particle exists”. SCC has a big role to play because of its substantial benefits in construction both qualitatively and quantitatively. [Coppola et al. 2004]<sup>[26]</sup>

For a concrete to be self-compacting, to occupy the full space, flowing through the form, without any external efforts, it has to have an acceptable level of passing ability, filling ability and stability. As concrete is a heterogeneous product of materials with various specific gravities, it is very difficult to keep its constituents in a cohesive form. Specially, when concrete has a consistency of a fluid, materials of higher mass tend to settle down. This problem however can be tackled by adding more amount of finer material (passing 100 microns) in unit content of concrete and super-plasticizers. Super-plasticizers are instrumental in reducing the water demand of a highly fluid mix, and producing optimally high-fluidity concrete while using the least possible amount of water.[EFNARC 2002]<sup>[36]</sup>

SCC can greatly improve construction systems previously based on conventional concrete requiring normal vibrating compaction. Vibration compaction, which can easily cause segregation, has been an obstacle to the rationalization of construction work. Once, this obstacle has been eliminated, concrete construction could be rationalized and a new construction system including formwork, reinforcement, support and structural design could be developed (Fig. 2.1). [Ouchi et al. 1997]<sup>[121]</sup>

Numerous research studies have been conducted with the objective of developing raw material requirements, mix proportions, material requirements and characteristics, test methods necessary to produce and test SCC.[Khayat 1996]<sup>[76]</sup>, [Ouchi 2000]<sup>[120]</sup>.
The studies related to SCC focused on improved reliability and prediction of properties, production of a dense and uniform surface texture, improved durability, and both high and early strength permitting faster construction and increased productivity. \cite{Khayat1996, Chan2003, Khayat2004, Gronewald2007, Zhuguo2007, Utsi2008}.

2.4 Scenario of SCC in India and abroad

Okamura proposed the use of SCC in 1986. Studies to develop SCC, including a fundamental study on the workability of concrete, were carried out by Ozawa and Maekawa at the University of Tokyo, and by 1988 the first practical prototypes of SCC was produced. By the early 1990s Japan started to develop and use SCC and by the year 2000, the volume of SCC used for prefabricated products and ready-mixed concrete in Japan was over 400,000 M³ \cite{Ouchi2003}.

In the early 1990’s there was only a limited public knowledge about SCC, mainly in the Japanese language. The fundamental and practical know-how was kept secret by the large corporations to maintain commercial advantage. The SCCs were used under trade names, such as the NVC (Normal vibrated concrete) of Kajima Co., SQC (Super quality concrete) of Maeda Co. or the Biocrete (Taisei Co.) \cite{Grace2005}.
Simultaneously with the Japanese developments in the SCC area, research and development continued in mix-design and placing of underwater concrete where new admixtures were producing SCC mixes with performance matching that of the Japanese SCC concrete (e.g. University of Paisley / Scotland, University of Sherbrooke / Canada) [Ferraris et al. 2000][38].

Anchorages of Akashi-Kaikyo suspension bridge (Fig. 2.2); Towers of a cable-stayed bridge; The Ritto Bridge, Yokohama Landmark Tower, Japan’s tallest tower with 74 stories, Wall of a large LNG tank belonging to Osaka Gas Company, pre-stressed concrete products are few projects in Japan (Fig. 2.3). [Phelan Sept. 2011][130]

![Fig. 2.2: Akashi-Kaikyo Bridge, Japan](image1)
![Fig. 2.3: SCC Tunnel Segment in Japan](image2)

In 1996, several European countries formed the “Rational Production and Improved Working Environment through using SCC” project in order to explore the significance of published achievements in SCC and develop applications to take advantage of the potentials of SCC. Since then, SCC has been used successfully in a number of bridges, walls and tunnel linings in Europe. [Ouchi et al. 2003][122]. In Neuchatel, Switzerland, the La Maladiere Football Stadium was made up of 60,000 cu.m. of SCC placed in 10 months in 2007. In the Burj Khalifa, the tallest building in the world, SCC was used throughout the building and was pumped 166 stories above the ground. SCC is used in different areas of Sodra Lanken Project (Fig. 2.4)—the roadway infrastructure connecting East and West Stockholm. Jin Mao Building (Fig. 2.5) & the Mori Tower, Shanghai; Beijing TV Centre Building, China, used SCC for foundation and structural frame. [Phelan Sept. 2011][130].
During the last couple of years, interest in SCC has grown up in the United States, particularly within the precast concrete industry. SCC has been used in several commercial projects. [Ouchi 2003][123]. Although self consolidating concrete (SCC) has many advantages for all types of concrete applications, its acceptance for cast-in-place construction has been slow in North America. The objective of the Industry Critical Technology Committee on Self-Consolidating Concrete is to change that to “15 by 15.” That is, the committee wants SCC to be 15% of all ready-mixed concrete by 2015. Freedom Tower, New York city; 301 Mission Street, San Francisco; Cincinnati’s Rosenthal Center; Eli & Edythe Broad Museum at Michigan State University, LNG Storage Tanks, Freeport, Texas; US Mission at the United Nations are few prestigious projects build using SCC in USA. [ICT-SCC 2011][54]

In India, self compacting concrete (SCC), has been used in bridges, buildings and tunnel construction since the early 1990’s. In the last five years, a number of SCC bridges have been constructed in Asia. In India, the application of SCC in highway bridge construction is very limited at this time. However, the Indian precast concrete industry is beginning to apply the technology to architectural concrete (Fig. 2.6 & 2.7). SCC has high potential for wider
structural applications in highway bridge construction. Applications of SCC results in a large payoff in not requiring vibration to achieve consolidation and the low noise level to meet stringent environmental requirements in urban and suburban construction sites. With the increasing use of Ready Mix Concrete (RMC) in India, use of SCC is also increasing. RMC used in 2012 was to the tune of 11 million M$^3$ which is expected to increase 300% by 2022. Mumbai-Pune expressway, Mumbai sewage disposal project, J.J. Flyover, Bangalore International Airport, Vivekanada Bridge,
Kolkata, Bandra-Worli bridge and Delhi Metro (Fig. 2.8, 2.9, 2.10 & 2.11) are few projects where SCC has been used successfully. [Kumar and Kaushik 2003][90]

![Fig. 2.8 Bangalore International Airport, India](image1)
![Fig. 2.9: Vivekanada Bridge, Kolkata, India](image2)

![Fig. 2.10: Mumbai-Pune expressway, India](image3)
![Fig. 2.11: Delhi Metro, India](image4)

2.5 Merits of SCC

Self compacting concrete offers many advantages. Some of these are as follows [Khayat K 1999][78, EFNARC 2002][36, Okamura and Ouchi 2003][116, Ladkany et al. 2007][93].

**Improved Quality of work**

- Flows through and around reinforcing steel under self weight and eliminates the need for vibration equipment or any other means of consolidation.
- Favors the placement of a large amount of reinforcement in small sections such as those most often seen in high-rise buildings.
- Allows the formwork to last longer due to the elimination of vibration equipment.
Results in greater strength due to enhanced compactness and reduced porosity.

Imparts improved water-tightness, and thus offers reduced transport properties and enhanced durability.

Confers high early strength, allows a quicker reuse of formwork, and thus enhances the production rate.

Extremely suitable for slim and complicated moulds (filigree elements)

**Improved work environment and safety**

- Reduces noise and improves the construction environment in the absence of concrete vibrating equipment.
- Rapid rate of concrete placement and thus increases construction ability.
- Requires fewer labor for transport and placement of concrete, thus improving work environment and safety.
- Productivity Improvements – SCC can increase the speed of construction.

**Improved aesthetics**

- Provides good finishing without any surface pores and improves the aesthetical appearance of concrete.

**Savings**

- Reduced labor costs – SCC reduces labor demands and compensates for lack of skilled.
- Saves quantity of concrete due to the reduced section of structural components.
- Saves energy due to elimination of vibration equipments and reduction in labor.
- Saves maintenance cost due to improve formed surface finish and thus reduce repair and patching costs.
- Reduce maintenance costs on equipment for vibration and and truck turn-around time.

However, the total cost for a certain construction cannot always be reduced, because conventional concrete is used in a greater percentage than self compacting concrete.
2.6 Limitations of SCC

Application: Caution should be taken when using SCC in flatwork as it has limited bleeding characteristics and may be subject to plastic shrinkage cracking if not properly protected and cured. Higher powder contents bleed less than conventional concrete and can also lead to plastic shrinkage cracking if not properly cured.

Production and Quality Control: SCC requires a higher level of quality control than conventional slump concrete. Combined aggregate grading, tightly controlled mix water, controlled cement source, and the use of advanced admixtures require a greater awareness on the part of all production personnel. Processes must be put in place to compensate for normal variation of materials such as: Coarse and fine aggregate grading, Coarse aggregate void volume & aggregate moistures. [Grace 2005][45, Desmyter 2007][28]

Development of Standards and/or Technical Guidance Documents: Development of standards and/or technical guidance documents should be a priority which is quite slow. This hinders the uptake of innovative technologies like SCC. Also the process of transfer of knowledge is not effective. Producers and users, not only the decision makers and company leaders but also the workforce on the field, should be addressed in a multi-level and multi-focus dissemination strategy. [Desmyter 2007][28]

2.7 Basic principles and requirements of SCC

With regard to its composition, SCC consists of almost same constituent materials as conventional concrete, which are cement, aggregates, water and with the addition of chemical and mineral admixtures (fly ash, silica fume, GGBS, lime stone powder etc.) in different proportions. Usually, the chemical admixtures used are high-range water reducers (HRWR) also called superplasticizers and viscosity-modifying agents (VMA), which change the properties of concrete. Mineral admixtures are used as an extra fine material, besides cement, and in some cases, they replace cement. However, high volume of superplasticizer for reduction of the liquid limit and for better workability, the high powder content as “lubricant” for the coarse aggregates,
as well as the use of viscosity-agents to increase the viscosity of the concrete have to be taken into account. [Dehn et al. 2000][27]. Fig. 2.12 shows the basic principles for the production of SCC.

![Fig. 2.12: Basic Principles for the Production of SCC given by Okamura and Ozawa (1995)](image)

### 2.8 Approaches to Obtain Self Compacting High Performance Concrete

Three approaches have been identified to produce SCHPC:

a. Powder-type SCC using limited coarse aggregate content and increased amount of binder [Okamura and Ouchi 2003][116]: This is achieved by using greater amount of fine aggregate and cementing material along with HRWR at low W/B ratio.

b. VEA-type SCC using VEA [Okamura and Ozawa 1995][117]: A VEA (Viscosity Enhancing Admixture) is used with HRWR without increasing the content of binder or cementing material to produce SCC.

c. Combination-type SCC using both VEA and increased amount of binder [Nagamoto and Ozawa 1999][106]: A VEA and an increased amount of cementing material are used with HRWR at low W/B ratio.

*Okamura and Ozawa [1995][117]* have employed the following methods to achieve self compactability of SCC:
• Limited aggregate content (coarse aggregate - 50% of the concrete volume and sand - 40% of the mortar volume),
• Low W/ P ratio, and
• Use of higher dosage of superplasticizer

Since, self-compactability is largely affected by the characteristics of materials and the mix proportions, it becomes necessary to evolve a procedure for mix design of SCC. Okamura and Ozawa have proposed a mix proportioning system for SCC [Okamura and Ozawa 1995][117]. In this system, the coarse aggregate and fine aggregate contents are fixed and self-compactability is to be achieved by adjusting the water /powder ratio and super plasticizer dosage. The coarse aggregate content in concrete is generally fixed at 50 percent of the total solid volume, the fine aggregate content is fixed at 40 percent of the mortar volume and the water /powder ratio is assumed to be 0.9-1.0 by volume depending on the properties of the powder and the super plasticizer dosage. The required water /powder ratio is determined by conducting a number of trials. One of the limitations of SCC is that there is no established mix design procedure yet.

Parupalli et al. [1995][126] suggested a mix proportion for M30SCC has cement, fine aggregates, coarse aggregates, fly ash, GGBS, Micro silica, superplasticizers and VMA in the ratio by weight 1, 8.81, 3.0, 0.55, 0.4, 0.01, 0.05 and 0.007 respectively. The compressive strength achieved was to the tune of 39 MPa at 28 days.
2.9 CONSTITUENT MATERIALS OF SCC

The constituent materials for SCC are the same as those used in conventional concrete. In most cases the requirements for constituents are depends upon the type of structures and locally available materials. However, in order to be sure of uniform and consistent performance for SCC, additional care is needed in initial selection and also in the continuous monitoring for uniformity of incoming batches.


2.9.1 Cement

Cement used for SCC should not contain higher C$_3$A to avoid the problems of poor workability retention [EFNARC 2002][36]. Selection of the type of cement depends on the overall requirements for concrete, such as strength and durability.

Ordinary Portland Cement (OPC) is most widely used to produce various types of concrete. OPC is also a key component of SCC. It is used alone or in combination with SCM. Portland cement improves the flowing ability of SCC when used with water to lubricate the aggregates [Okamura and Ozawa 1995][117]. Portland cement can also affect the segregation resistance of SCC by affecting the density of cement paste matrix of concrete. After reacting with water, portland cement also reduces the porosity and results in a packed concrete mass leading to low transport properties and good durability [Neville 2008][115].

