CHAPTER 1
INTRODUCTION

1.1 GENERAL

The development of self-compacting concrete (SCC) is an important achievement in the construction industry for overcoming problems associated with conventional concrete. SCC does not require skilled workers for compaction as conventional concrete does. Due to its high fluidity and resistance to segregation, SCC can be pumped long distances in closely spaced reinforced sections. The concept of SCC was proposed in 1986 by Professor Okamura (1997), but the prototype was first developed in 1988 in Japan by Professor Ozawa (1989) at the University of Tokyo. The SCC was named “high-performance concrete” and later changed to “self-compacting high-performance concrete” or simply, “self-compacting concrete.”

SCC was developed to improve the durability of concrete structures. Since then, various investigations have been carried out, and SCC has been used in practical structures in Japan, mainly by large construction companies. Investigations for establishing a rational mix-design method and self-compactability testing methods have been carried out from the viewpoint of making it a standard concrete. SCC is cast so that no additional inner or outer vibration is necessary for the compaction. It flows in a similar manner as honey and has a very smooth surface level after placing. SCC requires a large amount of powder content (either by fine aggregate or fillers) compared to conventional vibrated concrete to produce a homogeneous and cohesive
mix (Topcu & Uygunoglu 2010). Okamura & Ozawa (1995) stated that the self-compactability in SCC can be obtained by increasing the fine aggregate content; by limiting the maximum aggregate size; by increasing the powder content; by using viscosity modifying admixtures (VMA) and reducing the water-to-binder ratio through superplasticizer (SP) (Khayat 1999). The basic principle of SCC is shown in Figure 1.1.

![Figure 1.1 Principle of SCC](image)

In Japan, the volume of SCC use in construction has been increasing steadily over the years (Okamura & Ouchi 2003). Data indicate that the share of SCC use in the precast concrete industry is about three times higher than that of cast in-situ production, which is due to the higher cost of SCC. In 2002, the estimated average price of SCC supplied by the ready-mixed concrete (RMC) industry in Japan was 1.5 times that of conventional concrete. Research studies in Japan and other developing countries such as India, are also making efforts to develop new types of SCCs with lower costs and better structural properties and standard mix design/testing procedures than conventional concrete.

Since the development of SCC in Japan, many organizations across the world have carried out research on its properties. Noticeably, the Brite–
Euram project (1998) was set up to develop the use of SCC in some European countries. A state-of-the-art report on SCC prepared by Skarendahl and Petersson (2000) summarized the conclusions of the research studies on SCC sponsored by the Brite–Euram project. In addition, an organization with participation from the specialty concrete product industry and EFNARC (2002) has developed specifications and guidelines for the use of SCC that covers a number of topics ranging from material’s selection and mixture design to the significance of the testing methods.

The main disadvantage of SCC is the high cost associated with the use of chemical admixtures and high volumes of Portland cement. One alternative to reduce the cost of SCC is to use mineral additives such as rice husk ash (RHA), metakaolin (MK), limestone powder, natural pozzolans, fly ash, and slag, which are finely divided materials added to concrete as partial replacement material (Sahmaran et al. 2006). As these mineral additives replace part of the Portland cement, the cost of SCC will be reduced, especially if the mineral additive is an industrial by-product or waste. It is well established that the mineral additives might increase the workability, durability, and long-term properties of concrete (EFNARC 2002; Alyamac & Ince 2009).

Therefore, use of these types of mineral additives in SCC will make it possible not only to decrease the cost of SCC, but also to increase its long-term performance. Topcu & Uygunoglu (2010) reported that to assess the effectiveness of additions to SCC, some of the parameters, such as chemical composition, hydraulic reactivity, and fineness have to be carefully examined before use.

The current studies in SCC, which are being conducted in many countries, including India, can be divided into the following categories: (i) use of rheological properties measurements to obtain data about the flow behavior
(workability) of cement paste and concrete; (ii) mixture proportioning methods for SCC; (iii) characterization of SCC using laboratory testing methods; (iv) durability and hardness properties of SCC and their comparison with conventional concrete; and (v) construction issues related to SCC. These factors will be relevant to the immediate needs.

In addition, the following statements also require particular attention from a long-term perspective: (i) the development of mixture design guideline tables similar to those for conventional concrete; (ii) a shift to an optimum level of powder contents in SCC from the existing high powder mixtures; (iii) a better understanding of the long-term properties, such as permeability, chemical attack, sulfate attack, corrosion of steel on concrete, and autogenous and plastic shrinkage in SCC; and (iv) the development of site quality control parameters such as in “all-in-one” acceptance tests.

1.2 MATERIALS FOR SCC

The constituent materials for SCC are the same as those used in traditional vibrated concrete conforming to Indian Standard, IS 456:2000. However, in order to be sure of uniform and consistent performance for SCC, additional care is needed in the initial selection and also in the continual monitoring for uniformity of fresh concrete. To achieve these requirements the control of the constituent materials needs to be increased, and the tolerable variations restricted, so that the production of SCC is within the conformity criteria without the need to test and adjust every batch.

Mixture proportions of SCC differ from conventional concrete. The SCC has more powder content and less coarse aggregate, but lower powder content and more coarse aggregate. Moreover, SCC incorporates HRWR or SP in larger amounts and frequently a VMA in small doses. The questions that dominate the selection of materials for SCC are (i) limits on the amount
of marginally unsuitable aggregates, that is, those deviating from ideal shapes and sizes, (ii) choice of HRWR, (iii) choice of VMA, and (iv) interaction and compatibility between cement, HRWR, and VMA.

The materials for SCC and their requirements as per IS code provisions and EFNARC (2005) guidelines are discussed below:

1.2.1 Cement

All cements that conform to IS 456:2000 may be used for the production of SCC. The correct choice of cement type is normally dictated by the specific requirements of each application of SCC. Other combinations of Portland cement with mineral admixtures of quality conforming to relevant Indian Standards may also be used in the manufacture of SCC.

1.2.2 Additions

In general, the additions are used as filler or cement replacement material in the SCC mix. Due to the fresh property requirements of SCC, inert (limestone, dolomite etc.) and pozzolanic / hydraulic (Fly ash, Silica fume, RHA, MK, Ground granulated blast furnace slag etc.) additions are commonly used to improve and maintain the cohesion and segregation resistance. The addition will also regulate the cement content in order to reduce the heat of hydration, thermal shrinkage and the cost of production. The additions are classified according to their reactive capacity with water and are presented in Table 1.1.
Table 1.1  Classification of additions according to their reactivity with water

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Classifications or Types</th>
<th>Additions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inert or semi inert</td>
<td>Mineral fillers (Limestone, dolomite, etc.) Pigments</td>
</tr>
<tr>
<td>2</td>
<td>Pozzolanic</td>
<td>Fly ash conforming to IS 3812 (Part-1), Silica fume, Rice husk ash and Metakaolin, etc.</td>
</tr>
<tr>
<td>3</td>
<td>Hydraulic</td>
<td>Ground granulated blast furnace slag confirming to IS 12089</td>
</tr>
</tbody>
</table>

SCC is often selected for its high quality finish and good appearance, but this may be compromised if the source of the addition does not have good color consistency.

1.2.2.1  Mineral fillers

The particle size, shape and water absorption of mineral fillers may affect the water demand / sensitivity and therefore, suitable fillers alone can be used in the production of SCC. Calcium carbonate based mineral fillers are widely used and can give excellent rheological properties and a good finish. The most advantageous fraction is that smaller than 0.125 mm and in general it is desirable more than 70% pass through the 0.063 mm sieve. Fillers specifically ground for this application offer the advantage of improved consistency of particle size distribution, reducing water demand and making them particularly suitable for SCC compared with other available materials.

1.2.2.2  Fly ash

Fly ash gives remarkable contribution to sustainable, cost effective and durable SCC. It has rendered not only workability and filling ability, but
also gives strength at a later age. The mean particle size of the fly ash is seven microns against 25 microns in the ordinary Portland cement (OPC). Thus, fly ash gives particulate dense for the same weight. Hence, fly ash particles interfere with cement particles and allow pozzolanic reaction when water is added to the binder, and partially playing the role of SP.

1.2.2.3 Silica fume

The high level of fineness and spherical shape of silica fume (SF) result in good cohesion and enhanced resistance to segregation. However, SF is also very effective in eliminating bleed, and this can give rise to problems of rapid surface crusting. Hence, it can be used in cold joints / surface defects if there are any breaks in concrete delivery. It has also led to finishing problems in the top surface.

1.2.2.4 Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBS) provides reactive fines with low heat of hydration. GGBS is already present in some types of cement but is also available as an addition in some countries and may be added at the mixer. A high proportion of GGBS may affect the stability of SCC resulting in reduced robustness with problems of consistency control while slower setting can also increase the risk of segregation. Ground blast furnace slag is also available in some countries as a type I addition.