2.9.2 Filler or Mineral admixtures or Supplementary Cementing Materials (SCM)

Supplementary cementing materials are finely divided materials, which contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. They are greatly beneficial for concrete properties and durability due to their effective physical and chemical effects on material packing and microstructure. [Mehta and Aitcin 1990][101, Zhu et al. 2005][124, Selvamony et al. 2010][148]. SCM or Mineral admixtures are added to concrete as part of the total cementitious system.
They may be used in addition to or as a partial replacement of Portland cement in concrete depending on the properties of the materials and the desired effect on concrete [Mindess et al. 2003][104, Ilangovana et al. 2008][56].

2.9.2.1 Types of SCMs

Based on the sources, SCMs are also categorized as natural and artificial. Limestone powder, volcanic tuffs, pumicite, calcined clay, opaline cherts, and shales are some of natural SCMs. The industrial by-products such as silica fume, fly ash, and ground granulated blast-furnace slag are frequently used as artificial SCMs. In addition, SCMs can be obtained from agricultural wastes such as RHA, and can be industrially manufactured such as high reactivity metakaolin. The artificial SCMs such as silica fume, ground granulated blast-furnace slag, and fly ash have most commonly been used in SCC. [Agullo et al. 1999][8, Ferraris et al. 2001][39]

2.9.2.2 Characteristics requirements of SCMs

Mineral admixtures are used to improve a particular concrete property such as workability, strength or compactability. The optimum amount to use should be established by testing to determine (1) whether the material is indeed improving the property, and (2) the correct dosage rate, as an overdose or under-dose can be harmful or not achieve the desired effect, because they react differently with different cements. [Selvamony et al. 2010][148]

The particle size distribution and water absorption of mineral fillers directly affect the water demand in preparing of SCC. Calcium carbonate based mineral fillers are widely used and provides excellent properties and a good finish. Materials, such as fly ash, blast furnace slag, ground glass, limestone powder, silica fume etc. are commonly used as filler for producing SCC [Dhir and Dyer 1999][31, Ferraris et al. 2001][39, Ramsburg and Neal 2003][136].

Fly ash in appropriate quality may be added to improve the quality and durability of SCC. Fly ash increases the cohesion and reduces sensitivity to changes in water content.
Silica fume improves the resistance to segregation and mechanical properties because of its high level of fineness and spherical shape.

Ground granulated blast furnace slag (GGBS) provides low heat of hydration and improves the rheological properties.

Metakaolin, lime stone powder, natural pozzolana and other fine fillers have also been used for production of SCC but their short and long term effects on the concrete need to be carefully and individually evaluated.

Filler materials such as limestone filler, glass filler, slag and cement kiln dust (CKD) tested when used in their research (except CKD) improved the rheological and mechanical characteristics of SCCs towards conventional concretes. Limestone filler had the most positive effect in improving the compressive and flexural strength whereas glass filler resulted to the best fresh properties of SCC mixtures. [Georgiadis et al. 2007][42]

### 2.9.2.3 Fly Ash

Fly ash is the finely divided residue resulting from the combustion of coal. It is a pozzolanic material that is commonly used in cement-based materials and the particles are generally finer than cement particles. Fly ash has a high amount of silica and alumina in a reactive form. These reactive elements complement hydration chemistry of cement.

A Pozzolona is a material that provides a source of silica to combine with the calcium hydroxide in concrete to form a calcium silica hydrate (C-S-H) product that is similar to the C-S-H product formed during the hydration of portland cement.

It is not only the chemistry provided by fly ash that compliments chemistry of cement, but also the physical properties of fly ash improve the rheology and microstructure of concrete by a great extent. Fly ash, on itself, cannot react with water, it needs free lime, produced on hydration of Portland cement, to trigger off its Pozzolonic effect. Once it is triggered, it can go on and on. In simple words, it means a much longer life for concrete structure. Class F fly ashes are produced from the burning of bituminous and anthracite coals. [Mindess et al. 2003][104].
Class F fly ash have a higher carbon content and lower calcium oxide (lime) content than Class C fly ash, and only exhibits pozzolonic properties when it is introduced to water. However, due to its high calcium oxide content, Class C fly ash exhibits pozzolonic and cementitious properties when introduced to water. [Douglas 2004][34]

Naik et al. [1995][111] conducted tests on concretes containing between 15% and 25% by mass Class F and Class C fly ashes, to evaluate time of setting, bleeding, compressive strength, drying shrinkage, and abrasion resistance. The effects of moisture and temperature during curing were also examined. The results of the research showed that concretes containing Class C fly ash and were moist cured at 73°F (23°C) developed higher early age (1 to 14 days) compressive strengths than concretes with Class F fly ash. The long-term (90 days and greater) compressive strength of concretes containing fly ash was not significantly influenced by the class of fly ash.

Prajapati et al. [2012][131] carried out investigations on self compacting concrete using various percentages of fly ash, 10%, 20%, and 30% by weight of cement as partial replacement of cement. Based on the investigations they concluded that addition of Fly ash resulted in a decreases of super plasticizer content for same or better workability. The addition of Fly ash resulted as decrease in 7 days and 28 days compressive strength. The 28 days compressive strength decrease to 22-23% as the Fly ash content is increased to 30%. The reduction in 7 days strength is more as compared to 28 days strength. However all the mixes have good 28 days compressive strength 39 MPa or more.

2.9.2.4 Benefits of using fly ash

- It delays the heat of hydration and hence reduces the thermal cracks in concrete.
- It improves the workability of concrete.
- It makes the mix homogeneous and hence reduces segregation and bleeding.
- The concrete finish is improved due to perfectly spherical fly ash particles.
• The concrete permeability is substantially reduced which enhances the life of the structure.
• Fly ash contributes to the long term strength in concrete.

2.9.3 Aggregates: Coarse and Fine

The aggregates retained on the 4.75-mm (No.4) sieve are defined as coarse aggregates \[\text{ASTM-C-125 2002}\]\(^{14}\). They are granular materials, such as gravel or crushed stone, and are usually used with fine aggregate and cementing material or binder to produce concrete. As in any concrete, coarse aggregates are also a key component of SCC. Coarse aggregates significantly influence the performance of SCC by affecting the flowing ability, segregation resistance, and strength of concrete \[\text{Okamura and Ozawa 1995}\]\(^{117}\, \text{Nagamoto and Ozawa 1999}\]\(^{106}\).

• The maximum size and grading of the aggregates depends on the particular application. Maximum size of aggregate is usually limited to 20 mm. Aggregate of size 10-12 mm is desirable for structure having congested reinforcement. However possible size of aggregate higher than 20 mm could be used. For better workability of SCC, well-graded cubical or rounded aggregates are desirable.
• Fine aggregates can be natural or manufactured. The grading must be uniform and moisture content or absorption characteristics must be closely monitored, as quality of SCC is sensitive to such changes \[\text{EFNARC 2002}\]\(^{36}\).
• Particles smaller than 0.125 mm are considered as fines, which contribute to the powder content.
• The sand ratio (i.e. fine aggregate volume/total aggregate volume) is an important parameter for SCC and the rheological properties of SCC are improved with an increase in the sand ratio \[\text{Su et al. 2001}\]\(^{155}\).
• According to Okamura H. and Ouchi M., 2003, if the coarse aggregate content in a SCC mix exceeds a certain limit, blockage would occur independent of the viscosity of the mortar. Types and dosage of superplasticizer and water content are then determined to ensure desired self compacting characteristics. To increase the passing ability through congested reinforcement, reducing the volume of coarse aggregates in a SCC mix is more effective than decreasing the
sand-to-paste ratio. \cite{Nehdi2004} \cite{Nehdi2004}.

- The coarse aggregate should not contain clay seams that may produce excessive creep and shrinkage. Therefore, aggregates must be clean before their incorporation in the mix. \cite{Holschemacher2002} \cite{Holschemacher2002}.

\section{2.9.4 Admixtures}

Admixture is defined as a material, other than cement, water and aggregates, which is used as an ingredient of concrete and is added to the batch immediately before or during mixing. Additive is a material which is added at the time of grinding cement clinker at the cement factory. Various admixtures are categorized based on their function in the concrete namely Plasticizers, Superplasticizers, Retarders and Retarding Plasticizers, Accelerators and Accelerating Plasticizer, Air-entraining Admixtures, Damp-proofing and Waterproofing Admixtures, Gas forming Admixtures, Workability Admixtures, Grouting Admixtures, Bonding Admixtures, Colouring Admixtures. \cite{Kuehne2007} \cite{Kuehne2007}, \cite{Shetty2009} \cite{Shetty2009}.

\subsection{2.9.4.1 Superplasticizers}

Superplasticizer (SP) also called High Range Water Reducers (HRWR) is an essential component of SCC to provide the necessary workability \cite{Okamura2003} \cite{Okamura2003}. They reduce the yield stress and plastic viscosity of concrete by their liquefying action \cite{Skarendahl2000} \cite{Skarendahl2000}.

The main purpose of using a superplasticizer is to produce flowing concrete with very high slump that is to be used in heavily reinforced structures and in places where adequate consolidation by vibration cannot be readily achieved. The ability of a superplasticizer to increase the slump of concrete depends on such factors as the type, dosage, and time of addition, water / binder ratio and the nature of cement and filler materials. It has been found that for most types of cement, a superplasticizer improves the workability of concrete. The new generation superplasticizer are Poly- Carboxylate Ether (PCE) based particularly useful for production of SCC. \cite{Shetty2009} \cite{Shetty2009}.
Water-reducing admixtures are negatively charged organic molecules that adsorb primarily at the solid-water interface, whereas solid particles carry residual charges on their surfaces, which may be positive, negative, or both [Russell 1983][142].

The effect of superplasticizer on the balance between flowability and viscosity of paste in self compacting concrete was investigated by Ouchi et al. [1997][121]. From experimental results, the ratio of V-funnel speed to flow area of cement paste with a fixed amount of superplasticizer was found to be almost constant, independent of the water-cement ratio. A higher amount of superplasticizer resulted in a lower ratio of V-funnel speed to flow area. The ratio was proposed as an index for the effect of superplasticizer on cement paste flowing ability and viscosity from the viewpoint of achieving self compactability. However, the relationship between high range water reducer amount and its effect was found to differ depending on the type of cement or chemical admixture.[Aggarwal et al. 2008][7]

In their work, Roncero et al. [2000][141] evaluated the influence of two superplasticizers (a conventional melamine based product and a new-generation comb-type polymer) on the shrinkage of concrete exposed to wet and dry conditions. Tests of cylinders with embedded extensometers have been used to measure deformations over a period of more than 250 days after casting. In general, it was observed that the incorporation of superplasticizers increased the drying shrinkage of concretes when compared to conventional concretes, whereas it did not have any significant influence on the swelling and autogenous shrinkage under wet conditions. The melamine-based product led to slightly higher shrinkage than the comb-type polymer.

In cement paste, opposing charges on adjacent particles of cement can exert considerable electrostatic attractions, causing the particles to flocculate. A considerable amount of water is tied up in these agglomerates and adsorbed on the solid surfaces, leaving less water available to reduce the viscosity of the paste and hence that of the concrete. Molecules of the water-reducing admixtures interact to neutralize these surface charges and cause all surfaces to carry uniform charges of like sign [Mindess et al. 2003][104].
Some high-range water-reducing admixtures can retard final set by one to almost four hours and if prolonged setting times are not convenient, the admixture can be combined with an accelerating admixture to counteract the retarding tendencies or even to provide some net acceleration of setting. When water-reducing admixtures are used in concrete mixtures, some increases in compressive strength can be anticipated and these increases can be observed in as early as one day if excessive retardation does not occur. It is generally agreed that increases in compressive strength are up to 25% greater than would be anticipated from the decrease in water-cement ratio alone. Probably, this reflects the development of a uniform microstructure when the cement is dispersed [Ozyildirim and Lane 2003[124]. The reduction of the water-cement ratio and the creation of a more uniform pore structure mean that the permeability of concrete can be reduced by the use of superplasticizers, along with a general improvement of durability.

Using PCE polymers, give excellent water reduction as compared to normal plasticizers. This helps to reduce the w/c ratios and cement contents, even in normal concretes. Lower the w/c ratio, lower are the number of capillaries in concrete. It is also a well documented fact that PCE based admixtures do not have the side effects of retardation often seen with normal retarding superplasticizers. This is beneficial as workability time of concrete can be controlled but the hydration and setting of concrete will proceed unhindered. This ensures that any subsequent vibration to concrete after initial set will not open up capillaries, as is the case if concrete is retarded for a very long period of time, thereby rendering concrete relatively waterproof. [Surlaker 2011][156]

2.9.5 Self curing Admixtures

Some specific water-soluble chemicals added during the mixing can reduce water evaporation from and within the set concrete, making it ‘self-curing.’ The chemicals should have abilities to reduce evaporation from solution and to improve water retention in ordinary Portland cement matrix [Ambily and Rajamane 2007][12]. Internal curing (IC) is a method to provide the water to hydrate all the cement, accomplishing what the mixing water alone cannot do. [Neville 2008][115]
Dhir et al. [1995][29] reported results of several durability tests conducted on self cure concrete specimens. It was found that initial surface absorption, chloride ingress, carbonation, corrosion potential and freeze/thaw resistance characteristics were all better in air cured self cure concrete than in the air cured control concrete. This improvement appears to be dependent on the admixture dosage, although the durability properties obtained in the study were not as good as the film cured concrete. It may be possible to achieve such properties with higher quantities of self cure chemical.

2.9.5.1 Super-Absorbent Polymer (SAP) for self curing

SAPs are a group of polymeric materials that have the ability to absorb a significant amount of liquid from the surroundings and to retain the liquid within their structure without dissolving. SAPs are principally used for absorbing water and aqueous solutions. SAPs can be produced with water absorption of up to 5000 times their own weight. However, in dilute salt solutions, the absorbency of commercially produced SAPs is around 50 g/g. They can be produced by either solution or suspension polymerization, and the particles may be prepared in different sizes and shapes including spherical particles. Because of their ionic nature and interconnected structure, they can absorb large quantities of water without dissolving. SAPs exist in two distinct phase states, collapsed and swollen. The macromolecular matrix of a SAP is a polyelectrolyte, i.e., a polymer with ionisable groups that can dissociate in solution, leaving ions of one sign bound to the chain and counter-ions in solution. For this reason, a high concentration of ions exists inside the SAP leading to a water flow into the SAP due to osmosis. Another factor contributing to increase the swelling is water solvation of hydrophilic groups present along the polymer chain. Elastic free energy opposes swelling of the SAP by a retractive force. [Ambily and Rajamane 2007][12]

The common SAPs are added at rate of 0–0.6 wt % of cement. The SAPs are covalently cross-linked. They are Acrylamide/acrylic acid copolymers. One type of SAPs are suspension polymerized, spherical particles with an average particle size of approximately 200 mm; another type of SAP is solution polymerized and then...
crushed and sieved to particle sizes in the range of 125–250 mm. The size of the swollen SAP particles in the cement pastes and mortars is about three times larger due to pore fluid absorption. The swelling time depends especially on the particle size distribution of the SAP. It is seen that more than 50% swelling occurs within the first 5 min after water addition. [Naik and Canpolat 2006]\(^{108}\)

2.9.5.2 Poly Ethylene Glycols (PEGs)

Polyethylene glycols having a molecular weight of 1000 or above are freely soluble in water and with increased molecular weight, water solubility and solubility in organic solvents decrease. [Macrogol 1992]\(^{96}\)

Use of poly-ethylene glycol (PEG) reduces the evaporation of water from the surface of concrete and also helps in water retention. Polyethylene glycol is a condensation polymer of ethylene oxide and water with the general formula H(OCH2CH2)nOH, the abbreviation (PEG) is termed in combination with a numeric suffix which indicates the average molecular weights. One common feature of PEG appears to be the water-soluble nature. Polyethylene glycol is non-toxic, odorless, neutral, lubricating, non-volatile and non-irritating and is used in a variety of pharmaceuticals. PEG’s below 700 molecular weight occur as clear to slightly hazy, colorless, slightly hygroscopic liquids with a slight characteristic odour. PEG’s Between 700-900 are semi-solid. PEG’s over 1000 molecular weight are creamy white waxy solids, flakes, or free-flowing powders. [Macrogol 1992]\(^{96}\)

2.9.6 Membrane-forming curing chemicals:

Membrane-forming compounds consisting of waxes, resins, chlorinated rubber, and other materials can be used to retard or reduce evaporation of moisture from concrete. They are the most practical and most widely used method for curing not only freshly placed concrete but also for extending curing of concrete after removal of forms or after initial moist curing. Curing compounds should be able to maintain the relative Humidity of the concrete surface above 80% for seven days to sustain cement hydration. [Goel et al. 2013]\(^{43}\), [Kholia et al. 2013]\(^{80}\)
Membrane-forming curing compounds are of two general types: clear, or translucent; and white pigmented. Clear or translucent compounds may contain a fugitive dye that makes it easier to check visually for complete coverage of the concrete surface when the compound is applied. The dye fades away soon after application. On hot, sunny days, use of white-pigmented compounds is recommended; they reduce solar-heat gain, thus reducing the concrete temperature. Pigmented compounds should be kept agitated in the container to prevent pigment from settling out. Curing compounds should be applied by hand-operated or power-driven spray equipment immediately after final finishing of the concrete. The concrete surface should be damp when the coating is applied. On dry, windy days, or during periods when adverse weather conditions could result in plastic shrinkage cracking, application of a curing compound immediately after final finishing and before all free water on the surface has evaporated will help prevent the formation of cracks. [Shetty 2009][150]

Power-driven spray equipment is recommended for uniform application of curing compounds on large paving projects. Spray nozzles and windshields on such equipment should be arranged to prevent wind-blown loss of curing compound. Normally only one smooth, even coat is applied at a typical rate of 3 to 4m² per litre but products may vary, so manufacturer’s recommended application rates should be followed. If two coats are necessary to ensure complete coverage, for effective protection the second coat should be applied at right angles to the first. Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. [Kosmatka and Panarese 2002][86]

Curing compounds might prevent bonding between Hardened concrete and a freshly placed concrete overlay. And, most curing compounds are not compatible with adhesives used with floor covering materials. Curing compounds might prevent bonding between hardened concrete and a freshly placed concrete overlay. And, most curing compounds are not compatible with adhesives used with floor covering materials. Consequently, they should either be tested for compatibility, or not used when bonding of overlying materials is necessary. [Neville 2008][115]
2.9.7 Water

Water is the readily available most important component of SCC. The hydration of cement can take place only in the presence of water. Adequate water is required for the hydration of cement, leading to the formation of paste to bind the aggregates. In addition, water is required in conjunction with superplasticizer to achieve the self consolidation capacity of SCC [Okamura and Ozawa 1995][117]. It contributes to attain good flowing ability of SCHPC by lubricating the fine and coarse aggregates.

2.9.7.1 Physical quality of water

Water intended for use in concrete should be clean, fresh and free of deleterious substances. Water containing harmful substances such as silts, suspended particles, organic matter, oil, or sugar can unfavorably affect the strength and setting properties of cement and disrupt the affinity between aggregate and cement paste [Neville 2008][115]. Therefore, the suitability of water should be examined before use. As a rule, any water with a silt content below 2000 mg/L is suitable for use in concrete [Shetty 2009][150]. In general, the potable or drinkable water is safe for use in concrete.

2.9.7.2 Chemical quality of water

The mixing water for SCC should be chemically safe. The pH of mixing water should be in the range of 6.0 to 8.0 [Shetty 2009][150]. It should not contain high amount of dissolved solids, chlorides, alkalis, carbonates, bicarbonates, sulfates, and other salts, which can interfere with the performance of concrete. Water containing chloride ion, SO₃ ion, and dissolved solids below 500, 1000, and 2000 mg/L, respectively, is generally satisfactory for making concrete [Neville 2008][115]. Though dissolved solids exceeding 2000 mg/L are not always harmful, they can affect the strength and setting properties of cement adversely. Therefore, when the suitability of water is questionable, it must be tested prior to use in concrete.
2.10 MIX DESIGN FOR SCC

2.10.1 Typical Mix Proportions

SCC has the same constituent materials as those for CC but their relative proportions differ and need to be carefully selected. Generally speaking, lower coarse aggregate content and higher amounts of additions and cement, and admixtures (particularly superplasticizer) are required to achieve self compacting properties \cite{Persson2001, Klug2003, Okamura1995}. Okamura and Ozawa \cite{Okamura1995} have proposed a simple mix proportioning system for SCC. The coarse and fine aggregate contents are fixed so that self compactability can be achieved easily by adjusting the water / powder ratio and superplasticizer dosage only. The mix design procedure is as follows:

1. The coarse aggregate content (all particles larger than 4 mm and smaller than maximum size of aggregate) is fixed in the range of 28 to 35% of the concrete volume or 600 to 900 kg per cubic meter of concrete.
2. The fine aggregate content (all particles larger than 0.125 mm and smaller than 4.75 mm) is fixed in the range of 40 to 50% of the mortar volume.
3. The W/ P ratio is in the range of 0.8 to 1.0 (by volume), depending on the properties of the powder (i.e. cement and filler having particles smaller than 0.125 mm).
4. The superplasticizer dosage and the final W/ P ratio are determined through trial mixes so as to ensure self compactability using fresh properties tests.

\textit{Nagamoto and Ozawa [1999]}\cite{Nagamoto1999}, have proposed mix proportions of SCC and recommended that workability tests should be conducted until consistent and compliant results are obtained. SCC tends to dry faster than conventional concrete because there is little or no bleed water at the surface. Initial curing should therefore be commenced as soon as practicable after placing in order to minimize the risk of shrinkage cracking.
2.10.2 Comparison of Mix Proportions of NVC with SCC

SCC has the same constituent materials as those for CC but their relative proportions differ and need to be carefully selected. As shown in Fig.2.13, the coarse aggregate and W/P ratio of CC are significantly higher than those of SCC, the powder content is less, and the paste volume and sand/mortar volume ratio are within the SCC range. Table 2.1 shows the difference between mix designs of SCC and NVC.

![Fig. 2.13: Constituent of Conventional Vs Self Compacting Concrete (by volume) [Nagamoto and Ozawa 1999]](image)

<table>
<thead>
<tr>
<th></th>
<th>Conventional concrete</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/c ratio is fixed first, considering strength.</td>
<td>Coarse and fine aggregates are fixed first.</td>
<td></td>
</tr>
<tr>
<td>W/c or water/powder (W/P) ratio is sensitive to strength. Design of mix starts from w/c ratio.</td>
<td>W/P ratio is decided by self compactability. W/c ratio (by weight) is generally low for obtained W/P ratio (by volume).</td>
<td></td>
</tr>
<tr>
<td>Strength is precious to the design.</td>
<td>Strength could often be regarded as sufficiently high for ordinary structures.</td>
<td></td>
</tr>
</tbody>
</table>
2.10.3 Quantity Ranges of the Constituent Materials for SCC

From extensive literature survey, typical ranges of proportions and quantities of the constituent materials, the range for producing SCC, are given below:

1. Water content: 170 to 210 Kg/m$^3$ (EFNARC, 2005),
2. Cement content: 350 to 450 Kg/m$^3$ (EFNARC, 2005),
3. Total powder content (i.e., cement + filler): 400 to 600 kg/m$^3$ (EFNARC, 2005),
4. Dosage of superplasticizer: 1.5-1.8 % of the total powder content (by mass) (Su N., Hsu K C. and Chai H W, 2001. However, the recommended dosage varies from product to product.
5. W/ P ratio: 0.80 to 1.10 (by volume) (EFNARC, 2005). A W/ P ratio in the range of 0.30 to 0.38 (by mass)

The sand content balances the volume of other constituents. The sand content should be greater than 50% of the total aggregate content [Kapoor et al. 2003]$^{[73]}$. Sand ratio should be taken in the range of 50 to 57% [Su et al. 2002]$^{[154]}$.

2.11 KEY FRESH PROPERTIES OF SCC

SCC has the characteristics of filling ability, passing ability, segregation resistance, robustness and consistence retention and these characteristics should remain intact during transport and placing. [Skarendahl and Petersson 2000]$^{[151]}$, Ozyildirim and Lane 2003]$^{[124]}$, Bapat et al. 2004]$^{[18]}$.

- Filling ability reflects the deformability of SCC, i.e. the ability of fresh concrete to change its shape under its own weight [Okamura and Ozawa 1995]$^{[117]}$, Khayat 1996]$^{[76]}$. Deformability includes two aspects: the deformation capacity is the maximum ability to deform, that is, how far concrete can flow; and deformation velocity refers to the time taken for the concrete to finish flowing, that is, how fast concrete can flow. Filling ability is a balance between deformation capacity and deformation velocity. For example, a concrete with high deformation capacity
and very low deformation velocity tended to be very viscous and would take long
time to fill the formwork [Skarendahl and Petersson 2000].

- Passing ability is unique to SCC. It determines how well the mix can flow through
confined and constricted spaces and narrow openings, which ensures its
particular applications in densely reinforced structures such as bridge decks,
abutments, tunnel linings or tubing segments. It depends on the risk of blocking
which results from the interaction between constituent materials and obstacles.

- Segregation resistance is sometimes called ‘stability’. Since SCC is composed of
materials of different sizes and specific gravities, it is susceptible to segregation.
Segregation includes that between water and solid or between paste and
aggregate or between mortar and coarse aggregate in both stationary and flowing
states [Skarendahl and Petersson 2000].

The above three key properties are to some extent related and inter-dependent. A
change in one property will normally result in a change in one or both of the others.
Both poor filling ability and segregation can cause insufficient passing ability, i.e.
blocking. Risks of segregation increase as filling ability increases. SCC is actually a
trade-off between filling ability and segregation resistance as shown in Fig. 2.14.

Fig.2.14: Schematic of Ways to Achieve SCC [Skarendahl and Petersson
2000]
Nagamoto and Ozawa [1999][106] studied the effects of each component of concrete mixture in self compacting concrete on the fresh state. The main findings were:

1. There are certain combinations of slump flow and funnel speed that gave optimum self compactability.
2. Increasing the coarse aggregate content above the range G/Glim = 0.50, results in loss of compaction.
3. If the quantity of coarse aggregate is varied while the quantity of fine aggregate remains fixed, no clear change can be seen in the water-powder volume ratio required to achieve self compacting concrete, but the quantity of super-plasticizer required increases.

The self compactability tests commonly conducted on SCC mixes are briefly described below (As per EFNARC, 2005):

2.11.1 Slump Flow Test

The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. The basic equipment used is the same as use in conventional slump test. The test method differs from the conventional one.

The diameter of the spread of the concrete circle is a measure for the filling ability of the concrete. The slump flow test can give an indication as to the consistency, filling ability and workability of SCC. In case of unstable mix, most of the coarse aggregate
particles remain in the center of the flow and only cement mortar flows. It gives no indication of the ability of the concrete to pass between reinforcement without blocking, but may give some indication of resistance to segregation. The higher the slump flow value, the greater is its ability to fill formwork under its own weight. Acceptable range for SCC is from 650 to 800 mm. [EFNARC 2002][36].