1.2.2.5 Rice husk ash

RHA is an agro-waste and used as it enhances the excellent properties of SCC. Presently, it is well known as a cement-replacing pozzolanic material and there are also a number of research projects being conducted on it. Usually, it can be obtained by burning rice husks at about
600–800°C in a controlled manner, which causes the formation of amorphous silica with a high surface area (Ganesan et al. 2007). Finely ground RHA is responsible for the high reactivity in cement and is used to reduce the porosity as well as the width of the inter-facial transition zone (ITZ) (Nguyen et al. 2011; Safiuddin et al. 2010). However, when the replacement level of RHA is increased (more than 15%), the high surface area decreases the workability of the SCC (Antonios et al. 2012); this property is unfavorable when it comes to generating the SCC.

Therefore, to increase the workability and quantity of the total cement replacement level of the SCC, suitable water to binder (w/b) ratio may be increased with SP.

1.2.2.6 Metakaolin

MK is an amorphous material that is obtained by dehydrating kaolin at a temperature of about 800°C (Carlos et al. 2006). The high reactivity of MK with cement and its usability to accelerate the cement hydration differentiates it from other pozzolanic materials (Eva et al. 2011). It also accelerates the initial setting time and improves especially the mechanical and transport properties of SCC, especially since it can also attain high compressive strength at an early age (Jutice & Kurtis 2007).

1.2.2.7 Other additions

Natural pozzolana, ground glass, air cooled slag and other fine fillers have also been used or considered as additions for SCC, but their effects need to be carefully and individually evaluated for both short and long term effects on the SCC.
1.2.3 Aggregates

The aggregate for SCC should conform to IS 383:1970 and meet the strength requirements of IS 2386: 1963 (Part I to V). The moisture content, water absorption, grading and variations in the fine content of all aggregates should be closely and continuously monitored and must be taken into account in order to produce SCC of constant quality. Using washed aggregates will normally give a more consistent product. Changing the source of supply is likely to make a significant change in the concrete properties and should be carefully and fully evaluated.

1.2.3.1 Coarse aggregate

The aggregate retained on the 4.75 mm (No.4) sieve is defined as coarse aggregates (IS 383:1970). 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 with 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 (Xie et al 2002).

The physical characteristics such as the size, shape, surface texture, and porosity of coarse aggregates affect the properties and durability of concrete. The nominal maximum size for SCC can be 20 or 25 mm. However, the smaller size (12 to 20 mm) is preferable to produce higher strength (ACI 211.4R-93 2004; Kwan 2000) and to reduce segregation in fresh SCC. The shape and texture of coarse aggregates influence the packing of combined aggregates in SCC. The shape of the coarse aggregates also considerably affects the properties of SCC. Round aggregates are better than angular aggregates for the flowing ability of the SCC, since they induce less yield stress and plastic viscosity in the concrete mixture due to less inter-particle
friction (Geiker et al 2002). Conversely, rough and angular aggregates are conducive to high strength and strong interfacial bond due to rough surface texture and interlocking characteristic (Taylor et al 1996). But the surface texture, aspect ratio, and angularity of angular aggregates are not conducive to the flowing ability of the SCC because of greater water demand and increased yield stress and plastic viscosity. However, the required flowing ability can be maintained in the presence of HRWR.

The gradation of coarse aggregates also affects the flow properties and segregation resistance of SCC. The well-graded aggregates contribute to producing the optimum mixture with least particles interference, and thus enhance the flowing ability and reduce the tendency of segregation in fresh concrete. They also improve the hardened properties and durability of concrete due to dense particle packing (Tasi et al 2006).

1.2.3.2 Fine aggregate / sands

Fine aggregates are the second ingredient of aggregate phase in SCC. Sand is the most commonly used fine aggregate in concrete. It is passed through 4.75 mm (No. 4) sieve but are retained on the 75 μm sieve (IS 383: 1970; IS 2386: 1963). They occupy a greater volume in SCC, as compared to the ordinary concrete (Bonen & Shah 2005). Similar to coarse aggregates, fine aggregates also influence the performance of SCC. They increase the flowing ability and segregation resistance when used in a suitable amount (Okamura & Ozawa 1995; Su et al 2002). In addition, they modify the strength of concrete when used in varying proportions with cement and coarse aggregates (Xie et al 2002).

The physical properties of fine aggregate influence the performance of concrete in fresh and hardened states. For instance, the particle shape, surface texture, surface area, and void content affect the mixing water
requirement and compressive strength of concrete (ACI 211.4R-93, 2004). Also, the physical characteristics of fine aggregate considerably influence the mortar flow and thus they may affect the flowing ability of the SCC. The published guidelines show that fine aggregates may produce a more significant effect than coarse aggregates on the fresh properties of SCC (EFNARC 2005). Therefore, the physical properties of fine aggregate should be conducive to the performance of SCC.

Gradation of fine aggregates represents the size distribution of particles in the range of 4.75 mm to 150 μm. The gradation of fine aggregates has an effect on the viscosity of mortar and thereby on the flowing ability of fresh concrete. Poor sand grading affects the water and cement contents of concrete and causes most mixing problems (Shilstone 2002). In general, the fine aggregates selected for SCC should be well-graded to reduce the paste content (EFNARC 2005). The well-graded fine aggregates increase the flow of mortar and hence may improve the flowing ability of the SCC. The ‘fineness modulus’ is a ready index of the coarseness or fineness of fine aggregates. The larger the index, the coarser are the fine aggregates. A fineness modulus in the range of 2.5 to 3.2 is recommended for high-strength, high-performance concrete (ACI 211.4R-93, 2004), and can also be used for SCC.

1.2.4 Chemical Admixtures

SCC invariably incorporates chemical admixtures – in particular, HRWR or SP and sometimes, VMA. Other admixtures, including air entraining, accelerating and retarding may be used in the same way as in the traditionally vibrated concrete. However, the advice should be sought from the admixture manufacturer to use and the optimum time for additions and they should conform to IS: 9103:1999 and ASTM-C-494 Type 'F' depending on the dosages used.
Choice of admixture for optimum performance may be influenced by the physical and chemical properties of the binder/addition. Factors such as fineness, carbon content, alkalis and $C_3A$ may have an effect. It is, therefore, recommended that compatibility is carefully checked if a change in the supply of any of these constituents is to be made.

1.2.4.1 High range water reducer

High-range water reducer (HRWR), also known as superplasticizer, has made a breakthrough in the concrete industry. It is an essential material component that must be used to produce SCC. The HRWR improve the flowing ability of SCC by their liquefying and dispersing action. They reduce the yield stress and plastic viscosity of the concrete by their liquefying action (Yen et al. 1999), and thus provide a good flowing ability in SCC.

In addition, the HRWRs deflocculate the cement particles and free the trapped water by their dispersing action and hence enhance the flowing ability of the SCC. In dispersing action, the inter-particle friction and the flow resistance are also decreased, and therefore, the flowing ability of concrete is improved.

HRWR is formulated to produce high plasticity, normal-setting characteristics, and accelerated strengths in concrete. HRWR is usually available in clear dark brown liquid form, but also obtainable in solid state as a brownish powder. They usually possess a viscosity in the range of 60 to 80 centipoises, and a solid content may be varying from 22 to 42% by weight. Also, the relative density of HRWR is near to that of water and hence it can be easily dispersed with water.

HRWR can be used as a singular admixture or as a component in an admixture system, but it must fulfill some physical requirements and should
be compatible with cementing materials for good performance in concrete. The ASTM has specified some physical requirements for HRWR (IS 9103:1999 & ASTM C 494/C 494M, 2004). Polycarboxylate and Sulphonated Napthalene Polymers (SNP) based HRWR is used to produce SCC. They are produced from the relevant monomers by a free radical mechanism. High-range water reducers prevent the formation of cement-water agglomeration in the concrete mixture and disperse the cement particles in aqueous phase, as can be seen from Figures 1.2. Thus, the water demand of concrete mixture is significantly reduced.

![Dispersion of cement particles](image)

Figure 1.2 Dispersion of cement particles (a) without Water alone (b) with water and HRWR

1.2.4.2 Viscosity modifying agents

Viscosity modifying agent (VMA) also referred to as Viscosity-enhancing admixture (VEA), Stabilizers and water retaining admixture (WRA) is a relatively a new addition to the family of admixtures for cement paste, mortar and concrete. The common application of VMA is to produce non-dispersible underwater concrete and SCC. VMA improves the viscosity and cohesion of fresh concrete, and thus reduces the bleeding, surface settlement and aggregate sedimentation resulting in a more stable and uniform fresh concrete (Khayat & Guizani 1997). In addition, VMA makes the fresh
concrete more robust and less sensitive to the small variations in the conditions and proportions of other constituent materials (EFNARC 2005).

The most common VMAs are water soluble. They are available in liquid form. They are lighter than the other chemical admixtures such as HRWR and AEA with a relative density very close to that of water. They also contain a very small amount of solids, as compared to HRWR and AEA. Currently, there is no ASTM or Indian standard specification providing any physical requirements for VMA. Nevertheless, the VMAs should be compatible with the other chemical admixtures, particularly HRWR, to produce cohesive yet highly flowable concrete mixtures.