T50, the time from lifting to the concrete reaching a 50 cm diameter, is popularly used to indicate the deformation rate. Time required for the concrete to cover 50 cm diameter spread circle from the time the slump cone is lifted indicates the T50 value (Fig.2.15). The higher the T50 value is, the lower the deformation rate of the concrete. Acceptable range for SCC is from 2 to 5 second [EFNARC 2002][36].

2.11.2 J-Ring Test

This test denotes the passing ability of the concrete. The apparatus is composed of a ring with 16 or 18 vertical reinforcing rods, a slump cone and a rigid plate. When the cone is lifted, the concrete has to pass through the reinforcing bars as it flows across the plate. The passing ability is expressed as the height difference between the concrete inside and outside the bars, called the step height. Segregation resistance can be visually evaluated by observing the periphery after the concrete has stopped flowing. The number of bars has to be adjusted depending on the maximum size aggregate in the SCC mix. For SCC, maximum height difference up to 10 mm is considered as appropriate mix [EFNARC 2002][36].

2.11.3 V-Funnel Test

This test is used to determine the filling ability (flowability) of the concrete, which indicates the period of a defined volume of SCC, needs to pass a narrow opening. Filling ability of SCC is evaluated by measuring the time (T in second) taken for the mix to completely empty out through the V-funnel, which had a rectangular opening of 3.0 in. x 2.5 in. (76 mm x 64 mm). For SCC, a flow time in the range of 6 to 12 second is considered as appropriate mix [EFNARC 2002][36].
2.11.4 L – Box Test

This method uses a test apparatus comprising of a vertical section and a horizontal trough into which the concrete is allowed to flow on the release of a trap door from the vertical section and is made to pass through reinforcing bars placed at the intersection of the two areas of the apparatus (Fig. 2.16). The vertical section is filled with concrete,

![L-Box apparatus](image)

then the gate lifted to let the concrete flow into the horizontal section through vertically placed reinforcements. When the flow is stabilized, the height of concrete $h_1$ (at obstructions) and $h_2$ (at the end of horizontal section of ‘L’) with respect to base are measured. The ratio of $h_2$ to $h_1$ referred to as blocking value, a measure of passing ability of SCC. A locking value of a concrete 0.8 to 1.0 indicates the better passing ability [EFNARC 2002][36]. The L-Box test can give an indication as to the filling ability and passing ability.

2.11.5 U- Box Test

This test is used to measure the filling ability of SCC. The apparatus has the shape of English alphabet ‘U’ that is divided by a middle wall into two compartments as shown in Fig.2-17. An opening with a sliding gate is fitted between the two compartments with vertical reinforcements as obstructions. Concrete is made to flow through the obstruction and the level difference between the top surfaces of
concrete in the both components is the mode of measurement. Concrete is filled in one compartment up to the top. After one minute, the sliding gate is lifted to allow the concrete to flow into the other compartment through reinforcement obstacles. After the concrete comes to the rest, the difference in height is measured. If filling ability of concrete is good, difference in height should be minimum and not > 30mm.

Fig. 2.17: U-Box apparatus (Dimensions as per EFNARC)

Typical acceptance criteria for SCC with a maximum aggregate size of up to 20 mm are presented in Table 2.2.

Table 2.2: Acceptance criteria for SCC (As per EFNARC, 2005)

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Methods</th>
<th>Property</th>
<th>Unit</th>
<th>Typical range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>1</td>
<td>Slump-flow</td>
<td>Filling Ability</td>
<td>mm</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>2</td>
<td>T50</td>
<td>Filling Ability</td>
<td>Sec</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Slump flow with J-ring</td>
<td>Passing Ability</td>
<td>mm</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>V-funnel</td>
<td>Segregation resistance</td>
<td>Sec</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>L-box</td>
<td>Passing Ability</td>
<td>h2/h1</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>U-box</td>
<td>Passing Ability</td>
<td>h2-h1</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

2.11.6 GTM Segregation test

This is a very recent test measuring the separation of aggregate in a sample after a period of time and wet sieving. The test has a potential for detection of tendency to segregate [Dehn et al. 2000][27]. It completes the tests (Slump-Flow, L-Box, etc.) carried out to estimate the filling ability in free or shut-in environment (i.e. with
some "wall-effect") by specifying the segregation resistance. This test can be used in laboratory when developing a concrete mix, as well as on site, when carrying out suitability tests on the delivered concrete.

2.11.7 Stability monitoring

In order to ensure that the SCC has not lost its uniformity during transportation and placing due to its highly flowability and self leveling nature, it is suggested that the in-situ tests, such as rebound hammer, pull-out, etc. should be conducted. Non-variations in these near-surface properties may be considered as an indication of no loss in the uniformity. [Zhu et al. 2001][165, Ramsburg P. 2003][137].

In order to obtain adequate deformability, it is important to minimize the friction between the solid particles of the mix, reduction of the coarse aggregates and an increase in the paste volume is required to achieve the desired deformability. The size and quantity of coarse aggregates in a SCC mix are directly related to the concrete passing ability. The passing ability requirements depend on the formwork geometry and the extent of congestion of the reinforcement. Providing adequate viscosity reduces risk of blockage. Adequate cohesiveness can be obtained by incorporating a viscosity-modifying admixture (VMA) along with a high range water-reducing admixture to control bleeding, segregation, and surface settlement [Khayat et al. 2004][79].

2.11.8 Setting time of SCC

It is generally agreed that class F fly ashes delay setting and reduce early strength of concrete significantly, the effect increasing with replacement amount. Class C fly ashes have mixed effects on setting and early strength gain. Often these have been shown to delay setting, as much as 4-6 hours at high replacement levels. However, some class C ashes have been shown to reduce setting times [Naik et al. 1995][111] or have no effect [Naik and Ramme 1989][109]. Early strength gain in concrete with class C ashes has been seen to be greater than with F ashes and bleeding less [Gebler and Klieger 1986][41].
Some class C ashes participate in cementitious reactions in addition to pozzolonic reactions, altering their setting behavior. It has been suggested that this may also disrupt the optimal gypsum content of the cement, causing accelerated and sometimes even flash setting [Naik and Singh 1997].

Schindler (2002) from several field concrete mixes, found that initial set occurs when the degree of hydration reaches 0.15 times the water-to-cementitious materials ratio (w/cm) and the final set is 0.26 times the w/cm. He also developed correction factors for admixtures. Schindler observed that using maturity-based methods for predicting setting time worked in many cases, but was not successful for predicting setting of slag-containing mixes.

A review of the literature by Juenger et al. [2008] has shown that there are many variables that influence setting time and plastic shrinkage, such that discerning trends and making predictions is very difficult. The setting time decreases with increasing temperature, increases with a slag replacement, increases with excessive plasticizer, increases with a fly ash class F and class C replacement and increases as the w/c increases.

### 2.12 KEY HARDENED PROPERTIES OF SCC

Numerous papers have been published concerning all aspects of the hardened properties of SCC, often in comparison with CC [Trägårdh et al. 1999, Holschemacher and Klug 2002, Klug et al. 2003, Torrijos et al. 2008]. A brief review is summarized in this section.

#### 2.12.1 Hydration

The same hydration mechanism governs SCC as that of CC [Skarendahl and Petersson 2000]. However a higher content of admixtures and powder materials may exert some influence on hydration development. The setting time of SCC was reported to be twice as long as that of CC due to the superplasticizer and fly ash used.
2.12.2 Strength

Strength is one of the most important properties specified for concrete because it is a direct reflection of the capacity of the structure to resist forces and it is a reasonable indicator of other properties [Holschemacher and Klug 2002][52]. Klug et al. 2003][84].

Michael [2005][103] investigated the effect of heat treatment on the mechanical properties of SCC. Various SCCs were brought to a maturity corresponding to a durable storage of the concretes for 3 days at 20 °C. On these concretes, the compressive strength, the splitting tensile strength and the static Young’s modulus were determined and compared to reference concretes that had been stored for 3 days under standard conditions. The concretes with a low (w/c)-ratio, which are typically used in the precast industry, are hardly affected by the heat treatment conditions. This applies independent from the curing temperature. A high (w/c)-ratio leads in part to marked loss of strength, which in most cases increases with increasing curing temperature. For the splitting tensile strength, heat curing temperatures up to 60 °C can be regarded as uncritical. Beyond this temperature, strength losses compared to standard storage have to be reckoned with.

2.12.3 Compressive Strength

Self compacting concretes appear to develop in general higher compressive strength values as compared with conventional concrete of the same strength class. This is attributed to the changes in the interfacial transition zone (ITZ) caused by the different filler materials. [Zhu et al. 2005][164] investigated the micro-mechanical properties of the ITZ obtained by a depth-sensing nano-indentation method. They reported that the ITZ was denser and significantly more uniform in SCC than in NCC.

For SCC, achieving high strengths is not difficult, due to the presence of high powder content. However, achieving low and medium strength SCC is a difficult task. [Nanthagopalan and Santhanam 2009][113]. They noted that paste volume had a predominant effect on the fresh concrete properties in comparison with water or powder content individually (for a given combination of aggregates). A minimum of
50–70 liters of excess paste over and above the void content of the aggregates was found essential for achieving SCC with a slump flow of 550 mm.

Where the W/P ratios are similar, the compressive strength and the strength development of SCC are not significantly different from CC. The strength development of SCC and CC over a period of time is also similar [Selvamony et al. 2010][148].

A compressive strength of 50-60 MPa for SCC can be easily achieved at 28 days. The strength could be further improved by using fly ash as filler [Kapoor et al. 2003][73]. The characteristic compressive and tensile strengths have been reported to be around 60 MPa and 5 MPa, respectively [Domone 2007][33].

[Choi et al. 2006][24], worked on High strength light weight self compacting concrete (HLSCC) in which 28 days compressive strength has come out to more than 40 MPa in all mix except the case with (Light weight coarse aggregates) LC 100%. The relationship between the splitting tensile and compressive strength has been calculated as $f_s=0.076f_{ck}+0.5582$.

Vidivelli et al. [2013][162] while carrying out flexural tests on SCC and controlled concrete noted that the yield load and yield deflection for self compacting concrete beams was increased by 50% and 35% when compared with control beams. Compressive strength of self compacting concrete was increased 12.86% with comparing conventional concrete.

Super absorbent polymer (SAP) MPS-65 for use in self curing was experimented to predict the compressive strength, split tensile strength and flexural strength of the concrete containing SAP at a range of 0%, 0.2%, 0.3%, and 0.4% of cement and compared with that of normally cured concrete. The grade of concrete selected was M40. It was noted that the compressive strength increased by 28%, 34% and 2.16% at 3 days and 32.8%, 36.5% and 23% at 7 days and 2.5%, 7.23% and 6.34% at 28 days respectively for the Mix2, Mix3 and Mix4 when compared to control mix. It shows that by adding SAP content at 0.3% of cement maximum compressive strength is obtained. [Francis and John 2013][40]
2.12.4 Split Tensile Strength

Where the W/P ratios are similar, the splitting tensile strength of SCC was higher than that of CC [Zhu et al. 2001]^{165}, [Holschemacher and Klug 2002]^{52}; the tensile to compressive strength ratio of SCC was 10-30% higher than that of CC. This probably results from the better microstructure of SCC [Druta 2003]^{35}.

Almost all self compacting fly ash concretes showed higher split tensile strength values compared to normal vibrated concretes. This might be due to the high paste content in SCC which induces a slightly higher deformability and also due to better homogeneity coming from vibration free production compared to conventional concrete. [Dinakar et al. 2007]^{32}

Vidivelli et al. [2013]^{162} while carrying out tests on SCC and controlled concrete noted that the ultimate load and ultimate deflection for self compacting concrete beams was increased by 36% and 32.65% when compared with the control beams. Tensile strength of self compacting concrete was increased 9.82 % with comparing conventional concrete.

Almeida [Almeida Filho et al. 2010]^{11} studied hardened properties of self compacting concrete and has presented a statistical analysis on the main resistance of three SCC mixes. The experimental results were compared with eight formulations from codes and authors for the prediction of such material properties. Results were in accordance with the expected trends for conventional concrete. E noticeably increased with the hardened material density. The experimental relationship between fc and ft obtained by splitting tension is beneath the majority of the code provisions, except Spanish code.

[Parra et al. 2007]^{125} studied mechanical properties of SCC and noted that for the same compressive strength, the tensile strength of the Traditional Concretes (TCs) is about 18% higher than that of the SCCs. They propose a specific expression for the SCCs that would make it possible to estimate the tensile strength from the compressive strength in their case. If the empirical results from the study are compared with the theoretical estimates given by various codes and authors based on the compressive strengths, it is seen that in the specific case of the TCs most of
the formulas advanced provide a good fit, with differences of less than 10% between the estimated value and the real value. Logically, since lower tensile strengths were recorded in the SCCs it follows that the formulas are not applicable to them and the results that they give should be corrected downwards by 18%. In line with this, and taking as references the formulas given in Eurocode 2 and Model Code CEB-FIB 1990 for TC, the proposed equation for SCC: \( f_{ct} = 0.18 \left( f_{ck} \right)^{2/3} \).