1.2.4.3 Air entraining admixture

Air-entraining admixture (AEA) is used in Portland cement paste, mortar or concrete for the purpose of entraining air in the respective masses (Dodson 1990). The main application of the AEA in SCC is to protect the hardened concrete from frost attack and repeated freezing and thawing (Khayat 2000). An AEA incorporates millions of non-coalescing microscopic air bubbles in fresh concrete and forms a network of air-voids in the hardened concrete.

The air-voids act as pressure releasing valves and thus reduce the stresses caused by the expanding frost. In addition, the air bubbles act as ball-bearings and thus enhance the flowing ability of concrete. They can also decrease bleeding in concrete by reducing the differential movement of water (Shetty 2001). However, they may reduce the segregation resistance of SCC by affecting the plastic viscosity of concrete (Khayat 2000).

The relative density of AEA is closer to that of water. It is also soluble in water. Hence, the dispersion of AEA in concrete is enhanced when
used with the mixing water. Also, most AEAs are not totally evaporable. They contain some solids. The solid content depends on the AEA types. It usually varies in the range of 5% to 20% by weight.

1.2.5 Admixture Compatibility / Limitation

A large amount of HRWR or superplasticisers, typically SNP-based, is added to SCC to make it flowable at reasonable water contents. There exists the problem of incompatibility between cement and HRWR Admixture, which is felt highly for which mixtures having low water content. Jolicoeur & Simard (1998) have studied the interaction between SNP - based HRWR and cement. In concretes having low water content and high superplasticizer dosage, gypsum (present in cement) may precipitate out, causing a premature stiffening of the paste and consequent loss of slump. However, SCC mixtures typically may have a water content of 170-200 liters/m$^3$ and the compatibility problems associated with low water contents may not arise.

Sometimes HRWRs (superplasticizers) are blended with retarders or lignosulfonates (which may have sugar in them), for slump retention in hot weather conditions. When a VMA is used along with such blended HRWR, concrete may not set for nearly twenty h. This problem may be avoided by using pure SNP-based HRWR. The retarding effect of the VMA itself will be adequate for extending the slump retention time.

1.2.6 Water

Water is the readily available most important component of any concrete. 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 HRWR to achieve the self-consolidation capacity of SCC (Okamura & Ozawa 1995). It contributes to attaining good flowing ability of SCC by lubricating the fine and coarse aggregates.

Water intended for use in concrete should be clean, fresh and free of deleterious substances. Water containing harmful substances such as silt, suspended particles, organic matter, oil, or sugar cane affects the strength and setting properties of cement and disrupt the affinity between aggregate and cement paste (Nawy 1996). 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 2001). In general, the potable or drinkable water is safe for use in concrete. However, the criterion of potability is not absolute. Water not fit for drinking may also be used satisfactorily in making concrete.

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 2001). It should not contain a high amount of dissolved solids, chlorides, alkalis, carbonates, bicarbonates, sulfates, and other salts, which can interfere with the performance of concrete. Water containing the chloride ion, \( \text{SO}_3 \) ion, and dissolved solids below 500, 1000, and 2000 mg/L, respectively, is satisfactory for making concrete. Though dissolved solids exceeding 2000 mg/L are not always harmful, they can adversely affect the strength and setting properties of cement. Water including organic acids may also adversely affect the hydration of cement. Therefore, when the suitability of water is questionable, it must be tested prior to use in concrete. The Indian standard (IS 456: 2000) has specified required physical and chemical limits to assess the acceptability of questionable mixing water.
1.3 MIXTURE PROPORTIONING METHODS FOR SCC

The mixture design of SCC is different from that of ordinary concrete. In general, the compressive strength is the primary criterion for designing ordinary concrete. Conversely, the flowing ability and durability must be given equal importance with the compressive strength in designing SCC. Thus, different a design approach is needed for SCC.

1.3.1 Justification for a Different Mix Design Method

The process of mixture design for ordinary concrete is not applicable to SCC for the following reasons:

a. Established relationships between average and specified compressive strengths of ordinary concrete could be unacceptable for SCC possessing high strength.

b. Traditional curves for the relationship between w/b ratio and compressive strength could be misleading for SCC that needs a lower w/b ratio.

c. None of the traditional curves for w/b ratio and strength relationship are considered for the effect of supplementary cementitious materials (SCM), such as HRWR, and VMA, which are usually used to produce SCC.

d. The coarse aggregate content of ordinary concrete is relatively high and unsuitable for SCC.

e. The fine aggregate content obtained from the traditional method is much lower than that recommended for SCC.
f. The approximate water content of concrete mixture does not include the effects of SCM and HRWR, which are usually incorporated in SCC.

g. Slump alone is no longer a performance criterion for the flowing ability of the SCC.

The aggregate content, the incorporation of SCM, and the presence of various chemical admixtures may have a significant influence on the flow characteristics, strength, transport properties and durability of SCC. Therefore, a different design approach should be followed, instead of the traditional methods, to design the mixture composition of SCC.

1.3.2 Current Methods of Mixture Design

The mixture design method proposed by Okamura & Ozawa (1995) has mostly been used in Japan. The Japanese Ready-mixed Concrete Association (JRMCA) has simplified this method to standardize the mixture proportioning process of SCC in Japan (Su et al 2001). Okamura and Ozawa’s method has also been used in many countries like India, Europe, etc. with some modifications (EFNARC 2002, EFNARC 2005). In this method, the coarse and fine aggregate contents are fixed and then self-consolidation capacity is achieved just by modifying the w/b ratio and HRWR dosage. The disadvantage of this method is that the w/b ratio cannot be fixed based on the strength requirement like the conventional concrete mixture design since it has to be decided through achieving the self-consolidation capacity. Therefore, the w/b ratio fixed on the basis of self-consolidation capacity may not provide the expected strength. In addition, it may take many trial mixtures to fix the proper w/b ratio and HRWR dosage, as these two must be balanced to provide the optimum flowing ability and segregation resistance unless a
VMA is used. The general principle of SCC mixture design as per EFNARC (2005) is presented in Figure 1.3

![Diagram of SCC mixture design process]

**Figure 1.3 Principle of SCC mixture design as per EFNARC guideline**

There is no Indian standard mixture design method for SCC. The Indian Road Congress (IRC) is currently working to develop a mixture design procedure for SCC. IRC also recommend the use of SCC in bridges and the same is under the draft stage to be put in rigid pavement and cell fill
pavement by IRC. A study of SCC and the cell fill pavement (which requires SCC also) is largely being undertaken by PL Bongirwar Advisor L&T and Prof BB Pandey, IIT Kharagpur. However, it is tried in the field on many projects in India now. As a safeguard against separation of water, use of viscosity modifying agent is usually essential to minimize shrinkage due to high powder content in SCC besides additional requirements of fines passing 125 microns. There are typical mixes of SCC similar to the conventional concrete where the risk of cracking due to shrinkage and thermal stresses could be reduced. Addition of fly ash and other siliceous mineral admixtures such as RHA, SF and MK in the conventional concrete in addition to chemical admixtures, make sustainable 'SCC'.

There are many organizations / academic institutions / cement companies (CRRI, NCB, SERC, CBRI, L&T, ACC, Ultra-Tech, Ambuja Cements) in India who are working hard in the laboratory and the field for the advancement in the use of SCC. They are mainly focused to minimize carbon emission and to make a cost effective construction product. There is a need to formulate IRC / BIS specifications / guidelines for the use of SCC in respective structures based on the experience / data gained in India.

In North America also, there is no ACI or CSA standard mixture design method for SCC. The ACI is currently working to develop a mixture design procedure for SCC (ACI Committee 211H, 2006). Recently, the International Centre for Aggregates Research (ICAR) in the University of Texas at Austin has developed a mixture design for SCC (Koehler & Fowler 2006). This method satisfies the criteria of filling ability, passing ability and segregation resistance, but does not give equal importance to strength and durability. For example, it allows a w/b $\geq 0.45$, which is not suitable to achieve high strength and good durability. Therefore, this method may not be valid for SCC. Saak et al (2001) have also introduced a design methodology...
for SCC, assuming that the rheology and density of paste matrix dictate the flowing ability and segregation resistance of concrete. This methodology highlights how the segregation can be controlled in SCC, but it does not clearly explain how the aggregate characteristics and content influence the filling ability and passing ability of concrete. In addition, it does not give any clear guidelines for obtaining high strength and improved transport properties or durability. Nevertheless, the concrete industry is exploiting Shilstone’s method to produce SCC. This mixture design method is based on the aggregate particle distribution and several parameters for workability, coarseness and mortar fraction (Shilstone 1990). The self-consolidation capacity can be obtained by adjusting the workability and coarseness parameters and by fixing the water content and HRWR dosage based on trial mixtures.