Self curing distributes the extra curing water throughout the entire 3-D concrete microstructure so that it is more readily available to maintain saturation of the cement paste during hydration, avoiding self desiccation and reducing autogenous shrinkage. Experimental measurements were performed on to predict the compressive strength, split tensile strength and flexural strength of the concrete containing Super Absorbent Polymer (SAP) at a range of 0%, 0.2%, 0.3%, and 0.4% of cement and compared with that of cured concrete. The grade of concrete selected was M40. Addition of SAP leads to a significant increase of mechanical strength (Compressive and Split tensile). Split tensile strength of self curing concrete for dosage of SAP 0.3% of cement was higher than non self curing concrete. \([\text{Francis and John 2013}]^{40}\). It was noted that the split tensile strength increased by 8.5%, 20.5% and 2.56% at 3 days and 2%, 15.73% and 6.5% at 7 days and 15%, 18.6% and 4.64% at 28 days respectively for the SCC Mix2, Mix3 and Mix4 when compared to control mix.

2.12.5 Flexural Strength

\( \text{Vidivelli et al. [2013]}^{162} \) while carrying out flexural tests on SCC and controlled concrete noted that the yield load and yield deflection for self compacting concrete beams was increased by 50% and 35% when compared with control beams. The ultimate load and ultimate deflection for self compacting concrete beams was increased by 36% and 32.65% when compared with the control beams. The ultimate load for admixture concrete beams and self curing concrete beams was increased by 27.27% and 30.43% when compared with control beams. The ultimate deflection for admixture concrete beams and self curing concrete beams was increased by 14.5%
and 7.82% when compared with control beams. The deflection ductility for self compacting concrete beams was increased by 44% when compared with control beams. Whereas deflection ductility for admixture concrete beams and self curing concrete beams increased by 20.51% and 40.60% when compared with control beams. During early stages of loading, fine vertical flexural crack appeared around the mid span of beams, as expected. With further increase in load, the flexural cracks started to propagate diagonally towards the loading point and other new diagonal cracks began to form separately in other locations. In general, SCC beams had slightly lower number of cracks than those other beams.

Experimental measurements were performed to predict the compressive strength, split tensile strength and flexural strength of the concrete containing Super Absorbent Polymer (SAP) at a range of 0%, 0.2%, 0.3%, and 0.4% of cement and compared with that of cured concrete of grade M40. Addition of SAP leads to a significant increase of mechanical strength (Compressive and Split tensile). From the results it was noted that the flexural strength increased by 7.56%,11.68% and 10.4% at 3 days, 7 days and 28 days respectively for the Mix2, Mix3 and Mix4 when compared to controlled mix. Maximum flexural strength of self curing concrete for dosage of SAP 0.3% of cement was higher than non self curing concrete. [Francis and John 2013]^{40}

**2.12.6 Shear Strength**

The shear capacity of concrete can be of great concern, especially in certain shear-critical applications and given the extremely brittle and not well understood mechanisms of failure. The common practice of reducing coarse aggregate volume to increase paste and fine aggregate fractions in SCC mixtures has raised concerns about the possible reduction of shear capacity due to loss of aggregate interlock.

There are few studies available that have directly investigated the impact of the reduction of C.A. volume in SCC mixtures on aggregate interlock. One study did look at SCC in particular, and conducted “push-off” tests to directly investigate the impact of concrete compressive strength, aggregate type, and aggregate volume on
aggregate interlock. The results show what would traditionally be shown by theory; aggregate interlock decreases with increased concrete compressive strength, aggregate interlock decreases with reduced C.A. volumes, and that aggregate interlock is affected by the aggregate type [Trejo et al. 2008][160, Maroliya 2012][98].

SCC has lower shear strength compared to CC because of the presence of comparatively smaller amount of coarse aggregates in SCC; the fracture planes are relatively smooth as that may reduce the shear resistance of concrete by reducing the aggregate interlock between the fracture surfaces [Lachemi et al. 2005][92, Hassan et al. 2008][50].

Another researcher concludes that prestressed SCC and CC beams exceed nominal strength in all failure modes including shear, that progression of damage was consistent from SCC to CC, and that SCC exhibited increased ductility over CC in all cases [Naito et al. 2006][112].

Sable Kishor [Sable and Rathi 2012][143] noted that SCC developed shear strengths ranging from 3.56 to 7.29 kN at the end of 28 days and the NVC developed shear strengths ranging from 3.11 to 6.62 kN at the end of 28 days. Also it is observed that for same aspect ratio the hook ended fibers show pronounce improvement in all properties of concrete as compare crimped & straight fibers.

Researchers from Missouri-University-of-Science-and-Technology [2012][105] investigated by push-off tests to determine the shear contribution from aggregate interlock included concrete compressive strength (41.3 and 68.9 MPa target), coarse aggregate type (limestone and river gravel), and volumetric content level of the coarse aggregate portion (36%, 48%, 58%, and 60%). The effect of concrete type between SCC and CC and the effect of C.A. percentage was not seen. For some combinations of concrete compressive strength and aggregate type, a given SCC would appear to perform the best, but at other strengths and aggregate types another SCC or the CC would appear the most efficient. From the results, no conclusion can be made about the superiority of SCC or CC. Researchers have shown that high strength concrete has reduced shear resistance from aggregate interlock because a larger fraction of the aggregate actually fracture along with the paste matrix. The largest effect on shear resistance appeared to be aggregate type.
2.12.7 Modulus of Elasticity: (Elastic Modulus)

As it is known, the modulus of elasticity of concrete depends on the proportion of the Young’s modulus of elasticity of the individual components and their percentages by volume. Thus, the modulus of elasticity of concrete increases with high content of aggregates of high rigidity, whereas it decreases with increasing hardened cement paste content and increasing porosity [Claudio Mazzotti 2007][25]. For this reason, lower values of modulus of elasticity can be expected, because of the higher content of ultra fines and additives as dominating factor and the accordingly lower content of coarse, stiff aggregates with SCC [Holschemacher 2004][51].

Elastic modulus is used to calculate the elastic deflection, which is a controlling parameter in design of slabs, prestressed and post-tensioned structures. Since the coarse aggregate content of SCC is less than CC, the elastic modulus of SCC might be anticipated to be lower. This was confirmed by Dehn [Dehn et al. 2000][27]. Holschemacher [Holschemacher and Klug 2002][52], analyzed their database and found that the elastic modulus of SCC could be 20% lower than that of CC made of the same aggregate with the same strength. Leemann [Leemann and Hoffmann 2005][94], reported an average modulus of elasticity of SCC to be 16% lower than that of conventional concrete for an identical compressive strength.

For a given compressive strength, the lower elastic modulus of the SCC in comparison with the normal vibrated concrete (NC) is due to the larger amount of paste. In addition, the maximum size of the aggregate could also have influenced the relationship between compressive strength and elastic modulus. [Dinakar et al. 2007][32]

Dinakar et al. [2007][32] also noted that for strengths of 30 and 60 MPa, the modulus of elasticity curve for SCC was below that of normal vibrated concrete; this might be due to the influence of the excess paste layer on the aggregate particles which results in a higher deformability. For strengths beyond 60 MPa, both the curves coincide. This may be due to the low fly ash replacements that were used in the development of SCCs in high strength concretes.
2.12.8 Shrinkage and Creep

The use of a higher content of paste, powder and superplasticizer in SCC, all may contribute to higher shrinkage and creep than in CC. Creep is defined as the gradual increase in strain for a constant applied stress. It is also a time-dependent deformation. Creep takes place in the cement paste and is influenced by porosity, which relates to the W/C ratio. As cement hydrates and porosity decreases, creep decreases. In addition, aggregates restrain the creep of paste. For this reason, a higher amount of aggregates and a higher elastic modulus of aggregates will lead to a reduced creep. The creep of SCC is anticipated to be higher than CC due to its higher cement paste [Persson 2001]\(^{[129]}\).

The shrinkage and creep rates of SCC have been found to be approximately 30% higher at an identical compressive strength; this is because of the high amount of paste [Leemann and Hoffmann 2005]\(^{[94]}\). Since SCC is rich in powder content and poor in the coarse aggregate fraction, addition of fiber will be effective in counteracting drying shrinkage. Persson [2001]\(^{[129]}\), confirmed that creep was influenced by cement paste porosity and reduces with an increase in strength in the same way for both SCC and CC.

Cracking risk of restrained concrete is dependent on shrinkage, creep, E-modulus and tensile strength. At constant degree of restraint, the influence of these parameters is depending on drying velocity and curing. As a result, age of cracking of SCC and CVC is influenced differently by drying and curing. As an example, cracking risk of SCC can be lower compared to CVC of the same strength in slow drying building components (e.g. large building components, high surrounding relative humidity) despite its higher shrinkage rate. This behaviour is the result of the higher creep rate and the lower E-modulus of SCC compared to CVC at constant compressive strength which reduce stress development. On the opposite, fast drying building components with a high degree of restraint (e.g. thin concrete layers) made with SCC have a higher cracking risk than comparable structures made with CVC. [Loser et al. 2007]\(^{[95]}\)
2.12.9 Microstructure of concrete

Microstructure can be studied through the use of Scanning Electron Microscope (SEM) which has distinct advantages for characterization of concrete, cement and aggregate microstructure and in the interpretation of the cause for concrete deterioration. SEM images facilitate identification of hardened cement paste constituents with greater contrast and greater spatial resolution than for optical methods and provide ancillary capacity for element analysis and imaging. Quantitative information may be extracted from these data such as composition, phase abundance and distribution. [Stutzman 2000][153]

Many factors influence physical and mechanical properties of concrete, such as water/cement, type of cement, use of materials having pozzolonic activity, type and particle size distribution of aggregates, type and dosage of admixtures. But even other important parameters may have a strong influence on the microstructure and, hence, on elastic and mechanical properties of concrete. These factors, less generally focused on, are related to the fresh state of concrete and concern rheological properties (cohesion and plastic viscosity), transportation, handling and placing of fresh concrete, segregation and bleeding, plastic settlement and curing. Rheological properties, in fact, can significantly modify nature and structure of the concrete interfacial transition zone (itz), between aggregate and concrete paste, which is responsible for the mechanical properties, water tightness, fire resistance and durability of pre-stressed and reinforced concrete structures [Mehta and Aitcin 1990][101]. ITZ is an interface element at the cement particles/sand particles interface. ITZ’s relative stiffness and strength, with respect to the cement paste and or aggregate ones, and its thickness affects cracking. They are decisive in governing whether a crack should grow around an aggregate particle, or rather, would follow a path through the grain.
Fig. 2.18: SEM Image analysis
Residual Cement (RC) appears brightest followed by calcium hydroxide (CH), calcium-silicate-hydrate (CSH), monosulfoaluminate (Afm), and other hydration products like Ettringite and monosulfate. Source: [Stutzman 2000][153]

In freshly conventional compacted concrete, due to the presence of coarse aggregate, water films, initiated by vibration, tend to accumulate close to the aggregate surface. These films determine an increase in the w/c next to the aggregate compared to the bulk mortar. As a consequence of the higher water/cement, the crystalline hydration products ettringite and calcium hydroxide (CH) in the vicinity of the coarse aggregate consist of larger crystals and therefore they form a more porous structure than in the bulk mortar matrix [Scrivener et al. 1988][147]. For these reasons, even for low w/cm, amount and size of voids in the transition zone will be larger than in bulk mortar. Moreover, CH crystals tend to locate themselves with the c-axis perpendicular to the aggregate surface. This results in a less adhesion capacity both for the lower surface area, and consequently weaker Van der Walls forces, and also because of preferred failure sites for the oriented structure [Kjellsen et al. 1998][82].
In addition to larger amount and size of voids, the presence of micro cracking is the major reason for the weakness of itz. Due to the presence of micro cracks, the transition zone significantly influences the durability of concrete, since it is more permeable than the bulk mortar. This means that concrete durability cannot be exclusively related to the w/c, type of cement and pozzolonic material, but should be attributed even to parameters, such as size and grading of aggregate, cohesion, etc, that can influence properties of itz. Self-compacting concretes with high content of very fine particles (size lower than 0.150 mm), a lower volume and maximum size of coarse aggregates with respect those of conventional concrete, a more stable conveyor phase, improved rheological properties due to effective high-range water reducers and viscosity modifying agents, are expected to affect in a positive manner the itz, promoting a less porous microstructure. [Coppola et al. 2004][26].

### 2.13 Modeling of SCC

Concrete has been numerically modeled homogeneously using Computational Fluid Dynamics, CFD, as well as heterogeneously, using the Distinct Element Method, DEM. SCC test methods such as slump flow, J-ring and L-box have been simulated with DEM with a user defined Bingham material model. Half scale as well as full scale castings are modeled with CFD to get a broad picture of the form filling.

For predicting workability and hardened properties of Self Compacting Concrete (SCC) no well known explicit formulation is available. Statistical models were carried out to model the influence of key mixture parameter (cement, water to powder ratio, fly ash and super plasticizer) on hardened properties affecting the performance of SCC. Such responses included compressive strength at 3, 7 and 28 days and modulus of elasticity. Thirty one mixtures were prepared to derive the numerical models and evaluate the accuracy. The models were valid for a wide range of mixture proportioning. [Arabi et al. 2009][13]

The researchers presented derived numerical models that can be useful to reduce the test procedures and trials needed for the proportioning of self compacting concrete. The qualities of these models were evaluated based on several factors.
such as level prediction, residual error, residual mean square and correlation coefficients. Full quadratic models in all the response (compressive strength at 3, 7 and 28 days and modulus of elasticity) showed high correlation coefficient (R2), adjusted correlation coefficient, less level of significant and sum of square errors from the four predictions models (linear, interaction, full quadratic and pure quadratic) were developed.

\[ Y_{28} = 1.3 + 0.138X_1 - 86.3X_2 + 0.160X_3 - 0.947X_4 \] (Linear model with \( R^2 = 46.6\% \))

\[ Y_{28} = -1040 + 2.77X_1 + 1200X_2 + 3.79X_3 + 5.0X_4 - 3.10X_1X_2 - 0.00866X_1X_3 - 0.0505X_3X_4 - 1.38X_2X_3 + 23.5X_2X_4 + 0.0580X_3X_4 \] (Interaction model with \( R^2 = 55.4\% \))

\[ Y_{28} = -2992 + 8.65X_1 + 4136X_2 + 5.40X_3 + 27.9X_4 - 3.10X_1X_2 - 0.00866X_1X_3 - 0.0505X_3X_4 - 1.38X_2X_3 + 23.5X_2X_4 + 0.0580X_3X_4 - 0.00691X_1X_1 - 4318X_2X_2 - 0.00621X_3X_3 - 1.27X_4X_4 \] (Full quadratic model with \( R^2 = 82.3\% \))

\[ Y_{28} = -1951 + 6.01X_1 + 2850X_2 + 1.77X_3 + 21.9X_4 - 0.00691X_1X_1 - 4318X_2X_2 - 0.00621X_3X_3 - 1.27X_4X_4 \] (Pure quadratic model with \( R^2 = 73.5\% \))

Where \( X_1 \) - Cement Kg/m\(^3\), \( X_2 \) - W/P ratio, \( X_3 \) - Fine aggregates Kg/m\(^3\), \( X_4 \) - Superplasticizer Kg/m\(^3\), \( Y_{28} \) - 28 days compressive strength.
The high correlation coefficient of the response shows good correlations that considered at least 95% of the measured values can be accounted for proposed models. The accuracy of the proposed models was determined by comparing predicted to measured values.

[Gram 2009][47] investigated numerical simulation of concrete flow, using both discrete as well as continuous approaches. The discrete particle model here serves as a means to simulate details and phenomena concerning aggregates modeled as individual objects. The continuous approach has been used to simulate large volumes of concrete.

Khayat et al. [2000][77] reviewed statistical models using a factorial design approach to understand the effect of mixture parameters on key responses, including slump flow, rheological parameters, filling capacity, V-funnel flow time, surface settlement, and compressive strength. The proposed statistical models can simplify the test protocol required to optimize a given mixture by reducing the number of trial batches needed to achieve a balance among mixture variables. This is due to the use of the models in conducting simulations of various variables to secure adequate deformability, stability, and strength. The models established using a factorial design approach are valid for a wide range of mixture proportioning and provide an efficient means to determine the influence of key variables on SCC properties.

2.14 Cost of SCC

The overall material cost of SCC is higher than that of ordinary concrete. The cost involved in quality control is also high in case of SCC due to instability problems. However, the increased cost for materials and quality control can be compensated through concrete quantity savings and productivity improvement. SCC is generally stronger than ordinary concrete. Therefore, the structural components will be made of thinner sections, and thus savings can be attained due to a less amount of concrete. The productivity improvement also reduces the cost involved in formwork. Moreover, SCC offers better mechanical and durability performance and greater service life than ordinary concrete, and hence can be acceptable over the increased
initial cost. If the cost analysis is conducted based on the lifecycle costing, the cost-effectiveness of SCHPC in construction industry will be apparent.

The use of SCC in high-rise building, bridge, offshore platform and other special structures will be economical over the increased cost of materials and more rigorous quality control. In fact, the overall cost will be low due to drastic reduction in the geometry of the structural components, reduced number of laborers, decrease in reinforcement percentage, ease of conveyance and placement, and reduction in formwork and shoring. Indirect benefits can also be gained through the durability improvement leading to maintenance savings. The maintenance and repair costs are expected to be low in SCC. Thus, a lot of savings will be achieved particularly for the large projects if SCC is used [Ouchi et al. 2003][122, Struble and Godfrey 2003][152].

Wellington [Repetto 2007][139] noted that newly developed methods of proportioning have elevated the composition of Self Compacting Concrete (SCC) into the range of normal strength, making it a potentially competitive material for current applications. In order to quantify reduction in labor cost by replacing traditional concrete with SCC an evaluation was carried out. The applications of SCC and ordinary concrete were monitored during the construction of two consecutive floors, one using SCC and the other with ordinary concrete. Beams and composite precast beam-hollow ceramic brick slabs were cast jointly. The system or formwork materials were identical for both SCC and ordinary concrete. It was revealed that labor productivity is considerably higher during the application of SCC. The productivity depends mainly on the type of placing equipment employed. Conversely, the placing of normal concrete is a labor intensive operation, and if the placing rate is to be increased, the labor force must be significantly increased and in accordance with the type of placing equipment.
2.15 Literature Summary on SCC

- The self compacting concrete (SCC) was invented in late 1980s by Okamura in Japan. It was proposed for construction to offset a growing shortage of labour and as a tool to enhance long-term durability of structures.
- SCC has many benefits over Normal Vibrated Concrete (NVC), like faster rate of placement with no mechanical vibration and less screening resulting reduced labor for transport-placement and vibration, ease of placement operations due to improved pumpability, reduction in noise levels in absence of vibrators, energy saving, better life of formwork and better aesthetics with improved surface finishing.
- SCC has few limitations of skilled labor requirement, stringent mix design criteria and unavailability of code of practice.
- SCC consists of almost same constituent materials as conventional concrete, which are cement, aggregates, water and few chemicals called superplasticizers and mineral admixtures (fly ash, silica fume, GGBS, lime stone powder etc.) in different proportions.
- Self compactability of SCC can be achieved through: Limited aggregate content (Coarse aggregate - 50% of the concrete volume and sand - 40% of the mortar volume), Low W/ P ratio, and use of higher dosage of superplasticizer.
- SCC should have characteristics of filling ability, passing ability, segregation resistance, robustness and consistence retention of these characteristics during transport and placing. The above three key properties are to some extent related and inter-dependent.
- EFNARC 2005 has suggested self compactability tests commonly conducted on fresh SCC mixes such as Slump Flow Test, T50 test, J-Ring test, L-Box, U-Box & V-Funnel test.
- There are no specific methods available for mix design of SCC, normally its trial and error based.
• NVC has a porous matrix and weak interfacial zones resulting in inferiorities in hardened properties. Elimination of the compacting process and incorporation of powders led to a denser cement matrix in SCC resulting in improved hardened properties.

• The setting time of SCC was reported to be twice as long as that of NVC due to the use of superplasticizer and fly ash.

• Compressive strength of SCC is better than NVC with similar content of materials.

• Elastic modulus of SCC is lower than NVC, because of the higher content of ultra fines, lower content of coarse aggregates and additives.

• The splitting tensile strength of SCC may be equal or higher than that of NVC.

• SCC may have lower shear strength compared to NVC because of the presence of comparatively smaller amount of coarse aggregates.

• Due to use of a higher content of paste, powder and superplasticizer, SCC has higher shrinkage and creep than NVC.

• Microstructure of concrete is highly affected by rheological properties. Rheological properties can significantly modify nature and structure of the concrete interfacial transition zone (itz), between aggregate and concrete paste, which is responsible for the mechanical properties, water tightness, fire resistance and durability of pre-stressed and reinforced concrete structures.

• Researchers presented derived numerical models that can be useful to reduce the test procedures and trials needed for the proportioning of self compacting concrete.

• The overall material cost of SCC is higher than that of ordinary concrete. The cost involved in quality control is also high in case of SCC due to instability problems. However, the increased cost for materials and quality control can be compensated through concrete quality, time and energy savings and productivity improvement.
2.16 CURING OF NVC AND SCC

Even when good quality concrete is placed on the job site, curing is necessary to ensure the concrete provides good service over the life of the structure. Good concrete can be ruined by the lack of proper curing practices. Curing is even more important today than ever before for at least three reasons [Neville 2008][115]:

- Today’s cements gain strength earlier and allow contractors to remove formwork soon after concrete placement. This encourages discontinuing curing operations prematurely.
- The lower water-cement ratios being used with modern concretes (like HPC) tend to cause self desiccation (Chapter 3). Ingress of water from proper curing is necessary to control this phenomenon.
- Many modern concrete mixtures contain mineral admixtures, such as fly ash and ground granulated blast furnace slag, that have slower reaction rates. Curing over longer periods of time is needed for proper development of the properties of these mixtures.

Curing has a major impact on the permeability of a given concrete. The surface zone will be seriously weakened by increased permeability due to poor curing. The importance of adequate curing is very evident in its effect on the permeability of the “skin” (surface) of the concrete.

The properties of hardened concrete, especially the durability, are greatly influenced by curing since it has a remarkable effect on the hydration of the cement. The advancements in the construction and chemical industry have paved way for the development of the new curing techniques and construction chemicals such as Membrane curing compounds, self curing agents, Wrapped curing, Accelerators, Water proofing compounds etc. With the growing scale of the projects, conventional curing methods have proven to be a costly affair as there are many practical issues and they have been replaced by Membrane curing compounds and self curing agents up to some extent as they can be used in inaccessible areas, Vertical structures, Water scarce areas etc. In this study effort has been made to understand the working and efficiency of curing methods which are generally required to be
adopted in the construction industry and compared with the conventional water curing method.

While curing is obviously critical for all concrete construction, this is especially true for the top surface of SCC. Because of the increased quantity of paste, low water/fines ratio and lack of bleed water at the surface, SCC is highly susceptible to surface drying. This can result in shrinkage cracks caused by early age moisture loss or surface crusting. [RMC-Association 2009][140]

Curing temperature is one of the major factors that affect the strength development rate. At elevated temperature ordinary concrete loses its strength due to the formation of the cracks between two thermally incompatible ingredients, cement paste and aggregates. When concrete is cured at high temperature normally develops higher early strength than concrete produced and cured at lower temperature, but strength is generally lowered at 28 days and later stage. [ACI-committee-305R 2009][3]

It is found that the chemical reactions between cement & water produces C-S-H gel which bonds the ingredients of concrete, viz. coarse & fine aggregates, mineral admixtures, etc, and converts these fragments into a rock solid mass. It is understood that blended cements require prolonged curing to convert calcium hydroxide into C-S-H gel. However, in case of OPC as well, voids within the concrete mass gets filled up and disconnected by the formation of C-S-H gel after about 10 days of curing. To have a dense microstructure and impermeability, prolonged curing is a must which leads to enhanced durability. [Kulkarni S.B. August 2011][88]

2.16.1 Methods of curing

Concrete can be kept moist (and in some cases at a favorable temperature) by three curing methods: [CCAA 2006][22, Neville 2008][115, Bozcurt and Yazicioglu 2010][20, Nagesh Tatoba Suryawanshi 2010][107]

1. Methods that maintain the presence of mixing water in the concrete during the early hardening period. These include ponding or immersion, spraying or fogging, and saturated wet coverings. These methods afford some cooling through evaporation, which is beneficial in hot weather.
2. Methods that reduce the loss of mixing water from the surface of the concrete. This can be done by covering the concrete with impervious paper or plastic sheets, or by applying membrane-forming curing compounds.

3. Methods that accelerate strength gain by supplying heat and additional moisture to the concrete. This is usually accomplished with live steam, heating coils, or electrically heated forms or pads.

2.16.1.1 Dry-Air Curing

Dry curing is a curing method wherein the concrete cubes are left in open air to be cured at room temperature. Researchers have been working on the natural air drying of concrete since long. Safiuddin et al. [2007][144], carried out experiments to study the effect of this type of curing on the properties of Microsilica Concrete (Microsilica was used as a 10% weight replacement of cement) with a water binder ratio of 0.35. Dry-air curing produced 15.2%, 6.59% and 3.36% reduction in compressive strength, dynamic modulus of elasticity and ultrasonic pulse velocity respectively, this was owing to the early drying of concrete which virtually ceased hydration of the cement because the relative humidity within capillaries dropped below 80% [Neville 2008][115] and thus the formation of major reaction product Calcium silicate hydrate the major strength providing and porosity reducer stops before the pores are adequately blocked by it. Also, it caused 12.4% and 46.53% increase in initial surface absorption after 10 and 120 minutes respectively. This might be due to micro cracks or shrinkage cracks resulting from the early drying out of the concrete [Fauzi 1995][37]. Experimental results indicate that Dry-curing is not an efficient method to achieve good hardened properties of concrete.

2.16.1.2 Pounding or immersion

This is a curing technique wherein the flat concrete surfaces such as slabs and pavements are cured by pounding of water around the perimeter of the surface with the help of sand dikes. It is an effective technique as it maintains a uniform temperature in the concrete and also prevents the loss of the moisture from the concrete. This technique is used in laboratory experiments wherein the specimens
are dipped in water after 24 hours of casting. The specimens are then tested for the strength after 7 and 28 days. Since pounding requires considerable supervision and labour, this technique is generally used for small construction activity only. [Klieger 1957][83]

A uniform temperature should be maintained through the concrete section to avoid thermal cracking. Laboratory tests show that concrete in a dry environment can lose as much as 50 percent of its potential strength compared to similar concrete that is moist cured. Curing of the concrete is also governed by the moist-curing period, longer the moist-curing period higher the strength of the concrete assuming that the hydration of the cement particles will go on. American Concrete Institute (ACI) Committee 301 recommends a minimum curing period corresponding to concrete attaining 70% of the specified compressive strength. [ACI-Committee-301 1994][2]

Kumbhar et al. [May 2011][91] observed that the strength of concrete is affected by a number of factors, one of which is the length of time for which it is kept moist, i.e. cured, another being the method of curing. Inadequate or insufficient curing is one of main factors contributing to weak, powdery surfaces with low abrasion resistance and durability.