In China, Kwan (2000) developed a mixture design method for SCC incorporating SF. This method shows the process of getting SCC with a mean 28-day cube strength greater than 80 MPa and a slump above 200 mm. It uses a w/b ratio and strength relationship, which is different from that of the ordinary concrete. However, it fixes the dosage of HRWR at 3% by weight of the binder, which may not be practical for any other SCC. Another mixture design method for SCC has been developed in China (Xie et al 2002). It is specific to SCC incorporating ultra-pulverized fly ash. This method employs the fineness of ultra-pulverized fly ash and the optimum HRWR dosage to assess the flowing ability SCC. It includes a very high content of cementing material, which is not cost-effective. This method also uses a relatively high coarse aggregate content, which is not favorable for good passing ability.

In Taiwan, a mixture design method has been developed based on the concept of aggregate packing factor (Su et al 2001). This method can predetermine the amount of SCM and the dosage of HRWR although they
may need to be adjusted by trial mixtures. In this method, the fine aggregate content is high, which enhances the filling ability and passing ability but reduces the compressive strength. Also, this method assumes that the relationship between compressive strength and w/b ratio is similar to that of the ordinary concrete.

1.3.3 Statistical Methods

Several statistical mixture design methods such as factorial design approach (Ghezal & Khayat 2002) and three-factor central composite design method have been used in North America to produce SCC mainly for laboratory-based work. These approaches provide an optimum mixture composition from various mixture combinations. Nevertheless, they are not always practical due to the variability of the constituent materials and the involvement of a greater number of variables in mixture design.

In the Khayat (2000) study, five parameters—cementitious materials, water to cementitious materials ratio (w/cm), HRWRA concentrations, VMA concentration, and volume of coarse aggregate—at five different levels, were chosen. The response variables were the slump flow, relative flow resistance (analogous to torque measurement), and relative torque (viscosity). In addition, the V-funnel time, filling ability, and settlement were also measured. A total of 32 SCC mixtures were prepared to obtain the required relationships.

This method was useful in establishing interrelationships among mixture parameters for performance optimization. Trade-offs among various parameters of the same response were studied, such as lowering of w/cm and increasing HRWR dosage, keeping w/cm constant, and changing the cement content and adjusting HRWR dosages. This model could predict the self-compatibility of the different mix designs.
1.3.4 Empirical Methods

A customary method for the design of SCC is to follow the recommendations of Okamura & Ozawa (1995). In this method, 50 percent of the solid volume is taken up by coarse aggregate, while 40 percent of the mortar volume is fine aggregate. Paste composition of the concrete (that is the w/b ratio) is then determined using flow tests on mortar. This method was derived from numerous experiments using aggregates specific to the researchers’ area. A survey of the literature indicates that a number of researchers use this method as a starting point for their investigations. Adjustments in coarse and fine aggregate contents are then made to achieve the desired flow properties.

Edamatsu et al (2003) proposed a modified approach. In the Edamatsu’s method, the limiting coarse aggregate volume ratio is kept at 0.5. The fine aggregate content, in this case, is then fixed using the V-funnel test with standardized coarse aggregate. w/b ratio and SP dosage are determined from mortar flow and funnel tests.

The guidelines recommended by EFNARC (2005) are also based on Okamura’s method. The difference is that instead of fixing the coarse aggregate limit at 0.5, a higher amount is permitted in the case of the rounded aggregate (up to 0.6). The proportion of sand in the mortar is varied between 40 and 50 percent, and w/b ratio and SP dosage are determined through mortar slump flow and V-funnel tests. A comparison of the three methods discussed in this section is presented in Table 1.2. From Table 1.2, it can be noted that the Edamatsu’s method provides a more scientific basis for fixing the mortar content of SCC, the EFNARC method allows more freedom in coarse aggregate content.
Table 1.2 Empirical mixtures proportioning methods for SCC

<table>
<thead>
<tr>
<th>Proposed By</th>
<th>Maximum CA Volume Ratio</th>
<th>Maximum Proportion of Sand in Mortar, %</th>
<th>Paste Composition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okamura &amp; Ozawa (1995)</td>
<td>0.5</td>
<td>40 (Empirical)</td>
<td>Mortar flow and V-funnel tests</td>
<td>Originally developed using moderate heat or belite rich cement</td>
</tr>
<tr>
<td>Edamatsu et al (2003)</td>
<td>0.5</td>
<td>Determined by V-funnel test using standardized coarse aggregate</td>
<td>Mortar flow and V-funnel tests</td>
<td>Enables determination of stress transferability of mortar</td>
</tr>
<tr>
<td>EFNARC (2005)</td>
<td>0.5-0.6</td>
<td>40-50 percent (Empirical)</td>
<td>Mortar flow and V-funnel tests</td>
<td>Allows more freedom in coarse aggregate content</td>
</tr>
</tbody>
</table>

1.4 TEST METHODS FOR SELF-COMPACTABILITY

On the stage before placing, SCC is required to have three qualities: high-filling ability, resistance against segregation and passability, i.e, ability that is necessary to pass the space between reinforcing bars. Other additional properties, such as washout resistance and finish ability, may be significant and specified for individual projects / applications. Therefore, it is important to test whether the concrete is self-compactable or not and also to evaluate deformability or viscosity for estimating proper mix proportioning if the concrete does not have sufficient self-compactability.

The common tests currently used and their limitations given by EFNARC (2005) are presented in Table 1.3. Also, brief description of the tests for fresh state properties of SCC are given below one by one:
Table 1.3 Conformity criteria for fresh SCC as per EFNARC guidelines

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Property</th>
<th>Test</th>
<th>Class</th>
<th>Criteria (Limitations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Filling ability</td>
<td>Slump flow (SF) test</td>
<td>SF1</td>
<td>520 mm to 700 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SF2</td>
<td>640 mm to 800 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SF3</td>
<td>740 mm to 900 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V-Funnel (VF) test</td>
<td>VF1</td>
<td>≤ 10 sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VF2</td>
<td>7 sec to 27 sec</td>
</tr>
<tr>
<td>2</td>
<td>Passing ability</td>
<td>Passing ability (PA) or L-box test</td>
<td>PA1</td>
<td>≥ 0.75 (H₂/H₁ ratio), if 2 bars</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PA2</td>
<td>≥ 0.75 (H₂/H₁ ratio) if 3 bars</td>
</tr>
<tr>
<td>3</td>
<td>Segregation resistance</td>
<td>Sieve segregation resistance (SR) test</td>
<td>SR1</td>
<td>≤ 23 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR2</td>
<td>≤ 18 %</td>
</tr>
</tbody>
</table>

1.4.1 Filling Ability

Filling ability is defined as the ability of the fresh SCC to flow into and fill the spaces within the formwork under self-weight at the unconfined condition (EFNARC 2002). It is associated with the deformability, self-leveling capacity, and finishing ability of the SCC. The filling ability is an essential property of the SCC to achieve self-consolidation capacity. This property is crucial for concrete placement with proper casting technique (ACI 237R-07 2007). The filling ability primarily depends on the aggregate content, w/b ratio, binder content and HRWR dosage of concrete (Okamura & Ozawa 1995). A good filling ability can be achieved by limiting the coarse aggregate content and increasing the amount of fine aggregate and cementing materials, while adding a proper dosage of HRWR.
Filling ability is measured mostly using the slump flow test, which is simple and reliable. An estimate of the viscosity and the ability to parts through the narrow-opening can be obtained using the V-funnel test. However, it is reported that a number of factors, in addition to the viscosity, (namely, the deformation capacity (slump flow), size distribution and amount of coarse aggregate, and the shape of coarse aggregate) affect the V-funnel flow time. These effects have not been quantified, particularly the effect of aggregate shape. As stated earlier, the study of aggregate shape and its influence on various SCC properties could be helpful in improving the scope for SCC with marginally unsuitable aggregates.

1.4.2 Passing Ability

Passing ability is defined as the ability of the fresh SCC to flow through tight openings or spaces confined by steel reinforcing bars (EFNARC 2002). Where structures are heavily reinforced, good passing ability of SCC enables it to be placed and consolidated through dense reinforcing bars without any aggregate blockage (ACI 237R-07 2007). These factors affect the filling ability and also influence the passing ability of concrete. In addition, the passing ability depends on the number and spacing of the reinforcing bars. A good passing ability can be achieved by increasing the filling ability of fresh concrete and by limiting the segregation of coarse aggregates.

The resistance to blocking of concrete can be assessed by using the L-box test. This test indicates the one-dimensional filling ability in a restrained condition (as opposed to slump flow, which shows the two-dimensional unrestrained flow). This test is useful in two ways—both blocking and lack of stability can be detected visually. Further, modifications in this test could be helpful in analyzing the full flow behavior of concrete. For example, the size of the opening and its relative distance from the concrete could be varied to obtain a better understanding of the potential for blocking
at a lower velocity of flow. Passing ability of concrete can also be measured using the U-box apparatus, which has obstacles in the concrete flow path similar to those on the L-box test.

1.4.3 Segregation Resistance

The segregation resistance of SCC refers to its ability to remain uniform during and after placement without any loss of stability due to bleeding, mortar separation and coarse aggregate settlement (EFNARC 2002). In particular, the distribution of aggregates becomes non-uniform if SCC does not possess sufficient segregation resistance. It may affect the properties and durability of concrete. A recent study has reported that the water absorption and chloride penetration of SCC can be affected under poor segregation resistance. A good segregation resistance can be attained in SCC by a proper mixed composition. An increased amount of cementing materials, a small nominal maximum size of aggregate, limited content of well-graded coarse aggregates, and a low w/b ratio should be used to achieve good segregation resistance (Bonen & Shah 2005). In addition, the segregation resistance of SCC can be improved by using VMA (Okamura & Ozawa 1995).