Goel et al. [2013][43] observed that there was an increase of 42.1 percent in compressive strength at 7 days when compared to its strength at 3 days for specimens cured with immersion under water curing. For water curing an increase of 61 percent of compressive strength at 28 days over its strength at 7 days was observed. They noted that immersion curing gives the highest results when compared with dry curing and plastic film wrapping.

2.16.1.3 Steam/ Heat Curing

Steam curing is advantageous where early strength gain in concrete is important or where additional heat is required to accomplish hydration, as in cold weather. Two methods of steam curing are used: live steam at atmospheric pressure (for enclosed cast-in-place structures and large precast concrete units) and high-pressure steam in autoclaves (for small manufactured units).

Steam curing at atmospheric pressure is generally done in an enclosure to minimize moisture and heat losses. Tarpaulins are frequently used to form the
enclosure. Application of steam to the enclosure should be delayed until initial set occurs or delayed at least 3 hours after final placement of concrete to allow for some hardening of the concrete. However, a 3- to 5-hour delay period prior to steaming will achieve maximum early strength.

Steam temperature in the enclosure should be kept at about 60°C (140°F) until the desired concrete strength has developed. Strength will not increase significantly if the maximum steam temperature is raised from 60°C to 70°C (140°F to 160°F). Steam-curing temperatures above 70°C (160°F) should be avoided; they are uneconomical and may result in damage. It is recommended that the internal temperature of concrete not exceed 70°C (160°F) to avoid heat induced delayed expansion and undue reduction in ultimate strength. Use of concrete temperatures above 70°C (160°F) should be demonstrated to be safe by test or historic field data.

Besides early strength gain, there are other advantages of curing concrete at temperatures of around 60°C (140°F); for example, there is reduced drying shrinkage and creep as compared to concrete cured at 23°C (73°F) for 28 days [Klieger 1957][83].

Excessive rates of heating and cooling should be avoided to prevent damaging volume changes. Temperatures in the enclosure surrounding the concrete should not be increased or decreased more than 22°C to 33°C (40°F to 60°F) per hour depending on the size and shape of the concrete element.

The curing temperature in the enclosure should be held until the concrete has reached the desired strength. The time required will depend on the concrete mixture and steam temperature in the enclosure [ACI-Committee-517 1992][4, Jin et al. 2007][71]

Memon et al. [2011][102] investigated that longer curing time and curing the concrete specimens at higher temperatures result in higher compressive strength. There was increase in compressive strength with the increase in curing time; however increase in compressive strength after 48 hours was not significant. Concrete specimens cured at 70°C produced the highest compressive strength as compared to specimens cured at 60°C, 80°C and 90°C.
2.16.1.4 Cold weather curing

ACI 306 “Cold Weather Concreting” defines cold weather concreting as a period when for more than three (3) consecutive days, the following conditions exist:

- The average daily air temperature is less than 5°C (40°F) and,
- The air temperature is not greater than 10°C (50°F) for more than one-half of any 24 hour period.

Even though not defined as cold weather, protection is required during the first 24 hours to avoid freezing. The pore water in concrete starts to freeze around -1°C (30°F). At around -3 to -4°C (25 to 27°F), enough of the pore water will freeze so that hydration will completely stop, and depending on the extent of hydration, and thus the strength of the concrete, the forces generated by the expansion of ice (ice occupies ~9% more volume than water) may be detrimental to the long term integrity of the concrete. For every 10°C (18°F) reduction in concrete temperature, the times of setting of the concrete doubles.

Concrete that is protected from freezing until it has attained a compressive strength of at least 3.45 Mpa will not be damaged by exposure to a single freezing cycle. Concrete that is protected and properly cured will mature to its potential strength despite subsequent exposure to cold weather.

Various accelerators or Pozzolona may be used into concrete both before and after the addition of cement to the mix, they should also be included in trial mixes prior to placement. [Grace 2006][46]

2.16.1.5 Sea water curing

Now-a-days, as a progress of development, lots of engineering construction including high rise building, embankment walls, bridge etc is going on along the coastal belt of the country. In coastal areas, there has always been a deficiency of plain water as the available water is affected by sea salts. So it is difficult to arrange plain water for construction works in such location. Also it is economical to use sea water that is available near the construction site instead of plain water to be transported from other areas/sources. But sea water contains large amounts of sea salts, which may have adverse effect on the properties of concrete. So it is required
to investigate the effect of sea salts on strength properties of different types of concrete while using sea water for casting and curing of concrete. Although the existing literature and codes of practice reveal the effect of mixing and curing of sea water on durability of concrete, it still remains an area requiring study and research particularly effect on SCC. Primarily the study is to investigate the strength behavior of concrete cured with plain as well as sea water and compare their results.

Most sea waters are fairly uniform in chemical composition, which is characterized by the presence of about 3.5% soluble salts by weight. The ionic concentration of Na\(^+\) and Cl\(^-\) are highest typically 11,000 and 20,000 mg/liter, respectively. However, from the standpoint of aggressive action to cement hydration products, sufficient amount of Mg\(^{2+}\) and SO\(_4\)\(^-\) are present, typically 1400 and 2700 mg/liter, respectively. The pH of seawater varies between 7.5 and 8.4, the average value in equilibrium with the atmospheric CO\(_2\) being 8.2. Under exceptional conditions, pH value lower than 7.5 may be encountered. These are usually due to a higher concentration of dissolved CO\(_2\), which would make the seawater more aggressive to Portland cement concrete [Mehta 1985]\(^{100}\).

Sea water slightly accelerates the early strength of concrete but it reduces the 28 days strength by about 10 to 15 percent. It is pertinent at this point to consider the suitability of water for curing. Water that contains impurities which causes staining is objectionable for curing concrete members. The most common cause of staining is usually high concentration of iron or organic matter in the water. Water that contains more than 0.08 ppm of iron may be avoided for curing if the appearance of concrete is important and hence the use of sea water may also be avoided in such cases. In other cases, the water, normally fit for mixing can also be used for curing. [Shetty 2009]\(^{150}\)

*Islam et al. [2012]\(^{70}\) carried out investigations on four different grades of concrete made with plain and sea water, exposed to plain as well as sea water over a period of 180 days it was concluded that: Concrete specimens exposed to sea water environment showed some change in color from dark grey to light grey. Sea water affects the gain in strength of concrete when used for mixing and curing. It increases
the early strength gaining but ultimately the strength decreases. Sea water affects the rate of gain in strength of concrete when used for mixing. The strength of concrete made by using sea water is observed to be decreased by about 10% at 180 days. Concrete specimens made with plain water and cured in sea water showed a loss in strength of around 6% whereas concrete specimens made with sea water and cured in sea water environment showed loss in strength of around 10% as compared to the similar concrete specimens made and cured with plain water. Among the four grades of concrete studied the higher grade concrete A showed around 9% lowers strength deterioration as compared to the other grades of concrete B, C and D.

2.16.1.6 Fogging or Sprinkling

In this curing technique, a fine fog mist is frequently applied on the surface of the concrete through a system of sprayers or nozzles. It is an effective technique of curing when the humidity is low or the ambient temperature is well above the freezing point. This technique requires ample of water and a proper supervision. [Neville 2008]^{115}

2.16.1.7 Saturated wet covering

This is most often used curing technique in the construction industry. In this technique moisture retaining fabrics such as burlap cotton mats and rugs are used as wet covering to keep the concrete in a wet condition during the curing period, for if the drying is permitted, the cover will itself absorb the water from the concrete. Alternative cycles of wetting and drying during the early period of curing will cause cracking of the surface. The major disadvantage of this technique is discolouring of concrete.

Researchers are working in order to identify the effectiveness of the water curing methods over other curing methods. Rao Krishna [Rao et al. 2011]^{138} carried out an experimental study on the effect of elevated temperature on differently cured concrete of M40 grade and subjected to temperature of 150°C, 300°C and 450°C for 1 hour duration in muffle furnace. His study revealed that the 28-day compressive strength of the concrete specimen cured by water curing have been more than those
cured by membrane curing in both heated and high temperature exposure condition. Weight loss in both conventional water cured concrete and membrane cured concrete are comparable.

Safuddin [2007][144] investigated the effect of different curing techniques on the properties of Micro silica concrete (Micro silica was used as a 10% weight replacement of cement) with a water binder ratio of 0.35. His study revealed that Water curing is the most effective method of curing as it produced highest level of compressive strength, dynamic modulus of elasticity and ultra sonic pulse velocity and lower level of surface absorption because of improved pore structure and lower porosity resulting from greater degree of hydration and pozzolonic reaction without any loss of moisture from the concrete specimen.

Wet covering curing is the most efficient and preferred techniques in various construction projects, but they also encounter certain restriction in situ in construction of highways, canal lining, Shell structures, high-rise buildings and areas having scarcity of water.

2.16.1.8 Curing Compound

Various types of curing compound are available in the market, mainly includes water-based, resin-solvent based, chlorinated rubber, wax based etc. Water based curing compound is most used curing compound world-wide. These compounds are applied on the exposed surface of the concrete by the help of roller, brush or spray. Effectiveness of the curing compound is remarkable dependent on their application, time and generic type. It is difficult to apply such compounds on the vertical surfaces. Curing efficiency (E) for a particular method of curing can be determined by the following equation [Cabrera et al. 1989][21].

\[
E = \left[ \frac{k_1-k_2}{(k_1-k_3)} \right] \times 100
\]

Where, \( k_1 \) = studied property of a non-cured specimen, \( k_2 \) = studied property of a specimen cured by the method being evaluated, and \( k_3 \) = studied property of water-cured specimen till age of testing. If the curing method is equally good as water-curing (\( k_2 = k_3 \) ) then the value of \( E = 100\% \), while for poor curing method ( \( k_2 > k_3 \) ) the value of \( E \) tends to 0\%.
This definition gives a convenient scale with which to assess the efficiency of chemical curing compounds or traditional methods. Curing compounds namely, acrylic and water based are effective in decreasing plastic and drying shrinkage strain for both ordinary and blended cements and the curing efficiency of such compounds with respect to compressive strength are in the range of 84 to 96 percent \([\text{BASF-India 2006}]^{[19]} \text{ Al-Gahtani 2010}]^{[10]}\).

*Abdelaziz [2006]*\[^1\] investigated the effect of application time of water based curing compound (WBCC) on strength, hardness, sorptivity and porosity of blended concrete. His study revealed that application of WBCC in the early stage (within first 2 hours of casting) would yield best possible properties of concrete. The time of application of WBCC and pre-water curing had a greater effect on the durability properties of the concrete (sorptivity and porosity) than on mechanical properties (strength and hardness). He also suggested that compressive strength and Schmidt hammer tool are not suitable for assessing the efficiency of curing compound.

*Raghavendra and Aswath [2012]*\[^133\] from their comparative study on different curing methods reported that the efficiency of the membrane curing compound is 90% as compared to conventional standard water curing method. The compressive strength ratio of field curing using curing compound to standard curing reveals that, there is no ratio fall under 85% and this results also complies with the ACI 318 requirements, the results indicates 92.11% as minimum field-standard ratio.

*Qureshi et al. [2010]*\[^132\] experimented on high strength self compacting concrete by curing with 3 different techniques. First in a temperature controlled curing tank in the laboratory, second under prevailing site conditions and 3rd by application of a curing compound. They noted that 28-days compressive strength of cylinders cured under site conditions was 89 % of the compressive strength of cylinders cured in water tank in the laboratory (i.e., 11 % less). Similarly compressive strength of cylinders cured by applying curing compound was 93 % of the compressive strength of cylinders cured in the laboratory (i.e., 7% less).
2.16.1.9 Plastic Sheet

Plastic sheets such as polyethylene film are used to cure concrete. Polyethylene films are lightweight, impervious hence prevent the moisture movement from the concrete and can be applied to simple as well as on complex shapes. Major disadvantage of this type of curing is that it causes patchy discoloration especially if the concrete contains calcium chloride. Discoloration is more pronounced when the film develops wrinkles and it is difficult and time consuming on a large project to place the sheets without wrinkles. Polyethylene film should confirm to ASTM C171. Safiuddin et al. [2007] noticed that wrapping curing is more efficient than dry-air curing as it results in greater compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity and lower surface absorption. This is because in wrapped curing moisture movement from the concrete surface was hindered due to the impervious layer of the film and as a result good amount of moisture was available to be used throughout the hydration process. Yazicioglu et al. [2006] carried out experiments on SCC made with fly ash and silica fume and cured in three different conditions: normal water at 20°C, sealed and air cured. The results showed that water curing gives the highest values followed by cured as sealed and air irrespective of type and age of curing. For both compressive and tensile strength tests, SCC with silica fumes gives better results than fly ash made SCC.

2.16.2 Self curing or Internal curing of concrete

According to Marks et al. [2001] the mechanism of self curing can be explained as follows: “Continuous evaporation of moisture takes place from an exposed surface due to the difference in chemical potentials (free energy) between the vapour and liquid phases. The polymer added in the mix mainly form hydrogen bonds with water molecules and reduce the chemical potential of the molecules which in turn reduces the vapour pressure. Physical moisture retention also occurs. This reduces the rate of evaporation from the surface”. Self curing concrete is the newly emerging trend in the construction industry. Primary requirement of fast-track construction is high early strength in concrete. Early age concrete strength without costly heat treatment
is of greater significance in the construction industry.