The high filling ability of SCC makes the aggregates prone to settlement. Aggregate settlement depends on the viscosity of the cement paste. Tests for settlement enable quantification of the effect of mixture proportioning and height of placement on the stability of concrete.

In the early stages of SCC development, tendency for settlement was assessed using visual analysis of plane surfaces cut out of hardened concrete. The relative distribution of aggregates in the concrete has provided information about its potential for segregation and settlement. Apart from this, there have been some attempts to develop test methods to assess the stability of SCC in the fresh state itself. Cussigh et al (2003) have described three tests
to characterize the segregation potential of SCC. These tests-settlement column test, sieve stability test, and penetration test, are found to have acceptable repeatability and sensitivity.

In sieve segregation resistance tests, a fresh SCC sample is left undisturbed (static condition) for 15 minutes (min) in a bucket. The top layer of the sample is then poured onto a 5 mm sieve, and the mass of the mortar passing through the sieve is determined. Segregation potential is expressed as the ratio between the mass of mortar collected in the sieve and the original mass that is collected from the top portion.

The settlement column in the second test is a mould of height 400-500 mm, into which fresh SCC is poured. The test involves the collection of concrete samples from the top and bottom parts of this column after a controlled agitation (this simulates an additional disturbance) and the settlement period. The segregation potential is expressed as the ratio of the mass of coarse aggregates in the top and bottom parts.

The penetration test measures the segregation potential as the depth of penetration of a standard mass (54 gram) into the concrete. If the segregation is high, then the top part of the concrete would be mainly mortar, and the resultant depth of penetration would be high. For good SCC, penetration should not be more than 8 mm.

In spite of the large number of test methods, no single method or combination of methods has achieved widespread acceptance. Similarly, no single method has been found which characterizes all the relevant workability aspects of SCC, viz., filling ability, passing ability, and segregation resistance. Various combinations have been used to evaluate SCC behavior. For the initial mixture design of SCC, workability parameters such as filling ability (Filling ability), passing ability and stability (segregation resistance) should
be assessed. For site quality control, two test methods are sufficient to monitor production quality. Typical combinations are slump-flow and L-Box, or V-funnel and L-box. In addition, a critical portion of the proposed concrete structure can be tested in a mock-up trial.

1.4.4 Unit Weight

The unit weight of SCC refers to its mass per unit volume of fresh concrete. It depends on the mixture composition of the concrete. The unit weight of concrete becomes slightly lower when SCMs such as RHA, MK, fly ash and SF are incorporated (Zain et al 1999), because most SCMs are lighter than cement. However, it also depends on the physical and chemical properties of materials, and packing in concrete.

1.4.5 Air Content

Adequate air content must be maintained in SCC in order to protect it from freezing and thawing damage. The network of entrained air bubbles offsets the hydraulic pressure posed by freezing water, and thus improves the performance of concrete in freezing and thawing environment. However, obtaining the correct air content in SCC is not very straightforward. There are many factors such as mixture proportions, aggregate grading, the cement composition, HRWR, type and composition of SCM, mixing or placing method, and temperature, etc., which affect air-entrainment, and therefore, achieving the target air content becomes much more difficult (Du & Folliard 2005).
1.5 CURING PROCESS FOR SCC

Curing is ideally a process that keeps the concrete element as completely saturated as possible by the water-filled spaces. Concrete properties and durability are significantly influenced by curing since it greatly affects the hydration of cement. The hydration of cement virtually ceases when the relative humidity within the capillaries drops below 80% (Neville 1996). The lack of moisture in cement paste can also result in autogenous shrinkage due to self-desiccation. It is particularly a concern for the concretes with higher binder content and lower w/b ratio (Neville 1996). Moreover, the drying of the concrete surfaces results in shrinkage cracks that may aggravate the durability problems. Therefore, an efficient curing method is inevitable to prevent the concrete from drying and self-desiccation, and to maintain the relative humidity above 80%.

A proper curing of SCC is crucial to producing greater hydration products, and to reducing the porosity and drying shrinkage cracking of concrete, and thus to achieve higher strength and greater resistance to the physical or chemical attacks in aggressive environments. If SCC is not well cured, particularly at the early age, it will not gain the properties and durability at the desired level due to a lower degree of hydration, and would suffer from severe loss. Therefore, a suitable curing method such as water ponding, spraying of water, covering with wet burlap and plastic sheet, storing in a moist room, wrapping with polyfilm, or storing in the oven with controlled temperature is essential to produce strong and durable SCC.

1.6 HARDENED PROPERTIES OF SCC

Compressive strength, porosity, ultrasonic pulse velocity, absorption and permeability are some of the key hardened properties of SCC. They are briefly discussed below.
1.6.1 Compressive Strength

The Compressive strength is the most important mechanical property of concrete. In general, for a given set of cement and aggregates, and under the same mixing, curing and testing conditions, the compressive strength of concrete, primarily depends on w/b ratio, binder/aggregate (b/a) ratio, mixture composition, and degree of consolidation. However, it is the w/b ratio that mainly controls the development of compressive strength in concrete.

Ordinary concrete produces a compressive strength in the range of 20 to 40 MPa. The compressive strength of SCC is much higher than that of the ordinary concrete. For compressive strength varying from 50 to 125 MPa, the aforementioned range of w/b ratios is also valid for SCC (Persson 2001). Another observation is that the kinetics of strength increase is notably faster in SCC (Persson 2001) as compared to ordinary concrete due to increased gel/space ratio at lower w/b ratio.

1.6.2 Porosity

Porosity refers to a fraction of the total concrete volume that is occupied by pores in bulk cement paste, interfacial transition zone and aggregates. It is one of the major factors that control the strength of concrete (Neville 1996). Porosity also affects the electrical resistivity, and thus the corrosion resistance of concrete (Claisse et al 2001). The porosity of concrete can be characterized into two forms-total and capillary or suction porosity (Nokken & Hooton 2002). The total porosity is mainly comprised of capillary and air porosity. In contrast, the network of open pores mainly constitutes the capillary porosity of concrete. The capillary porosity has considerable effects on the transport properties and hence on the durability of concrete.
The total and capillary porosity is expected to be low in SCC (7 to 15%) as compared to the ordinary concrete due to the compacted pore structure. The pore system in SCC is more refined than that in the ordinary concrete, it is mainly because of proper hydration due to the high flow ability in nature. The higher degree of packing due to good consolidation, the greater degree of hydration due to deflocculation and dispersion of cement particles in the presence of HRWR, and the pozzolanic and micro-filling effects of SCM also contribute to forming a refined pore structure in SCC.

1.6.3 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity is defined as the traversed distance of the pulse or sonic wave per unit transit time. It is obtained from the path length (length of the interposed concrete specimen) and transit time. The ultrasonic pulse velocity of concrete is mainly influenced by the mixture composition of concrete, moisture and maturity of concrete, curing conditions and temperature. A high ultrasonic pulse velocity through concrete indicates that the concrete is of good quality. By the reference of IS 13311 (part-1) (1992), an ultrasonic pulse velocity above 4500 m/s states the ‘excellent’ quality of concrete, whereas an ultrasonic pulse velocity below 3000 m/s indicates ‘very poor or doubtful’ condition of the concrete.

Ultrasonic pulse velocity can be used to evaluate the physical quality of SCC. It is also useful to detect the dynamic modulus of elasticity, cracks and flaws, and to study the freeze-thaw durability of SCC. The ultrasonic pulse velocity of SCC is expected to be much higher than that of ordinary concrete and it is due to the refined pore structure and dense microstructure of SCC. However, no comprehensive studies have been conducted on the non-destructive evaluation of SCC using ultrasonic pulse velocity method.
1.6.4 Absorption

Absorption is the process by which a liquid gets into and tends to fill the open pores in a porous solid body, such as a component of concrete (ASTM C 125, 2002). From previous studies, the absorption is more significant in the surface layer than the core of the concrete due to strong capillary action. The rate at which a dry concrete surface absorbs a liquid can be taken as a predictor of the durability of concrete. Water is the most common liquid with which the concrete comes in contact. Hence, water absorption is widely used to indicate the absorptivity of concrete. It can be determined based on the increase in mass of a concrete specimen due to the penetration of water into its open pores.

Water absorption is directly related to concrete’s resistance to water penetration, which plays an important role in various deterioration mechanisms and carries many deleterious agents from the surroundings. Like other engineering properties, the water absorption of concrete is directly influenced by the porosity. The porosity controls the microstructure and thus the absorption of concrete, depending on the relative quantities of the pores of various types and sizes (Hearn et al 1997). When the porosity decreases, the water absorption is also reduced. It was reported that SCC provides a water absorption (percentage of water content at saturating condition) in the range of 3 to 6% (Vanwalleghem et al 2003).

1.6.5 Permeability

The permeability of concrete is defined as the movement of liquid and/or gas through a mass of concrete under a constant pressure gradient. It is an intrinsic property of concrete that chiefly depends upon the geometric arrangement and characteristics of the constituent materials. The permeability of concrete is mainly controlled by the compactness and the porosity of the
hydrated paste present in the bulk paste matrix and ITZ. In the hydrated paste, the capillary and gel pores can be distinguished. The gel pores may very small. Although they constitute a network of open pores, the permeability of this network is low. Conversely, the capillary pores are the relatively large spaces existing between the cement grains. It is the capillary porosity that greatly affects the permeability of concrete.

The permeability of SCC is typically lower than that of the ordinary concrete. The previous research showed that SCC results in very low water and gas permeability (Zhu & Bartos 2003). It is mostly attributed to the superior flow properties, dense microstructure and refined pore structure that develop in the presence of SCM and HRWR at low w/b ratio. Good flow properties result in excellent packing condition due to improved consolidation, and thus contribute to reducing the permeability of concrete.

1.7 LONG TERM PERFORMANCE OF BLENDED SCC

Issues of long-term performance of any concretes are receiving greater attention than ever before, due to a variety of causes. Hence, intensive research is carried out to address long-term performance as an important component in the design of concrete materials and structures.

A major emphasis has been given to the deterioration of concrete and reinforced concrete due to the transport properties of concrete, quantifying mechanism of diffusion of ions, permeation of fluids, capillary absorption and depassivation of steel reinforcement. It is well documented that Portland cement concrete incorporating supplementary cementing materials such as fly ash, blast-furnace slag, SF, RHA and MK develops excellent mechanical properties and long-term durability characteristics. In addition to that, the use of these materials is environmentally friendly because they partially replace Portland cement, reduce the release of carbon
dioxide to the environment, conserve the earth resources and solve the problem posed by waste management. Published data on those mineral admixtures suggest that they reduce the chloride ion penetration into concrete. For this reason, a superior corrosion resistance of the steel reinforcement in these admixtures blended cement concrete is expected.

1.7.1 Performance of Blended SCC on Water Permeability

In many concrete codes, the quality requirement is primarily based on the control of compressive strength. In order to ensure adequate durability and long term performance of the reinforced concrete structures exposed to aggressive environment, relevant quality parameters are needed, which can provide a better basis for the control of the concrete quality. Water absorption, volume of permeable voids, coefficient of water absorption, sorptivity, water permeability, chloride permeability and diffusion are being used in many countries as a general basis for the assessment of concrete durability.

The concrete society in the UK classifies concrete with water absorptions of amount 3 percent as good concretes. From the same specimens as for the water absorption, the measurement can also give information about permeable voids or porosity of concrete as per ASTM C 642. Characteristic difference in the pore system can often explain the difference in durability from one concrete to another. In addition to the total pore volume, it is valuable to know how much of this pore volume can be filled with water.

Water suction or capillary absorption parameters are being used in many countries as a general basis for assessment of concrete quality. Sorptivity is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of the material. The sorptivity test avoids many of the difficulties of the RCPT and can evaluate concrete containing conductivity materials. Lower sorptivity values are preferable to good concrete.
In literature a number of the different test methods for determining of water permeability (hydraulic conductivity) are given. Investigations into the permeability of concrete have shown that variation in the hydraulic gradient, water, temperature and possible evaporation from the output side may substantially affect the flow of water and mineral admixtures used. Therefore, when specifications based on water permeability are given, it is important to relate this to the corresponding test method to define the test condition.

1.7.2 Performance of Blended SCC on Chloride Permeability

For reinforced concrete structures, one of the major forms of environmental attack is chloride ingress, which leads to corrosion of reinforcing steel and subsequent reduction in the strength and durability of the structure (Ping Gu et al 1997). The ability of chloride ions to penetrate the concrete must be then known for design as well as quality control purpose.

The rapid chloride permeability test (RCPT) designated as AASHTO T-277 (ASTM 1202) in 1983 by the American Association of State Highway and Transportation Officials (AASHTO), was the first-ever test proposed for rapid qualitative assessment of chloride permeability of plain cement concrete. The total charge passed is determined in this RCPT to rate the concrete according to the criteria included in Table 1.4.

RCPT has been used to compare the resistance of different concretes to chloride ingress. Hence, it has proved very useful in finding economic mixes for high durability applications and has also helped in understanding the factors that improve resistance of concrete to chloride ingress. The charge passed through the concrete mixtures containing mineral admixtures such as SF and GGBFS can be used as a measure of the overall conductivity of concrete (Wee et al 2000).
Table 1.4 RCPT Rating (ASTM 1202)

<table>
<thead>
<tr>
<th>Charge Passed (Coulombs)</th>
<th>Chloride Ion Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4000</td>
<td>High</td>
</tr>
<tr>
<td>2000-4000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1000-2000</td>
<td>Low</td>
</tr>
<tr>
<td>100-1000</td>
<td>Very Low</td>
</tr>
<tr>
<td>&lt;100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Transportation of chloride ions inside a moist concrete is commonly assumed to be governed by a diffusion process which obeys Fick’s law of diffusion. The diffusion of chloride ions in hardened concrete is widely recognized as being of importance in relation to the corrosion of reinforcing bars. It is significant as a process by which chlorides from external sources penetrate the normal thickness of concrete cover. More generally, whenever chloride ions are present in concrete their influences on the passivity and anodic dissolution of the embedded metal must depend on their mobility in the vicinity of the metal / concrete interface, ionic mobility being linked to diffusivity.

1.7.3 Performance of Blended SCC on Chemical Resistance

Concrete structure, in general, is regularly subjected to aggressive environmental conditions. By its interactions with external influences, the mechanical and physical properties of concrete may be threatened and lost. When comparing the types of acids, sulfuric acid (H₂SO₄) and hydrochloric acid (HCl) are classified as the most aggressive natural threats for concrete structures (Turkel et al 2007). Their spectrum media are wide. Usually they originate from industrial processes, but they can even be due to urban activity. Free acids in natural waters are rare. Exceptions are carbonic waters and
sulfurous and sulfuric acids in peat waters. Soils may contain huminous acids. Several organic and inorganic acids may occur in the shallow regions of seawater as a consequence of bacteriological activity. Significant quantities of acids are present in sewage systems (Bassuoni et al 2007). The acidic attack is affected by the processes of decomposition and leaching of the constituents of cement paste. The very important volume of the addition in the paste of the SCC can be influenced positively or negatively by their resistances to acid aggressions depending on their physical and chemical properties (Dinakar et al 2008). Hence, studies of the effect of natural pozzolan, fly ash, SF, RHA, MK and others incorporated SCC against acid attacks are more important.

According to Zivica & Bajza (2002), blended Portland cements with pozzolans and GGBFS, are considered to be more resistant to the acidic attack than Portland cements. It should also be considered that the efficiency of blending for acid resistance may be affected by other factors, such as the cement used for blending, the amount and fineness of pozzolan used and especially curing conditions (Mehta 1985). Nevertheless, the blended Portland cements with pozzolans, such as blast furnace slags, fly ashes and others, have slower strength gain and hence slower reduction in permeability properties at early ages. Additionally, these cements are more curing sensitive than Portland cement. While the cement types differ in their degree of resistance to acids, these differences are small, and none of the concretes made with such materials is truly and continuously resistant to inorganic acids. Current emphasis is on producing dense and compact high performance concrete/ SCC to achieve durability and better performance of concrete in aggressive environments.
1.7.3.1 Mechanism of acid attack

Concrete is very alkaline in nature, and is extremely vulnerable to acid attack. The mechanism for this process is very simple. The products of cement hydration are forms as follows.

\[ \text{CS + H} \rightarrow \text{C-S-H + CH} \quad (1.1) \]

(Calcium Silicate + Water $\rightarrow$ Calcium Silicate Hydrate + Calcium Hydroxide)

Acid attack is caused by the reaction of an acid and the calcium hydroxide portion of the cement paste, which produces a highly soluble calcium salt by-product. These soluble calcium salts are easily removed from the cement paste, thus weakening the paste’s structure as a whole. This basic reaction is shown below:

\[ \text{Acid X + CH} \rightarrow \text{CX + H} \quad (1.2) \]

(Acid + Calcium Hydroxide $\rightarrow$ Calcium Salt + Water)

More aggressive acids such as hydrochloric, acetic, nitric, and sulfuric acids produce calcium salts that are very soluble. Less aggressive acids such as phosphoric and humic acids produce calcium salts with a lower solubility. These low soluble salts can act as a partial inhibitor to the overall process by blocking tiny passage in the cement paste through which water flows. Hence, it reduces the amount of calcium salts that enters into solution and retards the overall process.