*Ambily and Rajamane [2007]* observed that unconventionally, ‘internal curing’ is allowing for curing ‘from the inside to outside’ through the internal reservoirs created (in the form of saturated lightweight fine aggregates, superabsorbent polymers, or saturated wood fibres). ‘Internal curing’ is often also referred as ‘Self–curing.’

The following conclusions were drawn based on the results of their investigations: 

*Schliesser et al. 2010*

- A reduction or elimination of autogenous shrinkage is observed for internally cured mixtures. This reduces or eliminates the potential for early age cracking.
- Plastic shrinkage cracking is reduced in internally cured concrete.
- Internally cured concrete has a higher degree of hydration resulting in reduced water absorption.
- Internally cured concrete mixtures are less susceptible to early age thermal cracking.
- Large scale testing showed a reduction in the cracking potential when internal curing was used.
- The results of this investigation indicate that internally cured concrete has great potential for use in transportation structures. This occurs specifically due to the reduced potential for shrinkage and thermal cracking, the reduced fluid transport, and the increased densification of the matrix.

Water soluble alcohols are generally used as self curing agents. With conventional ingredients it is possible to design reasonably good fast track concrete mixture using admixture [*Ideker 2009*][55, *Karjinni and Ahmed 2012*][74].

*Nagesh Tatoba Suryawanshi  [2010]* carried out an experimental study to investigate the use of water soluble polyvinyl alcohol as a self curing agent. He concluded that Concrete mixes incorporating self curing agent has higher water retention and better hydration with time as compared to conventional concrete. Use of 0.48% of polyvinyl alcohol by the weight of cement as a self curing agent provides higher compressive, flexural as well as tensile strength than the strength of conventional mix. With increase in the percentage of polyvinyl alcohol there is a
reduction the weight loss of concrete. Efficiency of the self cured concrete is 92.5% as compared to the conventional standard water curing method [Raghavendra and Aswath 2012]^{133}.

Karjinni and Ahmed [2012]^{74} investigated the effect of non-chloride hardening accelerator and the type of curing on the compressive strength of the pavement concrete, produced with Portland Slag Cement (PSC). His study revealed that for a given dosage of accelerator and for a given age of concrete all the water cured specimens acquired the stipulated design strength where as none of the specimens cured by curing compound could attain the same. The average efficiency of the curing compound was found to increase in the early stage of curing but reduced at the later stage.

Kumar et al. [2012]^{89} found that PEG400 could help in self curing by giving strength on par with conventional curing. It was also found that 1% of PEG400 by weight of cement was optimum for M20, while 0.5 % was optimum for M40 grade concretes for achieving maximum strength without compromising workability. Higher flowability, excellent deformability and better resistance to segregation and bleeding are some of the unique properties of SCC. The use of SCC is gaining rapid popularity in modern construction industry due to the requirement of high rise buildings and column free spaces.

Vidivelli et al. [2013]^{162} carried out tests on SCC and controlled concrete noted that the ultimate deflection for admixture concrete beams and self curing concrete beams was increased by 14.5% and 7.82% when compared with control beams. The deflection ductility for self compacting concrete beams was increased by 44% when compared with control beams. Compressive strength of self curing concrete and admixture was increased 8.9% and 12.03% with comparing conventional concrete.

It is widely accepted that the placing of appropriate mix must be followed by curing in a suitable environment during the early stages of hardening in order to obtain better concrete with desired strength. The objective of curing is to promote the hydrations of cement and consists of a control of temperature and of the moisture movement from and into the concrete. However, in the case of site concrete, active curing stops nearly always long before the maximum possible hydration has taken
place. Thus, it is important to study the effect of curing condition on strength development of SCC.

It is concluded from the literature review that only few methods of curing have been studied despite availability of numerous methods for curing. Therefore, aim of the research is to investigate the effect of comprehensively selected nine different curing techniques on mechanical properties of SCC and compare these properties with NVC. The properties to be studied include compressive, tensile, flexural and shear strength. Also it is intended to develop self curing self compacting concrete (SCSCC) with the use of chemicals admixtures. SCSCC can serve as a good alternative of curing in the areas with water and labor scarcity.

*Sathanandham et al. [2013]* carried out studies with the use of shrinkage reducing admixture polyethylene glycol (PEG 4000) in concrete and noted that it helps in self curing and helps in better hydration and hence strength. He examined the effect of admixture (PEG 4000) on compressive strength, split tensile strength and modulus of rupture by varying the percentage of PEG by weight of cement from 0% to 2% for M20. It was found that PEG 4000 could help in self curing by giving strength on par with conventional curing. It was also found that 1% of PEG 4000 by weight of cement was optimum for M20 grade concretes for achieving maximum strength without compromising workability.

Self curing distributes the extra curing water throughout the entire 3-D concrete microstructure so that it is more readily available to maintain saturation of the cement paste during hydration, avoiding self desiccation and reducing autogenous shrinkage. Experimental measurements were performed on to predict the compressive strength, split tensile strength and flexural strength of the concrete containing Super Absorbent Polymer (SAP) at a range of 0%, 0.2%, 0.3%, and 0.4% of cement and compared with that of cured concrete. The grade of concrete selected was M40. Addition of SAP leads to a significant increase of mechanical strength (Compressive and Split tensile) Maximum compressive stress develop in M-40 grade self curing concrete by adding sap 0.3% of cement. Split tensile strength of self curing concrete for dosage of SAP 0.3% of cement was higher than non self curing concrete. Flexural strength of self curing concrete for dosage of SAP 0.3% of cement was higher than non self curing concrete. Performance of the self curing agent will
be affected by the mix proportions mainly the cement content and the \( w/c \) ratio. \cite{francis2013}

### 2.16.3 Advantages of Internal Curing

Internal curing or self curing has many advantages over conventional and other curing methods. \cite{ambily2007}

- Reduces autogenous cracking,
- Reduces permeability,
- Increases early age strength sufficient to withstand strain,
- Provides greater durability,
- Higher early age (say 3 day) compressive strength and flexural strength,
- Greater curing predictability,
- Higher performance,
- Improves contact zone,
- Does not adversely affect finishability,
- Reduces effect of insufficient external curing.

### 2.16.4 Self desiccation

One of the potentially detrimental side effects from the use of the low water-cement ratio concretes is self desiccation. Self desiccation refers to the process by which concrete dries itself from the inside. It is the localized drying resulting from a decreasing relative humidity (RH) which could be the result of the cement requiring extra water for hydration. It is the reduction in the internal relative humidity of a sealed system when empty pores are generated \cite{ambily2007}. Internal moisture is consumed from within the paste by the hydration reactions, and the internal relative humidity continues to decrease to the point at which there is not enough water to sustain the hydration process. The result is that the hydration and maturity of the concrete will terminate at an early age if additional moisture is not provided. Therefore, self desiccation effects are important considerations in the performance of high-performance concrete, particularly in the curing practices that involve “sealing” the concrete.
Self desiccation may be especially harmful to the durability properties of high-performance concrete since the microstructure of the paste is adversely affected. With inadequate hydration, the near-surface regions become more susceptible to the penetration of deleterious materials from the surrounding environment. For this reason, proper curing of low water-cement ratio concrete at early ages is essential if the concrete is to attain its potential properties. The detrimental effects of self desiccation can be largely controlled by careful attention to curing, especially during the initial 7 days after placement. [Meeks and Carino 1999]^{99}

2.16.5 Literature Summary on curing

- Curing has a strong influence on the properties of hardened concrete; proper curing will increase the durability, strength, volume stability, abrasion resistance, impermeability and resistance to freezing and thawing.
- To have a dense microstructure and impermeability, prolonged curing is a must which leads to enhanced durability.
- Broadly concrete can be cured by: Water adding techniques, water retaining techniques by supplying heat and additional moisture.
- Curing of concrete is mostly governed by two parameters Temperature and Period.
- Conventional water curing is the most efficient technique of curing as compared to Membrane curing, Self curing, Wrapped curing and Dry air curing techniques.
- In case of heat curing through steam or other techniques the temperature in the enclosure should be kept at about 60°C (140°F), it gives early strength gain and reduced drying shrinkage as compared to concrete cured at 23°C (73°F) for 28 days. Temperatures above 70°C (160°F) should be avoided as they may result in damage to ultimate strength.
- In cold weather, protection is required during the first 24 hours to avoid freezing. If the pore water freezes the hydration will completely stop and the forces generated by the expansion of ice may be detrimental to the long term integrity of the concrete.
• Sea water slightly accelerates the early strength of concrete but it reduces the 28 days strength by about 10 to 15 percent.

• Wet covering or wrapping curing is more efficient than dry-air curing as it results in greater compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity and lower surface absorption.

• Using membrane curing technique one can achieve about 90% of efficiency as compared to conventional water curing technique. Membrane curing compounds are most practical and widely used technique it is most suitable in water scarce area.

• Wrapped curing is less efficient than membrane curing and self curing it can be applied to simple as well as complex shapes.

• Dry-Air curing should be avoided at the construction sites because experimental results indicate that Dry-curing is not an efficient method to achieve good hardened properties of concrete. Dry-air curing produced 15.2%, 6.59% and 3.36% reduction in compressive strength, dynamic modulus of elasticity and ultrasonic pulse velocity respectively, this was owing to the early drying of concrete which virtually ceased hydration of the cement.

• The average efficiency of the curing compound increases with curing age initially and reducing at later age. Application of the curing compound is significantly dependent on the time of application of the compound.

• Water soluble alcohols are generally used as self curing agents. With conventional ingredients it is possible to design reasonably good fast track concrete mixture using admixture. Self curing technique is most suitable for high-rise buildings especially in columns and inaccessible areas.

• It is found that Polyethylene Glycol (PEG) could help in self curing by giving strength on par with conventional curing. The dose of PEGs ranges from 0.5 to 1% by weight of cement depending upon grade of concretes.

• There is no comprehensive study or models on curing which can give comparison between different curing techniques and provide relations between properties development through different curing techniques.
2.17 MOTIVATION

It has been found through various research and practical observations that in-situ concreting is highly affected by insufficient and improper compaction and curing and both the factors are neglected most of the times. Lack of compaction and curing leads to a concrete with reduced STRENGTH and DURABILITY. In order to achieve a “STRONG” and “DURABLE” concrete, the secret lies in making a Dense concrete. The key elements for achieving dense concrete and thereby strength and durability is proper compaction and curing.

Thus the motive for development of self compacting concrete was itself the problem on strength and durability of concrete (Also other benefits of SCC as mentioned in section 2.15). The usage of SCC is growing in the India, however, there is a need to decrease the material cost and a gain a deeper understanding of SCC technology. One way to reduce the material cost of SCC is through adequate mix proportioning and the addition of supplementary powder materials, such as fly ash. Once compaction is achieved, the strength and durability can be achieved through proper curing. It is observed that conventional curing techniques of ponding, wet covering and spraying are difficult to follow on field due to scarcity of labor and casual supervision. Also in extreme weather conditions curing becomes uncontrolled. Self curing of concrete may prove an extremely helpful tool for sustainable development. Thus the work will be useful to the Indian and global community for sustainable development in the concrete industry dealing with SAVING of materials, water, labor & energy and by getting STRONG and DURABLE structures which will long lasting and having resistance to withstand severe weather conditions.

2.18 OBJECTIVE OF STUDIES

The main objective of this research is to find the effect of different techniques of curing on mechanical properties (compressive, tensile, flexural strength and shear strength) of M30 Grade and M50 grade self compacting concrete (SCC). It is also aimed to identify the effect of extreme weather conditions curing such as ice, hot water and sea water on SCC. The research also dealt with developing self curing self compacting concrete (SCSCC) and study its mechanical properties.
2.19 SCOPE OF WORK

The scope of work is limited to study effect of selected curing techniques namely: water immersion, hot water, ice, sea water immersion, wet covering, polyethylene film, coating of external curing compound, dry curing and internal curing admixture on mechanical properties such as compressive, tensile, flexure and shear strength of selected grades of concretes (M30SCC, M30NVC & M50SCC) after curing for different periods 7 days, 28 days, 56 days and 90 days. The properties are studied based on experimental methods suggested by appropriate codes and with the help of microstructure. The results of M30SCC are compared with M30NVC. Since M50 grade of concrete is not commonly used in the normal buildings in India, the comparison between SCC and NVC is made only for M30 grade. Finally the results are analyzed and validated with appropriate standards.

This research program consists of experimental and analytical phases comprising of:

- Finalizing the mix proportions of high workability M30 grade and M50 grade SCC by various trials according to the EFNARC specification.
- Identifying various curing techniques for concrete and its procedures including curing in extreme weather conditions.
- To study mechanical properties of selected grades of SCC namely compressive, tensile, flexure and shear strength of hardened SCC and find the effect of different techniques of curing on these properties.
- To identify admixture(s) for self curing of SCC and develop self curing self compacting concrete (SCSCC) and consequently find mechanical properties namely compressive, tensile, flexure and shear strength of SCSCC.
- To finalize the design mix of the Normal Vibrated Concrete (NVC), almost same grade of the reference SCC (M30) with same available materials and compare their mechanical properties with different curing techniques.
- To analyze the work including comparison of mechanical properties achieved through different curing techniques and validate the results with empirical formulae in relevant codes and other results found from literature review.
- To develop mathematical correlation formulae between the compressive strength with different curing techniques.
- To study the effect of curing techniques on microstructure of concrete and consequently strength and durability of concrete.