A more aggressive and destructive case of acid attack occurs when concrete is exposed to sulfuric acid. The calcium salt produced by the reaction of the sulfuric acid and calcium hydroxide is calcium sulfate that in turn causes an increased degradation due to sulfate attack. This process is illustrated below:
\[ \text{H}_2\text{SO}_4 + \text{Ca(OH)}_2 \rightarrow \text{Ca(SO)}_4 + 2\text{H}_2\text{O} \] (1.3)

(Acid + Calcium Hydroxide \(\rightarrow\) Calcium Sulfate + Water (calcium sulfate product contributes to sulfate attack))

The disbanding of calcium hydroxide caused by acid attack proceeds in two phases. The first phase consists of acid reaction with calcium hydroxide in the cement paste. The second phase consists of acid reaction with the calcium silicate hydrate. As one would expect the second phase does not begin until all calcium hydroxide is consumed. The dissolution of the calcium silicate hydrate (C-S-H), in the most advanced cases of acid attack, can cause severe structural damage to concrete.

1.7.4 Performance of Blended SCC in Sulfate Attack

Sulfate attack is one of the most important problems concerning the durability of concrete structures. In general, the main sources of sulfate attack on concrete are from internal and external sources. The internal source is rare but originates from such concrete-making materials as hydraulic cements, fly ash, aggregate, and admixtures. However, the external sources are more common and usually are the result of high-sulfate soils and ground waters, or can be the result of atmospheric or industrial water pollution. Sulfates are highly soluble salts in the form of sodium sulfate (\(\text{Na}_2\text{SO}_4\)), calcium sulfate (\(\text{CaSO}_4\)), potassium sulfate (\(\text{K}_2\text{SO}_4\)), and magnesium sulfate (\(\text{MgSO}_4\)). Sulfate attack is a process in which sulfates react with the various phases of hydrated cement paste leading to deterioration of the concrete matrix through spalling, softening and mass loss, which in turn may result in the expansion and loss of strength and elasticity. It is recognized as a complex process due to the effect of numerous controlling factors (Shehata et al 2008).
Sulfate attack causes concrete deterioration by chemical and/or physical reactions. In this phenomenon, sulfate ions penetrating from the soil or ground water or already being in the concrete, mainly react with the aluminate phase of the cement. As a result, gypsum and an ‘ettringite’ type salt are produced that cause concrete deterioration due to expansion. The deterioration process is further accelerated when sulfate attack destabilizes calcium silicate hydrate, the major strength-providing hydration product of concrete (Attiogbe et al 2002).

Limited published works presented SCC, as showing better resistance to sulfate attack. Nagai et al (1999) developed an SCC that exhibited excellent sulfate resistance. A more recent study has also reported improved sulfate resistance of SCC. These studies indicate that the ingress of sulfate ions into SCC is impeded due to its reduced porosity and decreased transport properties. It is recognized that the addition of pozzolan reduces the calcium hydroxide in cement paste and improves the permeability properties of SCC. In this way it helps to increase the resistance of concrete to the attack of sulfate and other harmful solutions. The increase in the service life of the structure made from the blended cement containing pozzolan would further reduce the amount of Portland cement use.

1.7.4.1 Mechanism of sulfate attack

Dissolved sulfate salts can enter into chemical reactions with cement-based materials causing expansion, cracking and spalling, and/or softening and disintegration. The classical form of sulfate attack involves alkali sulfates such as sodium sulfate (Na₂SO₄) which reacts with portlandite (CH), monosulfate and unreacted C₃A to form gypsum (C-S-H) and ettringite (C₆A₃S·H₃₂), which can cause expansion, cracking, and deterioration of concrete. The exact mechanism of expansion and the role of gypsum and ettringite in the deterioration process remain subjects of controversy.
Santhanam (2001) has indicated the role of gypsum formation in the expansion and deterioration of cementitious matrices under external sulfate attack. He has also reviewed the mechanisms (topochemical growth, through-solution reactions, oriented crystal growth, etc.) by which ettringite can cause disruptive pressures in cement-based materials.

Migration of sulfate ions in concrete has been reported to cause the following chemical reactions:

\[
SO_4^{2-} + Ca^{2+} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O \quad (1.4)
\]

\[
SO_4^{2-} + 2Ca^{2+} + Ca_4Al_2(OH)_{12}.SO_4 \cdot 6H_2O \rightarrow Ca_6Al_2(OH)_{12}(SO_4)_3 \cdot 26H_2O \quad (1.5)
\]

The above equations indicate the possible decomposition of CH and C-S-H leading to softening along with the expansion. Hydroxyl ions (OH\(^{-}\)) may leach away to the surrounding solution resulting in a pH increase. In the case of alkali sulfates, alkali ions such as Na\(^+\) can migrate to the pore solution, which increases the risk of alkali aggregate reaction. Hydrated pozzolanic pastes with limited portlandite content and sulfate resistant cements with low C\(_3\)A content (less than 8\%) have a high resistance, but are not completely immune to alkali sulfates.

If carbonates/bicarbonates are available in the cementitious matrix with an abundance of moisture and a prevailing low temperature (less than 15°C), thaumasite (C\(_3\)SSCH\(_{15}\)) can readily form and eventually lead to thaumasite sulfate attack (TSA) (Crammond 2003). Thaumasite has been reported to form directly from C-S-H:

\[
SO_4^{2-} + 3Ca^{2+} + 3CO_3^{2-} + 3SiO_3^{2-} + 15H_2O \rightarrow 3CaO.SiO_2.CO_2.SO_3.15H_2O \quad (1.6)
\]
Progressive replacement of C-S-H with thaumasite usually produces a pulpy mass with non-binding characteristics. Numerous cases of this special form of sulfate attack have been reported since the last decade.

1.8 CORROSION OF REINFORCED STEEL IN CONCRETES

The corrosion of reinforced steel in concrete is an electrochemical process, where at the anode iron is oxidized to ferrous ions that pass into solution and at cathode oxygen is reduced to hydroxyl ions. Anode and cathode form a short-circuited corrosion cell with the flow of electrons in the steel and ions in the pore solution of the concrete.

The simplest expression of the basic electrochemical cycle considers the reaction of the anodic and cathodic zones of corroding steel. The flow of current in the steel from an anode to a cathode area, in the presence of oxygen and water, results in the production of hydroxyl ions at the cathode. As the hydroxyl ion migrates to the anode, it reacts with ferrous iron and forms hydrous iron oxide as per the following electrochemical equations:

$$\text{Fe} \rightarrow \text{Fe}^{++} + 2e^- \quad \text{[Anodic reaction]} \quad (1.7)$$

$$\text{H}_2\text{O} + \frac{1}{2}\text{O}_2 + 2e^- \rightarrow 2(\text{OH}^-) \quad \text{[cathodic reaction]} \quad (1.8)$$

$$\text{Fe}^{++} + 2(\text{OH}^-) \rightarrow \text{Fe(OH)}_2 \quad \text{[Anodic reaction] Ferrous hydroxide} \quad (1.9)$$

The total cell reaction, summarizing the equations (1.7) to (1.9), is ferrous hydroxide.

$$2\text{Fe} + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 2\text{Fe(OH)}_2 \quad (1.10)$$
The ferrous hydroxide further reacts with available oxygen and water resulting in

\[
4\text{Fe(OH)}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3 [\text{Anode}] \text{ Red rust} \quad (1.11)
\]

\[
3\text{Fe}^{++} + 8(\text{OH})^- \rightarrow \text{Fe}_3\text{O}_4 + 4\text{H}_2\text{O} + 8e^- \text{ Anode Black rust} \quad (1.12)
\]

The \(\text{Fe(OH)}_3\) constitutes hydrated red rust, the final product that precipitated from the solution. Corrosion in the form of rust formation and/or loss in cross-section of the rebar occurs in the presence of oxygen and water (humidity). Once this attack commences, corrosion products start to build up on the steel surface. Gradual accumulation of these products results in the development of disrupting tensile force, which may rupture the surrounding concrete and expose the steel bars to corrosive element (Figure 1.4).

**Environment**

Moisture enters into reinforcement and corrosion starts

Rust begins to form bulky corrosion products (Cracking & Staining)

Pressure build up causes spalling off concrete and exposure of reinforcement

**Figure 1.4 Mechanism of corrosion of steel in concrete**

Reinforcing steel in good quality concrete does not corrode, even if sufficient moisture and oxygen are available. This is due to the spontaneous formation of a thin passive protective film \(\gamma\)-\(\text{Fe}_2\text{O}_3\) on the steel surface in a highly alkaline pore solution of the concrete. It normally has a pH value in
excess of 12.5 (12.5 to 13.2). This protective coating remains intact at high pH value (around 13). The protection afforded to steel by high pH value persists while the concrete hardens and remains intact so long as the concrete environment surrounding the steel does not change significantly.

Once the hardened concrete has dried to equilibrium moisture content, the combined protection of steel depends entirely on the ability of the concrete to maintain the appropriate alkaline environment. However, the protective film of $\gamma$-Fe$_2$O$_3$ on the steel surface is usually disrupted when the pH value is reduced by the ingress of chloride or carbon dioxide due to capillary action, cracking and spalling of concrete and poor construction practices.

The most common cause of the rebar corrosion problem starts with the introduction of chloride ions. The chloride induced corrosion starts as pitting, i.e. there will be local corrosion in areas where the chloride ions have been able to penetrate into the oxide film. Pitting corrosion is auto catalytic, i.e. once started, it is a “Perpetuum mobile”.

\[
\begin{align*}
4\text{NaCl} & \rightarrow 4\text{Na}^+ + 4\text{Cl}^- & \text{(1.13)} \\
2\text{Fe} & \rightarrow 2\text{Fe}^{++} + 4\text{e}^- & \text{(1.14)} \\
2\text{Fe}^{++} + 4\text{Cl}^- & \rightarrow 2\text{FeCl}_2 & \text{(1.15)} \\
2\text{FeCl}_2 + 4(\text{OH})^- & \rightarrow 2\text{Fe(OH)}_2 + 4\text{Cl}^- & \text{(1.16)} \\
2\text{Fe} + \text{O}_2 + 2\text{H}_2\text{O} & \rightarrow 2\text{Fe(OH)}_2 & \text{(1.17)}
\end{align*}
\]

The iron-free chloride reaction itself perpetuates in that the free chloride originally responsible for the reaction is released for reuse when iron hydroxide is formed (Figure 1.5). In fact, the free chloride acts as a reaction catalyst.
The reasons for the corrosion of reinforcing steel in concrete can be listed as given below:

(a) The introduced salt dissolves in the pore water, resulting in free chloride ions:
(b) The steel dissolves at the anode
(c) As the oxygen is reduced at the cathode using the electron released at the anode.
(d) The chloride ions migrate towards the anode to maintain electro-neutrality
(e) The iron ion simultaneously tends to migrate towards the cathode, always in electrical equilibrium with the chloride ions. At the mouth of the pit, the former reacts with the hydroxyl ion formed on the cathode, releasing the chloride ions which are free to further attack
(f) The resulting net reaction consumes oxygen, water and iron.

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]

\[ Fe^{3+} + 3e^- \rightarrow Fe^{0} \]

\[ 2Cl^- \rightarrow Cl_2 + 2e^- \]

\[ Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \]

\[ Fe(OH)_2 + O_2 + 2H_2O \rightarrow Fe(OH)_3 \]

\[ Fe(OH)_3 + 3H^+ \rightarrow Fe^3+ + 3H_2O \]

Figure 1.5 Corrosion process due to chlorides
1.9 CORROSION MONITORING TECHNIQUES

Considerable effort has been invested in research and development over the past thirty years to devise a reliable technique for accurately assessing the state of corrosion and corrosion rate of steel in reinforced concrete structures. Since the corrosion is an electrochemical process, the traditional electrochemical methods are valuable also in assisting in the on-site monitoring of corrosion in concrete structure. The non-electrochemical methods indicate the composition and environmental factors which contribute to corrosion whilst the electrochemical methods measure the corrosion state and in situ kinetics.

The important techniques used for assessing the causes and state of corrosion of steel in concrete are:

1. Resistivity measurement
2. Gravimetric weight loss measurement
3. Electrochemical potential measurement
4. A.C Impedance technique
5. Macro cell corrosion technique

1.9.1 Resistivity Measurement

The Wenner array probe is a technique for determining the resistivity on concrete in situ, without removing cores to place between plates. It consists of a set of four probes, each at a constant distance apart. The two outer points are where the current is applied while the potential is measured with the two inner probes. Resistivity techniques have the advantages of speed and deal with the test method already familiar to many concrete
researchers. These techniques also provide a value that may be useful when determining corrosion rates in concrete, namely resistivity of the concrete. Electrical resistivity measurements are another indicator of the concrete composition and performance; high resistance would suggest a decrease in corrosion probability from galvanic effects. Table 1.5 gives some guidelines for qualitative identification of corrosion prone areas based on concrete resistivity.

Table 1.5 Concrete resistivity and probability of corrosion

<table>
<thead>
<tr>
<th>Resistivity (Ω-cm)</th>
<th>Corrosion Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;20,000</td>
<td>Negligible</td>
</tr>
<tr>
<td>10,000-20,000</td>
<td>Low</td>
</tr>
<tr>
<td>5000-10,000</td>
<td>High</td>
</tr>
<tr>
<td>&lt;5,000</td>
<td>Very High</td>
</tr>
</tbody>
</table>

1.9.2 Gravimetric Weight Loss Method

The gravimetric method has been used as the most accurate method to quantify the corrosion attacks in the laboratory experiments. The technique consists of weighing the specimen bars before and after being introduced into the concrete to be tested. The difference in weight (gravimetric loss) is a quantitative average of the attack. From the weight loss, the corrosion rate in mm per year is determined. The differential or instantaneous corrosion rate cannot be measured, but only a mean during the period of test. This technique is very time consuming and numerous specimens are necessary if the evolution of the process needs to be evaluated.
1.9.3 Electrochemical Potential Measurement

Visual and gravimetric methods, despite their usefulness under special circumstances, fail to meet the minimum requirement for adequate corrosion monitoring method owing to their destructive character and long time required to obtain significant results. While qualitative visual observation methods are non-destructive (require no samples of reinforcement pieces), they have very low speed of response to changes. Even though observations can be made instantaneously, detection of changes in systems with a high corrosion resistance takes too long. Direct corrosion measurement of the reinforced concrete structures by use of gravimetric technique is laborious, as it entails destruction of the specimen in order to obtain a single datum. For the above reasons, electrochemical methods are used for corrosion monitoring as they are reliable and accurate measurements in the corrosion process.

The simplest and fastest electrochemical techniques are that involving open circuit half cell potential ($E_{corr}$) measurement. The tendency of any metal to react to the environment is indicated by the potential it develops on contact with that environment. In reinforced concrete structures, concrete acts as an electrolyte and the reinforcement will develop a potential depending on the concrete environment. The principle involved in this technique is essentially a measurement of corrosion potential of rebar with respect to a standard reference electrode, such as saturated calomel electrode, copper / copper sulfate electrode, silver-silver chloride electrode and others. The corrosion potential measurement is made using a reference electrode placed on the concrete surface, which is connected via the negative terminal of high impedance voltmeter, and positive terminal is connected to the working electrode (rebar). The reference electrode is moved along the surface of the concrete and the corresponding potential are recorded as per ASTM C876.
Stratfull (1957) has adopted surface potential mapping as a method of detecting active corrosion area in the San Manteo Hayward Bridge, California. Potential distribution pattern identified the affected area of corrosion in concrete structures. In this technique, one reference electrode is kept fixed on the structure on a symmetrical point. The other reference electrode called moving electrode is moved along the structure on the nodal points of the grid as mentioned in open circuit potential measurements. The potential of movable electrode, when placed at nodal points, is measured against the fixed electrode using a high impedance voltmeter. A more negative potential reading represents area where corrosion is possible. The greater the potential difference between anodic and cathodic areas the greater is the probability of corrosion.

1.9.4 A.C. Impedance Technique

The use of the AC impedance technique in reinforced concrete corrosion studies was first started in the 1980s (Ping Gu et al. 2000). This technique has been used by an increasing number of researchers for the determination of corrosion current in the rebar in concrete. Instead of a DC perturbation being applied to the steel reinforcement as in LPR measurement, an AC voltage $\Delta E (+10$ to $20$ mv) is applied. This may be done either in the time or frequency domains using a spectrum or frequency response analyzer to measure the phase shift of current and voltage components and their amplitude. Both the phase shift and amplitude are frequency-dependent and the impedance data are obtained over a wide frequency range (100 kHz to 10 mHZ). The A.C impedance technique is to some extent subsidiary to the LPR technique; in fact, its kinetic estimation is obtained by using charge transfer resistance ($R_{ct}$) value deduced from an impedance diagram by alternating current technique.
1.9.5 Macro Cell Corrosion Technique

The corrosion of reinforced steel in concrete, is essentially an electrochemical process, where at the anode iron oxidized to iron ions (Fe++) that pass into solution and at the cathode oxygen is reduced to hydroxyl ions (OH-). Anode and cathode form a short-circuited corrosion cell, with the flow of electrons in the steel and of ions in the pore solution of the concrete. According to the different spatial location of anode and cathode corrosion in concrete can occur in different forms:

- As micro cells, where anodic and cathodic reactions are immediately adjacent, leading to uniform iron dissolution over the whole surface. Uniform corrosion is caused by the carbonation of the concrete or very high chloride content at the rebar.

- As macro cells, where a net distraction between corroding areas of the rebars (anode) and non-corroding passive surface (cathode) are found. Macro cell occurs mainly in the case of chloride induced corrosion (pitting), and the anode part is small with respect to the total (passive) rebar surface.

The macro cell corrosion technique introduces the theme of long term corrosion monitoring by embedding of macro cell devices. This includes galvanic couples of different steels or embedding steel in high chloride concrete to create a corrosion cell, as is popular in cathodic protection monitoring systems, particularly North America. This approach is also popular in laboratory corrosion studies of corrosion inhibitors and mineral admixtures and is being developed as an ASTM standard.